U–Pb (LA–ICP-MS) dating of detrital zircons from Cambrian clastic rocks in Avalonia: erosion of a Neoproterozoic arc along the northern Gondwanan margin

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Abstract: Most Neoproterozoic and Early Palaeozoic tectonic syntheses place Avalonia and related peri-Gondwanan terranes facing an open ocean along the northern margin of Gondwana, thereby providing important constraints for palaeocontinental reconstructions during that time interval. However, the precise location of Avalonia along the margin and its position relative to other peri-Gondwanan terranes is controversial. We present laser ablation–inductively coupled plasma mass spectrometry U–Pb data for detrital zircons from Cambrian clastic rocks in two localities in Avalonia: the Antigonish Highlands of Nova Scotia (62 analyses) and the British Midlands (55 analyses). The data from both samples are very similar, and taken together indicate an overwhelming dominance of Neoproterozoic (*c*. 580–680 Ma) or Early Cambrian source rocks with minor older Neoproterozoic clusters at *c*. 710 Ma or of Mesoproterozoic age, three Palaeoproterozoic zircons and one Archaean zircon. The zircons can all be derived from local Avalonian sources. The Neoproterozoic zircons are attributed to erosion of the underlying Avalonian arc. Mesoproterozoic and Palaeoproterozoic zircons of similar ages are also found in Avalonian Neoproterozoic clastic rocks and their presence in the Cambrian clastic rocks could represent recycling of Neoproterozoic strata and do not necessarily imply the presence of Mesoproterozoic or Palaeoproterozoic basement rocks within their respective drainage basins. Comparison with the data from the Neoproterozoic arc-related clastic sequences suggests significant differences between their respective drainage systems. Whereas the Neoproterozoic data require extensive drainage systems, the Cambrian data can be attributed to localized drainage systems. The change in drainage patterns could reflect rifting and isolation of Avalonia from Amazonia between *c*. 585 and 540 Ma. Alternatively, it might reflect the creation of topographical barriers along the northern Gondwanan margin, in a manner analogous to the Cenozoic rise of the Andes or the creation of the Basin-and-Range topography in the Western USA.

Keywords: Avalonia, Neoproterozoic, lower Palaeozoic, U–Pb, palaeogeography.

The late Neoproterozoic–Cambrian time interval is characterized by world-wide orogenic events, rapid continental growth, profound changes in climate and ocean geochemistry, and an explosion in biological activity that led to irreversible global change (e.g. Worsley *et al*. 1984; Hoffman 1991; Dalziel 1997; Hoffman *et al*. 1998). However, palaeocontinental reconstructions for this interval are relatively poorly constrained. Avalonia and related terranes (collectively termed 'peri-Gondwanan') formed along the northern Gondwanan margin (Fig. 1). Together, they record a protracted (*c*. 780–600 Ma) history of subduction followed at *c*. 600–550 Ma by a diachronous transition to a continental San Andreas-type transform fault environment, which terminated orogenic activity, followed by the development of a stable platform environment in the Early Cambrian (e.g. O'Brien *et al*. 1983; Keppie 1985; Murphy & Nance 1989, 1991; Taylor & Strachan 1990; Nance *et al*. 1991; Murphy *et al*. 1985, 2000; Nance *et al*. 2002; Keppie *et al*. 2003). This record implies that the peri-Gondwanan terranes faced an open ocean throughout the late Neoproterozoic and early Palaeozoic so that their locations provide important constraints on continental reconstructions for that time interval.

A wealth of varied geological data support strong tectonothermal linkages and possible former continuity between Avalonia and peri-Gondwanan terranes of Europe (e.g. Cadomia, Iberia, Bohemia; Quesada 1990; Rabu *et al*. 1990; Strachan *et al*. 1996*a*; Samson & D'Lemos 1998; Fernández-Suárez *et al*. 2000; Linnemann *et al*. 2000), the eastern USA (e.g. Carolina, Samson *et al*. 1995; Hibbard *et al*. 2002) and central America (e.g. Oaxaquia, Yucatan, Chortis; Keppie & Ortega-Gutiérrez 1995, 1999) in the Neoproterozoic. Although there is broad agreement on the peri-Gondwanan location of these terranes, their precise position with respect to each other is unclear. Dating of detrital mineral suites is a powerful tool that can be used to establish the possible provenance of clastic sedimentary rocks and hence assist in the development of palaeogeographical reconstructions (e.g. Adams & Kelley 1998; Rainbird *et al*. 2001; Fernández-Suárez *et al*. 2002*a*,*b*; Sherlock *et al*. 2002; Cawood *et al*. 2003; Friend *et al*. 2003). The interpretation of such information is inevitably highly problematic in rock sequences that have been detached from their source regions by transcurrent faulting and/or subsequent continental rifting and ocean formation. Nevertheless, such data can identify basement sources for the detritus and so are potentially useful for determining the palaeogeographical setting of terranes. Dating of detrital zircon suites has proved a

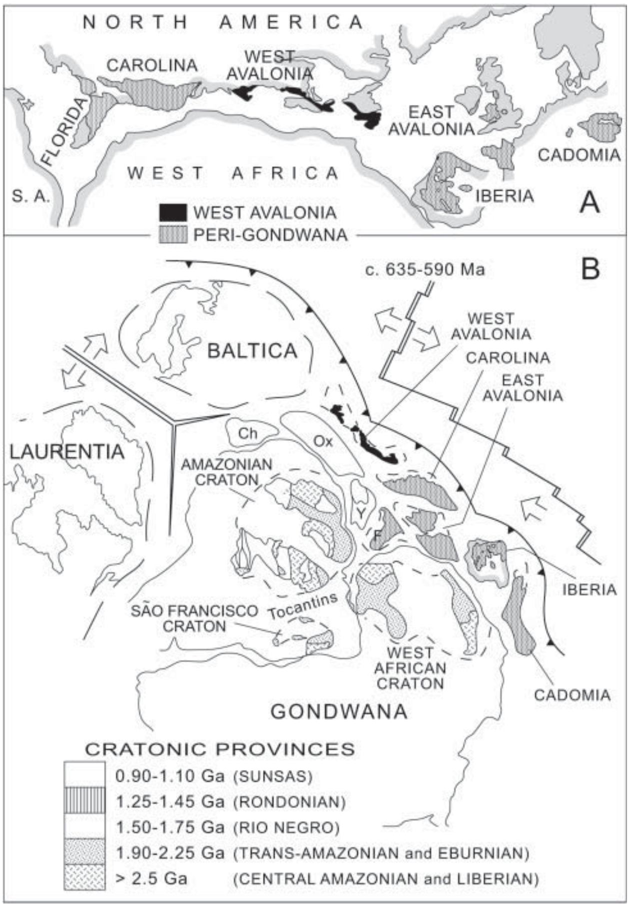

Fig. 1. (**a**) Early Mesozoic reconstruction of Pangaea A showing the locations of Neoproterozoic peri-Gondwanan terranes (modified from Nance & Murphy 1994). (**b**) Late Neoproterozoic reconstruction (modified from Nance *et al*. 2002) relative to the continental reconstruction of Dalziel (1997) showing Late Neoproterozoic orogens and adjacent cratonic provinces. Collisional belts shown include the Brasiliano fold belts (which contain the Tocantins and Borborema provinces), and the Trans-Saharan belt of West Africa. Accretionary belts include the Arabian–Nubian shield. Peri-Gondwanan terranes occur along the northern periphery of Gondwana (Ch, Chortis Block; Ox, Oaxaquia; Y, Yucatan Block; F, Florida).

particularly useful technique because zircon is very resistant to subsequent metamorphic and diagenetic effects. It is clear that zircons can be transported for long distances across cratons, but the age ranges of detrital mineral suites when combined with other data can constrain the identity of the cratonic landmass from which the detritus was derived. Along the northern Gondwanan margin, for example, the contrasting tectonothermal histories of the Amazonian and West African cratons provide a test for deducing the location of terranes along that margin. The West African craton is characterized by tectonothermal events at 2.6, 2.1 and 0.6 Ga, whereas the Amazonian craton also has Mesoproterozoic tectonothermal activity at *c*. 1.6 Ga and 1.1 Ga (Dallmeyer & Lecorché 1991; Ramos & Aleman 2000).

Recent publications have provided detrital zircon data for parts of Cadomia, Iberia and Bohemia (Fernández-Suárez *et al*. 2000, 2002*a*,*b*; Linnemann *et al*. 2000; Samson *et al*. 2001; Linnemann & Romer 2002; Gutiérrez-Alonso *et al*. 2003). In this paper, we provide similar data for Early Cambrian clastic sedimentary rocks in two parts of Avalonia (the Antigonish Highlands of Nova Scotia, Canada, and the English Midlands) and briefly compare these data with those for clastic rocks of a similar age in other peri-Gondwanan terranes.

General geology

A generalized tectonostratigraphy for Avalonia is shown in Figure 2. Avalonia is characterized by voluminous 635–570 Ma arc-related Andean-style magmatism, development of arc basins and mafic to felsic broadly calc-alkaline plutonism. Vestiges of early arc magmatism, ranging from *c*. 750 Ma to 660 Ma are locally preserved (e.g. Doig *et al*. 1993; Strachan *et al*. 1996*b*). Between 590 and 540 Ma, there is a transition from an arc to a San Andreas-type transform setting (Nance *et al*. 2002), followed by Early Cambrian development of a platform setting with laterally extensive lithostratigraphic units (e.g. Landing 1996).

Nova Scotia

In the Antigonish Highlands of Nova Scotia, Avalonia consists of the *c*. 615 Ma Georgeville Group, a *c*. 4000 m succession of arc-related volcanic rocks overlain by a thick sequence of turbidites that represents the development of a volcanic arc basin (Murphy & Keppie 1987; Murphy *et al*. 1991). These rocks are poly-deformed, metamorphosed to lower greenschist facies and syn- to post-tectonically intruded by *c*. 610–605 Ma calc-alkalic mafic to felsic plutons. These Neoproterozoic rocks are unconformably overlain by Cambrian to Lower Ordovician rocks (Fig. 3) which are divided into two groups that are lateral facies equivalents, the predominantly sedimentary Iron Brook Group and the predominantly volcanic McDonalds Brook Group (Keppie & Murphy 1988). The present contacts between these groups are thrusts (Keppie & Murphy 1988). The Iron Brook Group consists of basal red fluviatile conglomerates and red slates, overlain by red

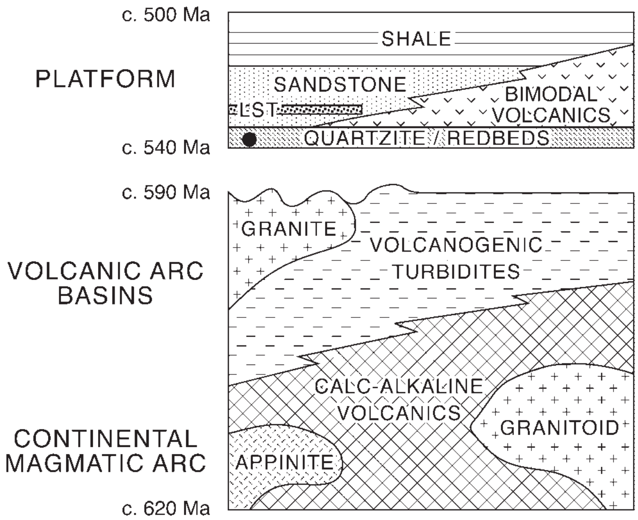

Fig. 2. Schematic diagram summarizing the Neoproterozoic and Palaeozoic tectonothermal evolution of Avalonia in mainland Nova Scotia and Britain. The sequence is similar in other parts of Avalonia, although the timing may be different because the development of each tectonic event was diachronous (e.g. Nance *et al*. 2002). The nature of the contact between the early arc volcanic rocks and the continental magmatic arc is not known. The contact between the volcanic arc basins and arc to rift transition varies from conformable to unconformable.

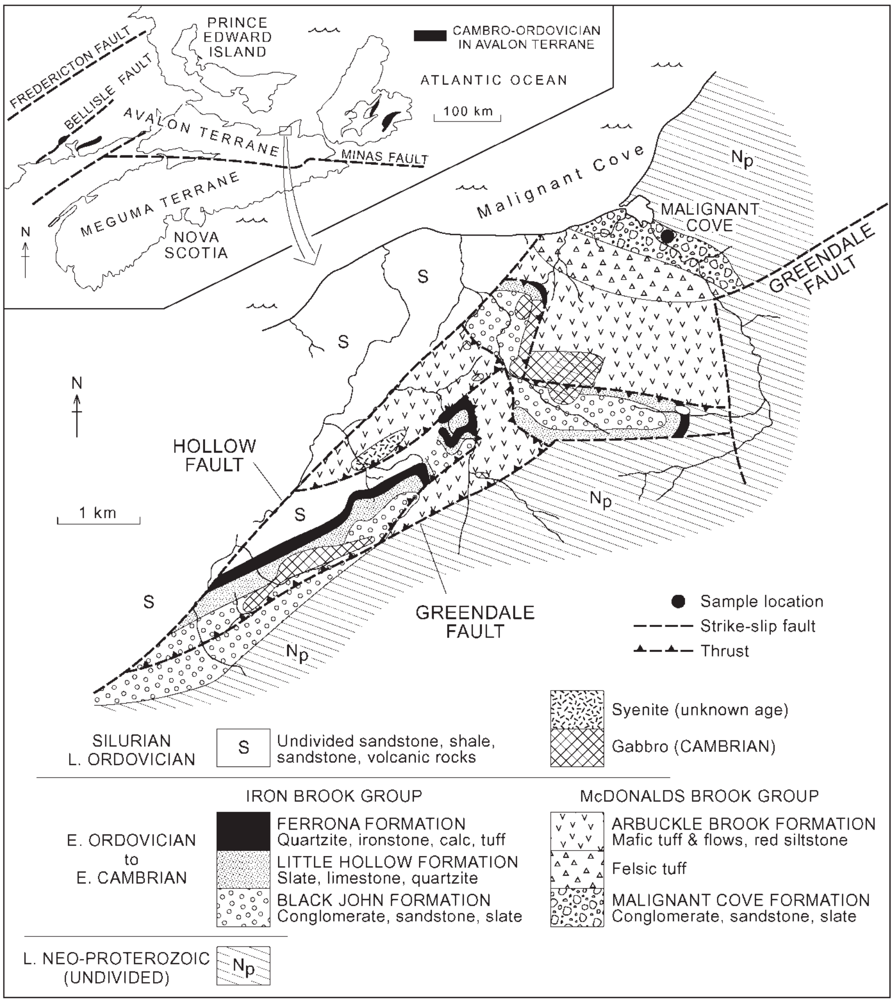

Fig. 3. Simplified geological map of the Cambro-Ordovician rocks of the Antigonish Highlands (modified after Murphy *et al*. 1991).

slates and pink limestones that contain Early Cambrian fossils (Landing & Murphy 1991), and followed by ironstones and quartzites that may be Early Ordovician in age. The McDonalds Brook Group consists of red conglomerates and shales at the base (Malignant Cove Formation) overlain by a thick sequence of bimodal volcanic rocks and minor red clastic rocks (Arbuckle Brook Formation). The sample analysed for this study is a conglomerate from the Malignant Cove Formation (Fig. 3). The conglomerate was deposited in a fluviatile environment and contains clasts of mafic to felsic volcanic rocks, green sericitic slate, siltstone, wacke, granite, jasper, perthitic feldspar, albite and quartz. Many of these clasts are similar to the lithologies of the underlying Georgeville Group (Murphy *et al*. 1991). The matrix is dominated by sericite, chlorite and quartz. Thick (*c*. 5–9 km) turbidite deposits of similar stratigraphic age are found in the Meguma terrane in southern Nova Scotia but the original relationship between the Avalon and Meguma terranes is controversial (see Keppie *et al*. 1997; Schenk 1997).

English Midlands

Inliers of Avalonian strata crop out in the west of the English Midlands in Shropshire (Fig. 4). The oldest rock unit exposed is the arc-related Uriconian Group, consisting of lavas and tuffs of basaltic, basaltic-andesite, dacitic and rhyolitic composition (Pharaoh *et al*. 1987). A rhyolitic lava from the group has yielded a precise U–Pb zircon age of 566 ± 2 Ma (Tucker & Pharaoh 1991). The Uriconian Group is intruded by the Ercall Granophyre, a small granitic intrusion of possible subvolcanic origin (Fig. 4) that has yielded a precise U–Pb zircon age of 560 ± 1 Ma (Tucker & Pharaoh 1991). A period of folding may have occurred after the intrusion of the Ercall Granophyre (Compston *et al*. 2002), but its effects at outcrop scale are negligible. Both the Uriconian Group and the Ercall Granophyre are overlain unconformably by the Lower Cambrian Wrekin Quartzite (Fig. 4); the contact is spectacularly exposed at the Ercall Quarry (National Grid reference SJ 643 096) and has been the focus of much discussion concerned with the age of the base of the Cambrian in this part of Avalonia (Cope & Gibbons 1987; Wright *et al*. 1993; Rushton 1999). The unconformity is the classic marine sub-Cambrian planar unconformity seen in many parts of the English Midlands and South Wales, where it is usually overlying the eroded remnants of the Avalonian volcanic arc.

The Wrekin Quartzite comprises a lower conglomeratic member, *c*. 6 m thick, which is overlain by a white–grey quartzite, *c*. 28 m thick (Wright *et al*. 1993). The overall sedimentary facies are consistent with deposition in a shallow-marine environment.

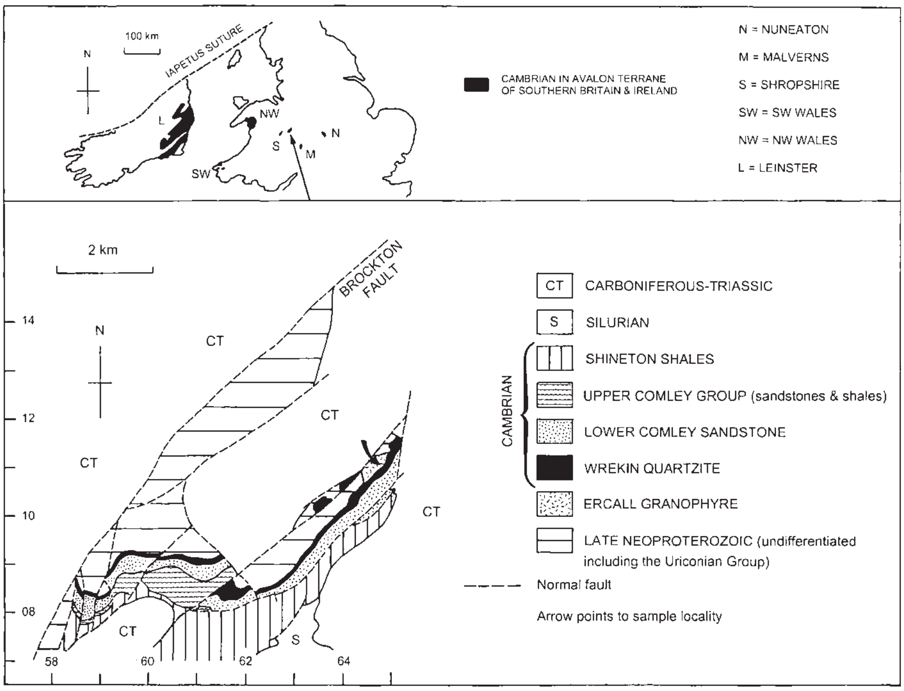

Fig. 4. Generalized geological map of the location of the Cambrian Wrekin Quartzite and the underlying Ercall Granophyre in Shropshire, England (simplified fromBritish Geological Survey 1978). The Lower Comley Limestone is included within the Lower Comley Sandstone map unit.

The basal conglomerate member is mainly pebble-grade, with well-rounded clasts of mostly fine-grained igneous rocks, including some flow-banded lavas and tuffs as well as granophyric material that is presumed to have been derived directly from the underlying pluton. A shale horizon within the quartzite member contains acritarchs of Tommotian age (Wright *et al.* 1993), indicating that it was deposited shortly after 535 Ma (Compston *et al.* 2002). A disconformity separates the Wrekin Quartzite from the overlying Lower Comley Sandstone and Lower Comley Limestone (Fig. 4), both deposited in a nearshore marine setting (Fig. 5; Brasier *et al.* 1992; Woodcock 2000). These are overlain disconformably by the offshore marine shales of the Upper Comley Group (Figs 4 and 5), reflecting the influence of the mid-Cambrian transgression. A further disconformity separates these strata from the upper Cambrian to Tremadoc Shoot Rough Road Shales and the Shineton Shales, both deposited in an offshore marine environment (Figs 4 and 5; Woodcock 2000). The sample analysed for this study is a conglomerate from the lowermost part of the Wrekin Quarztite; it was collected less than a metre above the basal unconformity that separates the unit from the underlying Ercall Granophyre.

Analytical techniques

Samples HMB and ERCALL were crushed with a jaw crusher and pulverized with a disc mill. Zircons were separated at the Complutense University of Madrid by heavy fraction enrichment on a Wilfley table followed by magnetic separation in a Frantz isodynamic separator and density separation using di-iodomethane (CH_2I_2). Zircons were hand-picked in alcohol under a binocular microscope and grains representing all sizes and morphological types were selected for laser ablation–inductively coupled plasma mass spectrometry (LA–ICP-MS) analysis. Grains were set in synthetic resin mounts, polished to approximately half their thickness and cleaned in a warm HNO_3 ultrasonic bath. Analytical instrumentation consisted of a UP213 frequency quintupled Nd:YAG based laser ablation system (NewWave Research, Fremont, USA) coupled to a (Thermo Elemental) PQ3, quadrupole based ICP-MS instrument with enhanced sensitivity (S-Option) interface. Instrument and operating parameters used for individual zircon analyses were as given by Jeffries *et al.* (2003).

Samples and standard were ablated in an airtight sample chamber flushed with helium for sample transport. The laser was focused on the sample surface and energy density was kept constant for each analysis.

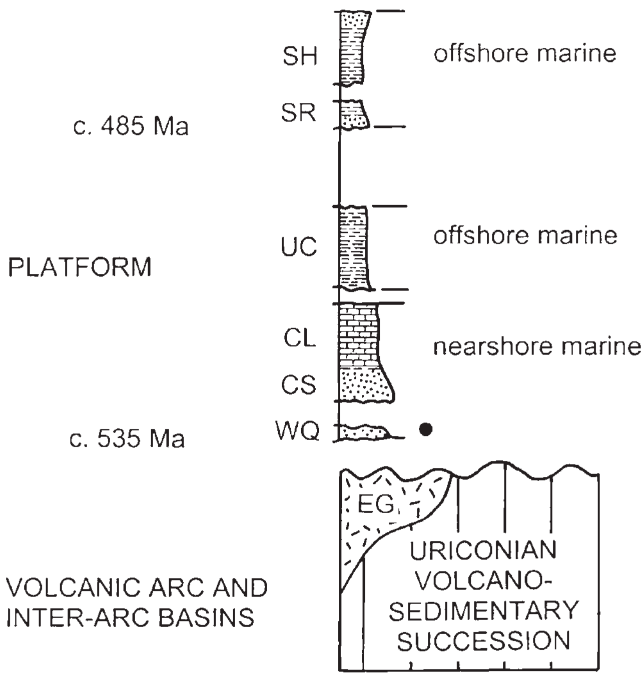

Fig. 5. Generalized tectonostratigraphic column for the Wrekin area of Shropshire, England. EG, Ercall Granophyre; WQ, Wrekin Quartzite (● emphasizes stratigraphic level of dated sample); CS, Lower Comley Sandstone; CL, Lower Comley Limestone (included within CS in Fig. 4); UC, Upper Comley Group; SR, Shoot Rough Road Shales; SH, Shineton Shales (the latter two grouped within SH in Fig. 4).

The samples were rastered along lines *c*. 30–60 μm long, using a constant raster speed for each analysis. Beam diameter was typically 25 μm and in the case of small zircon grains a beam diameter of 15 μm was used.

Data were collected in discrete runs of 20 analyses, comprising 12 unknowns bracketed before and after by four analyses of the standard zircon 91500 (Wiedenbeck *et al*. 1995). Twenty determinations of the standard zircon 91500, measured as an unknown, were taken throughout the analytical sessions. The weighted average of the $^{206}Pb/^{238}U$ is 1062.6 ± 0.9 Ma (isotope dilution thermal ionization mass spectrometry (ID-TIMS) $^{206}Pb/^{238}U$ is 1062.4 ± 0.4 Ma) and the weighted average of the $^{207}Pb/^{206}Pb$ is 1065.7 ± 0.8 Ma (ID-TIMS $^{207}Pb/^{206}Pb$ is 1065.4 ± 0.3 Ma).

Data for sample zircons were collected for up to 150 s per analysis with a gas background taken during the initial *c*. 60 s. For each analysis, time-resolved signals were collected and then carefully studied to ensure that stable flat signal intervals (free from inclusions, core–rim features, zones of high common Pb or evidence of fractionation) were used in the age calculations. Preliminary selection of background and sample isotope ratio values and data calculation was performed using lamtrace, a macro-based spreadsheet written by S. Jackson (Macquarie University, Sydney). Background and mass bias corrected intensities and counting statistics were calculated for each isotope. Errors on the ratios and ages represent 2σ internal precision. Concordia and intercept age calculations, and concordia and cumulative probability plots were performed using isoplot/ex rev. 2.49 (Ludwig 2001).

Data treatment, assignment of final ages and errors for individual analyses, estimation of common Pb and criteria for rejection of analyses are those detailed by Fernández-Suárez *et al*. (2002*b*) and Jeffries *et al*. (2003).

Common Pb

The ages reported in this paper are not common-lead corrected as ^{204}Pb measurements are rendered useless by the isobaric interference from Hg, a contaminant present in the argon supply gas. ^{204}Hg interferes on ^{204}Pb and the ^{202}Hg peak is too small to allow a reliable overlap correction of acceptable precision. It should also be noted that the $^{208}Pb/^{232}Th$ age is very sensitive to common Pb contamination, resulting in $^{208}Pb/^{232}Th$ ages (not reported in Tables 1 and 2) that are significantly older than the $^{206}Pb/^{238}U$ ages. In this study we rejected only three analyses based on that criterion. The ^{208}Pb correction method (Compston *et al*. 1984) cannot be applied reliably to U–Pb analyses as the assumption of ideal concordance between $^{206}Pb/^{238}U$ and $^{208}Pb/^{232}Th$ is not always justified.

Recently, Anderson (2002) has proposed a common lead correction method that neither uses ^{204}Pb nor assumes concordance, but relies instead on the assumption of coherent behaviour of the U–Pb and Th–Pb systems during Pb loss. Application of this correction algorithm did not reveal any significant shift as a result of common lead in the reported analyses (Tables 1 and 2), which are those selected based on the examination of time-integrated isotope ratio plots and degree of discordance. It is worth noting here that, in our experience, a judicious examination of the time-integrated U–Pb, Th–Pb and Pb–Pb isotope ratio plots allows the analyst to detect analyses (or parts of an analysis) that are likely to contain significant amounts of common lead. Furthermore, it should be noted that *c*. 95% of the analyses in sample ERCALL and *c*. 70% of analyses in sample HMB are concordant at the 2σ confidence level, and those whose 2σ error ellipses do not overlap concordia have a discordance (calculated from ($^{206}Pb/^{238}U$)/($^{207}Pb/^{206}Pb$) age) of less than 10%.

Results

A total of 138 analyses (one analysis per grain) were performed on zircons from samples HMB (72 analyses) and ERCALL (66 analyses). Of those analyses 21 were rejected (10 for HMB and 11 for ERCALL) based on the presence of features such as discordance >10%, high common Pb detected in the Pb–Pb isotope ratio plots, elemental U–Pb fractionation or inconsistent behaviour of U–Pb and Th–Pb ratios in the course of ablation.

Table 1 reports U–Pb and Pb–Pb ratios and ages for the 62 HMB selected analyses, and Table 2 reports those for the 55 ERCALL selected analyses. The ages labelled as 'reported age' in the tables are calculated as follows. For concordant analyses (ages whose corresponding isotope ratios have a 2σ error ellipse that, to a greater or lesser extent, overlaps the concordia curve) we report concordia ages and errors as defined by Ludwig (1998). For normally discordant analyses we report the $^{207}Pb/^{206}Pb$ age and 2σ error. For slightly reversely discordant zircons younger than *c*. 900 Ma and whose $^{207}Pb/^{206}Pb$ ages have large errors owing to small amounts of ^{207}Pb we use the more precise $^{206}Pb/^{238}U$ age and corresponding 2σ error. These results are illustrated in the concordia and cumulative probability plots of Figs 6 and 7.

Sample HMB features an overwhelming dominance of Neoproterozoic zircons (56 in a total of 62) with a continuous cluster spanning from 585 ± 5 Ma (age of the youngest zircon dated in this sample) to 676 ± 8 Ma (Fig. 6). In the cumulative probability plot, there are relative peaks at *c*. 588, 600, 612, 626, 644 and 664 Ma (Fig. 6b). An older Neoproterozoic cluster (six analyses) features three concordant analyses at 707–715 Ma and three discordant (6–8% discordance) analyses with older $^{207}Pb/^{206}Pb$ ages (756–764 Ma) (Fig. 6c). Of the remaining six analyses (Table 1, Fig. 6), five are Mesoproterozoic at *c*. 1023, 1154, 1218, 1542 and 1608 Ma and one is Palaeoproterozoic (1938 Ma).

Sample ERCALL (Table 2, Fig. 7) is dominated by Neoproterozoic and early Cambrian zircons. Both the concordia plot and the cumulative probability plot show the presence of three clusters with apparent gaps between them. The youngest cluster (17 analyses) contains latest Neoproterozoic and earliest Cambrian ages from 564 ± 5 to 534 ± 8 Ma. This cluster is separated by a gap of *c*. 30 Ma from an older Neoproterozoic cluster (23 analyses) with ages ranging from 598 ± 6 Ma to 628 ± 7 Ma. This cluster is in turn separated by a *c*. 20 Ma gap from an older cluster (eight analyses) ranging in age from 651 ± 10 to 672 ± 9 Ma. Finally, one analysis yielded an older Neoproterozoic age of 714 ± 10 Ma. Of the remaining six analyses (Table 2, Fig. 7) four are Mesoproterozoic at *c*. 1036, 1061, 1198 and 1539 Ma. Two discordant analyses yielded Palaeoproterozoic (*c*. 1.7 Ga) and Archaean (*c*. 3 Ga) ages.

Interpretation

Comparison between Cambrian Avalonian samples

In both samples, the bulk of zircons can be attributed to erosion of the Avalonian Neoproterozoic arc. In addition, there is a paucity of detrital zircons between *c*. 670–680 and *c*. 700–710 Ma, a time of relative quiescence within the Avalonian arc (e.g. Murphy *et al*. 2000; Nance *et al*. 2002; Keppie *et al*. 2003). These data suggest that the bulk of the detritus was derived from local sources.

Both samples are characterized by the scarcity of pre-Neoproterozoic zircons (around 10% in both samples). Within the 12 pre-Neoproterozoic zircons, 10 are Mesoproterozoic (1–1.6 Ga), clearly indicating that old cratonic sources were not an important source of detritus for either rock. In addition, as zircons of these ages are also found in Avalonian Neoproterozoic clastic rocks (e.g. Keppie *et al*. 1998), their presence in the Cambrian clastic rocks could represent recycling of Neoproterozoic strata and does not necessarily imply the presence of Mesoproterozoic or

Table 1. *LA–ICP-MS detrital zircon data for sample HMB-1, Malignant Cove Formation, Antigonish Highlands, Avalon terrane of Nova Scotia*

Analysis number	i.s. (s)	Isotopic ratios and 2σ (%) errors						Ages and 2σ absolute errors (Ma)						Reported age		
		$^{206}Pb/^{238}U$	±2σ	$^{207}Pb/^{235}U$	±2σ	$^{207}Pb/^{206}Pb$	±2σ	$^{206}Pb/^{238}U$	±2σ	$^{207}Pb/^{235}U$	±2σ	$^{207}Pb/^{206}Pb$	±2σ	Age (Ma)	±2σ	Disc. %
jn17a06	51	0.0955	1.12	0.7762	1.26	0.0589	1.38	588	6	583	6	564	30	585	5	−4.3
jn17a05	43	0.0952	1.36	0.7810	1.68	0.0595	1.00	586	8	586	7	584	20	586	7	−0.3
jn17b05	59	0.0946	1.88	0.7836	1.98	0.0600	1.56	583	10	588	9	604	32	586	9	3.5
jn17b15	64	0.0948	1.06	0.7890	1.66	0.0604	1.54	584	6	591	7	616	34	586	6	5.2
jn17a07	41	0.0956	0.76	0.7840	1.50	0.0595	1.54	588	4	588	7	584	32	588	4	−0.7
jn18a05	72	0.0951	0.84	0.7932	1.58	0.0605	1.60	586	5	593	7	620	36	588	5	5.5
jn17a08	36	0.0954	1.88	0.7943	3.60	0.0604	3.80	587	11	594	16	616	82	589	10	4.7
jn17a09	54	0.0961	1.22	0.7850	2.12	0.0593	2.50	591	7	588	9	576	54	590	6	−2.6
jn17a10	49	0.0959	1.18	0.7911	1.76	0.0598	1.20	591	7	592	8	594	26	591	7	0.5
jn17a11	54	0.0965	1.12	0.7952	1.70	0.0598	2.12	594	6	594	8	594	46	594	5	−0.1
jn17b11	61	0.0964	0.96	0.8017	1.10	0.0603	1.48	593	5	598	5	612	32	596	5	3.1
jn18a06	64	0.0964	1.38	0.8046	1.76	0.0605	1.34	593	8	599	8	622	30	596	8	4.7
jn17a12	36	0.0972	0.92	0.7976	1.62	0.0595	1.76	598	5	595	7	584	40	597	5	−2.4
jn17a13	66	0.0970	1.72	0.8114	2.50	0.0607	2.54	597	10	603	11	626	54	599	9	4.6
jn17a14	61	0.0975	0.90	0.8123	1.66	0.0604	1.38	600	5	604	8	616	30	600	5	2.6
jn17a15	59	0.0983	2.98	0.8091	2.58	0.0597	1.44	604	17	602	12	592	32	601	11	−2.0
jn17a16	77	0.0976	1.02	0.8115	1.16	0.0603	1.20	601	6	603	5	612	26	602	5	1.8
jn17b06	56	0.0983	1.14	0.8146	1.96	0.0601	2.02	604	7	605	9	606	44	605	6	0.3
jn17b08	51	0.0987	1.06	0.8138	1.36	0.0598	1.14	607	6	605	6	596	24	606	6	−1.8
jn17b09	74	0.0933	1.52	0.7747	1.46	0.0602	0.44	575	8	582	6	610	10	610	10	5.7
jn17b10	43	0.0991	1.26	0.8289	1.16	0.0607	1.42	609	7	613	5	626	30	612	5	2.7
jn17b12	69	0.0993	1.00	0.8306	1.38	0.0606	1.46	610	6	614	6	626	32	612	5	2.6
jn17b13	33	0.0994	2.26	0.8292	2.74	0.0605	2.34	611	13	613	13	620	50	612	11	1.5
jn18d08	46	0.0996	1.60	0.8074	1.94	0.0588	1.48	612	9	601	9	558	32	612	9	−9.7
jn17b14	49	0.0998	1.34	0.8360	2.54	0.0607	1.76	613	8	617	12	628	38	613	8	2.4
jn17b16	49	0.0936	1.98	0.7810	2.52	0.0605	1.18	577	11	586	11	620	26	620	26	6.9
jn18a14	61	0.1007	1.28	0.8464	1.06	0.0610	1.16	618	8	623	5	636	26	622	5	2.8
jn18a09	66	0.1020	1.52	0.8440	2.02	0.0600	1.74	626	9	621	9	602	36	624	8	−4.0
jn18a07	49	0.1017	0.80	0.8512	1.10	0.0607	1.12	625	5	625	5	626	24	625	4	0.2
jn18a08	46	0.0956	1.70	0.8000	2.48	0.0607	1.76	589	10	597	11	626	38	626	38	5.9
jn18d09	31	0.1019	1.48	0.8680	2.94	0.0618	2.42	625	9	634	14	666	52	626	9	6.2
jn18d11	89	0.1027	1.24	0.8467	1.88	0.0598	1.96	630	7	623	9	594	44	627	7	−6.1
jn18d10	49	0.1026	0.94	0.8402	2.16	0.0594	1.84	629	6	619	10	582	40	629	6	−8.1
jn18a10	41	0.0968	1.62	0.8118	2.66	0.0608	1.76	596	9	603	12	630	38	630	38	5.4
jn18a11	69	0.1032	0.90	0.8566	1.34	0.0602	1.22	633	5	628	6	610	26	631	5	−3.8
jn18a12	46	0.0966	1.10	0.8111	1.44	0.0609	1.44	595	6	603	7	634	30	634	30	6.2
jn18a13	79	0.0973	0.88	0.8175	1.66	0.0609	1.52	599	5	607	8	636	34	636	34	5.8
jn18a15	49	0.1036	1.78	0.8714	2.02	0.0610	1.94	636	11	636	10	638	42	636	9	0.3
jn18a16	59	0.1043	1.32	0.8722	1.94	0.0606	1.78	640	8	637	9	626	38	638	7	−2.2

jn18b12	51	0.1043	1.32	0.8948	1.94	0.0622	2.06	639	8	649	9	682	44	643	7	6.3
jn18b05	69	0.0970	1.62	0.8193	2.18	0.0612	1.28	597	9	608	10	646	28	646	28	7.6
jn18b06	33	0.1055	1.54	0.8959	3.64	0.0616	3.56	647	9	650	17	658	76	647	9	1.7
jn18b07	43	0.1064	1.72	0.9046	3.18	0.0617	2.94	652	11	654	15	662	64	652	10	1.5
jn18b08	54	0.0984	1.54	0.8342	1.86	0.0615	1.40	605	9	616	9	656	30	656	30	7.8
jn18b09	64	0.1082	2.30	0.9273	3.46	0.0622	2.58	662	14	666	17	678	56	663	14	2.4
jn18b10	59	0.1010	1.26	0.8603	1.48	0.0618	0.90	620	8	630	7	664	18	664	18	6.6
jn18b11	94	0.1085	1.44	0.9025	1.72	0.0603	1.78	664	9	653	8	614	38	664	9	−8.1
jn18d14	59	0.1106	1.30	0.9228	1.90	0.0605	1.22	676	8	664	9	620	26	676	8	−9.0
jn18b14	36	0.1042	1.80	0.9048	1.50	0.0630	1.54	639	11	654	7	706	32	706	32	9.5
jn18b15	77	0.1160	1.38	1.0034	2.00	0.0627	2.04	707	9	706	10	698	44	707	8	−1.3
jn18b16	43	0.1162	1.38	1.0180	1.96	0.0635	1.76	709	9	713	10	726	38	710	8	2.3
jn18c05	66	0.1184	1.56	1.0150	1.82	0.0622	1.82	721	11	711	9	680	38	715	8	−6.0
jn18c06	43	0.1154	1.28	1.0262	2.08	0.0645	2.28	704	9	717	11	756	48	756	48	6.9
jn18c07	56	0.1194	1.24	1.0631	1.32	0.0645	1.16	727	9	735	7	758	24	758	24	4.1
jn18c08	43	0.1157	1.26	1.0327	1.70	0.0647	1.86	706	8	720	9	764	38	764	38	7.6
jn18c09	84	0.1496	1.58	1.4449	1.58	0.0700	1.04	899	13	908	9	928	20	928	20	3.1
jn18c10	74	0.1724	1.08	1.7369	1.24	0.0731	1.38	1025	10	1022	8	1014	28	1023	7	−1.1
jn18c11	54	0.1969	1.54	2.1181	1.28	0.0780	0.94	1159	16	1155	9	1146	20	1154	8	−1.1
jn18c12	61	0.1998	1.28	2.2290	1.26	0.0809	0.44	1174	14	1190	9	1218	8	1218	8	3.6
jn18c13	46	0.2614	0.84	3.4532	1.02	0.0958	0.72	1497	11	1517	8	1542	14	1542	14	2.9
jn18c14	33	0.2791	2.12	3.8490	1.72	0.1000	1.32	1587	30	1603	14	1622	26	1608	13	2.2
jn18c15	56	0.3481	1.38	5.7311	1.46	0.1194	1.06	1925	23	1936	13	1946	20	1938	13	1.1

Details of reported age are given in text. i.s., signal interval integrated for isotope ratio and age calculation (in seconds); Disc.%, per cent discordance calculated from $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ ages (negative values indicate reversely discordant analyses).

Palaeoproterozoic continental basement rocks within their respective drainage basins.

The main differences between samples HMB (early Cambrian of West Avalonia) and ERCALL (early Cambrian of East Avalonia) as regards detrital zircon U–Pb ages can be summarized as follows.

(1) Sample ERCALL contains a latest Neoproterozoic–earliest Cambrian zircon population; this suggests that igneous activity apparently continued into the early Cambrian, although igneous bodies of this age have yet to be identified *in situ*. In contrast, zircons of this age are absent in sample HMB (see Figs 6 and 7), for which the youngest detrital zircon has an age of *c*. 585 Ma. The lack of Cambrian aged detritus in the HMB sample may be because it stratigraphically underlies the oldest volcanic rock-bearing Cambrian strata in the Antigonish Highlands (Arbuckle Brook Formation, Murphy *et al*. 1985).

(2) Sample HMB has an apparently continuous record of ages between *c*. 585 and 676 Ma whereas ERCALL seems to feature a gap between 630 and 650 Ma. Vestiges of pre-630 Ma rocks are exposed in Cape Breton, Nova Scotia (Keppie & Dostal 1991) and these rocks may have formed a source of zircons for HMB. In the English Midlands, the calc-alkaline plutons of the Malverns Complex were intruded at *c*. 670 Ma (Tucker & Pharaoh 1991) and subsequently metamorphosed within the low amphibolite facies at *c*. 650 Ma (Strachan *et al*. 1996*b*). The Malverns Complex would therefore be a suitable source for some of the zircons dated at *c*. 650–670 Ma within the ERCALL sample. A poorly constrained older population at *c*. 710–760 Ma is significantly represented in HMB, whereas only one zircon yielded an age of 714 Ma in sample ERCALL. The older population in HMB may be derived from the *c*. 734 Ma Economy River Gneiss and correlatives (Doig *et al*. 1993). The Economy River Gneiss is exposed in the adjacent Cobequid Highlands in Nova Scotia, which were probably contiguous with the Antigonish Highlands before Carboniferous rifting formed a pull-apart basin between them (Yeo & Ruixiang 1987; Murphy *et al*. 1992). The only rock units in East Avalonia that might be of this approximate age are the granites and diorites of the Stanner Hanter Complex in Wales, which has yielded a Rb–Sr whole-rock isochron of 702 ± 8 Ma (Patchett *et al*. 1980).

Comparison with late Neoproterozoic sedimentary rocks

Detrital zircon age data (15 analyses) for *c*. 610 Ma late Neoproterozoic rocks underlying the Malignant Cove Formation in the Antigonish Highlands (Keppie *et al*. 1998) include a concentration (five zircons) between 613 ± 5 and 623 ± 7 Ma, a second concentration (four zircons) between 1153 ± 9 and 1215 ± 3 Ma, five zircons between 1.5 and 2.0 Ga, and one zircon dated at *c*. 2.6 Ga. Other late Neoproterozoic samples analysed in Nova Scotia, New Brunswick and New England yield similar results to the Antigonish Highlands data (Bevier & Barr 1990; Karabinos & Gromet 1993). The compilation by Keppie *et al*. (1998) suggests that Avalonian Neoproterozoic clastic rocks are characterized by abundant zircons of Mesoproterozoic age, which have been interpreted to have been derived from the Amazonian craton. In contrast, the Cambrian clastic rocks are characterized by a paucity of these zircons, suggesting a significant difference between Neoproterozoic and Cambrian drainage systems. Unfortunately, there are no detrital mineral ages available for late Neoproterozoic sedimentary rocks in East Avalonia.

Table 2. *LA–ICP-MS detrital zircon data for sample ERCALL from the Wrekin area of Shropshire, Avalon terrane of Britain*

Analysis number	i.s. (s)	Isotopic ratios and 2σ (%) errors						Ages and 2σ absolute errors (Ma)						Reported age		
		$^{206}Pb/^{238}U$	±2σ	$^{207}Pb/^{235}U$	±2σ	$^{207}Pb/^{206}Pb$	±2σ	$^{206}Pb/^{238}U$	±2σ	$^{207}Pb/^{235}U$	±2σ	$^{207}Pb/^{206}Pb$	±2σ	Age (Ma)	±2σ	Disc. %
fe10c09	52	0.0862	1.60	0.6943	2.26	0.0584	1.82	533	8	535	9	542	40	534	8	1.7
fe10a14	33	0.0869	2.20	0.6869	3.42	0.0573	4.48	537	11	531	14	502	98	535	10	−6.5
fe10c08	13	0.0870	2.42	0.7029	4.82	0.0586	4.72	538	13	540	20	552	104	538	12	2.6
fe11c06	23	0.0886	2.52	0.7001	4.26	0.0573	3.52	547	13	539	18	502	78	546	13	−8.2
fe11a16	48	0.0891	2.72	0.7203	2.70	0.0586	1.18	550	14	551	11	552	26	551	11	0.4
fe11c13	25	0.0892	2.02	0.7191	2.98	0.0584	1.72	551	11	550	13	546	38	551	11	−0.9
fe11a06	27	0.0892	1.40	0.7273	1.58	0.0591	1.00	551	7	555	7	570	22	554	7	3.4
fe11b07	33	0.0895	2.40	0.7300	2.34	0.0591	2.60	553	13	557	10	570	56	555	9	3.1
fe11c05	19	0.0898	1.38	0.7170	3.94	0.0579	3.44	554	7	549	17	524	76	555	7	−5.4
fe11c15	25	0.0910	1.80	0.7221	1.94	0.0575	2.54	561	10	552	8	510	56	556	7	−9.1
fe10b13	33	0.0904	1.50	0.7245	2.46	0.0581	2.32	558	8	553	10	534	50	557	7	−4.3
fe10c14	38	0.0904	1.32	0.7320	1.12	0.0587	0.96	558	7	558	5	556	20	558	5	−0.4
fe11a13	13	0.0898	2.26	0.7392	2.82	0.0597	3.88	555	12	562	12	590	84	558	10	6.3
fe11c14	27	0.0911	1.98	0.7221	3.82	0.0575	4.02	562	11	552	16	508	88	559	10	−9.6
fe10c12	36	0.0908	1.48	0.7338	2.72	0.0586	3.16	560	8	559	12	552	70	560	8	−1.4
fe10b15	38	0.0917	1.18	0.7397	1.58	0.0585	1.90	566	6	562	7	548	42	564	5	−3.2
fe10a13	36	0.0981	1.36	0.7920	1.92	0.0586	2.30	603	8	592	9	550	50	598	6	−8.8
fe10a05	46	0.0975	1.24	0.8125	1.84	0.0604	1.26	600	7	604	8	618	28	601	7	3.0
fe11a15	33	0.0981	1.86	0.7955	3.36	0.0588	3.24	603	11	594	15	560	70	601	10	−7.1
fe10c16	17	0.0986	1.64	0.8096	1.70	0.0595	2.04	606	9	602	8	586	44	604	7	−3.3
fe11c11	31	0.0990	2.26	0.8067	3.44	0.0591	3.42	608	13	601	16	570	74	606	12	−6.3
fe10b12	33	0.0988	1.52	0.8136	3.00	0.0597	3.10	608	9	604	14	592	66	607	8	−2.6
fe11a11	29	0.0988	1.38	0.8021	3.10	0.0589	3.46	607	8	598	14	562	74	607	8	−7.4
fe11c12	29	0.0984	1.28	0.8250	2.32	0.0608	2.34	605	7	611	11	630	52	607	7	4.1
fe11c10	21	0.0989	1.36	0.8282	5.36	0.0607	5.86	608	8	613	25	628	126	608	8	3.3
fe11b06	27	0.0991	2.26	0.8230	2.52	0.0602	2.26	609	13	610	12	610	48	610	11	0.2
fe10c05	44	0.0992	1.28	0.8312	2.16	0.0607	2.22	610	7	614	10	628	48	611	7	3.0
fe10a06	46	0.0996	1.36	0.8343	2.10	0.0607	1.60	612	8	616	10	628	36	613	9	2.6
fe10b08	36	0.0999	2.78	0.8313	3.22	0.0603	2.56	614	16	614	15	614	56	614	14	0.0
fe11a07	31	0.1002	1.78	0.8322	2.04	0.0602	1.60	616	11	615	9	610	36	615	9	−1.0
fe11c16	35	0.1004	1.48	0.8341	1.66	0.0603	1.28	617	9	616	8	612	28	616	7	−0.8
fe11b08	29	0.1003	1.82	0.8548	3.28	0.0618	3.08	616	11	627	15	666	66	619	10	8.1

fe10b16	50	0.1010	1.12	0.8397	1.66	0.0603	0.80	621	7	619	8	612	16	620	7	−1.4
fe11a10	38	0.1010	1.30	0.8429	1.92	0.0605	1.70	620	8	621	9	620	36	620	7	0.0
fe11a12	42	0.1016	1.62	0.8366	1.90	0.0597	2.28	624	10	617	9	592	50	620	7	−5.1
fe10a15	42	0.1012	1.46	0.8470	2.36	0.0607	2.68	622	9	623	11	626	58	622	7	0.6
fe10b14	31	0.1018	1.54	0.8366	2.16	0.0596	2.66	625	9	617	10	588	56	622	8	−5.9
fe10c13	56	0.1020	1.36	0.8527	1.86	0.0606	1.22	626	8	626	9	626	26	626	8	0.0
fe11c09	40	0.1026	1.92	0.8486	2.50	0.0600	3.72	630	12	624	12	602	80	627	10	−4.4
fe10a10	59	0.1024	1.30	0.8539	1.76	0.0605	1.74	628	8	627	8	620	38	628	7	−1.3
fe10a11	31	0.1061	1.50	0.9060	2.32	0.0619	1.64	650	9	655	11	670	36	651	10	3.1
fe11a05	25	0.1072	1.76	0.8982	2.30	0.0608	2.26	656	11	651	11	630	48	654	9	−4.0
fe10b09	52	0.1068	1.28	0.9155	2.56	0.0622	2.30	654	8	660	12	678	48	655	8	3.7
fe10b11	21	0.1082	1.76	0.9058	2.96	0.0607	3.20	662	11	655	14	628	68	660	9	−5.1
fe11a14	52	0.1078	1.08	0.9211	1.72	0.0620	1.54	660	7	663	8	672	32	661	6	1.8
fe10b05	36	0.1085	1.56	0.9249	1.36	0.0618	1.12	664	10	665	7	666	24	665	7	0.3
fe10c06	17	0.1099	1.62	0.9391	3.22	0.0620	3.14	672	10	672	16	672	68	672	10	0.0
fe10c11	29	0.1099	1.60	0.9395	2.04	0.0620	1.80	672	10	673	10	672	40	672	9	0.0
fe10a16	38	0.1164	1.68	1.0299	2.32	0.0642	2.28	710	11	719	12	746	48	714	10	5.1
fe10a08	50	0.1740	1.34	1.7800	1.98	0.0742	1.66	1034	13	1038	13	1046	34	1036	11	1.2
fe10b07	50	0.1779	1.68	1.8387	1.28	0.0749	0.92	1056	16	1059	8	1066	18	1061	8	0.9
fe10c10	38	0.1988	1.64	2.1956	1.76	0.0801	0.78	1169	18	1180	12	1198	16	1198	16	2.5
fe10a09	46	0.2680	1.54	3.5436	1.82	0.0959	0.94	1531	21	1537	14	1544	16	1539	14	0.8
fe11b10	25	0.2767	2.80	3.9476	2.84	0.1035	1.38	1575	39	1624	23	1686	24	1686	24	7.0
fe11c07	31	0.5494	1.92	17.7410	1.46	0.2341	0.90	2823	44	2976	14	3080	14	3080	14	9.1

Details of reported age are given in text. i.s., signal interval integrated for isotope ratio and age calculation (in seconds); Disc.%, per cent discordance calculated from $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ ages (negative values indicate reversely discordant analyses).

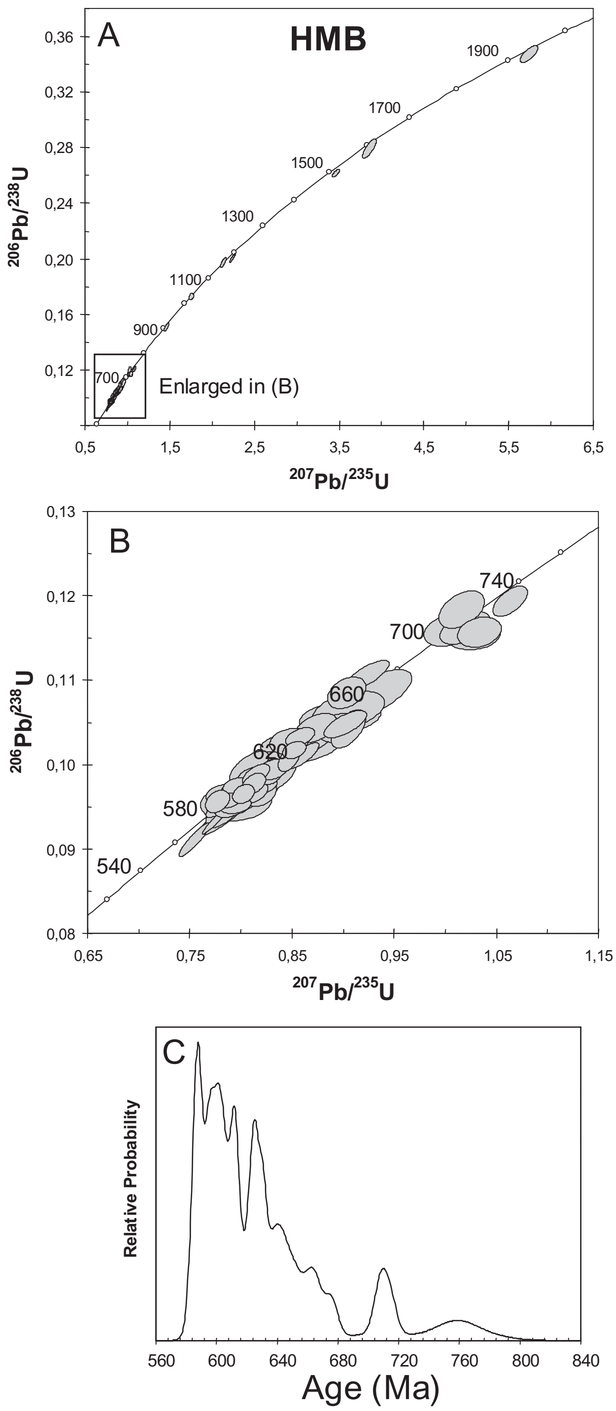

Fig. 6. (**a**) U−Pb concordia plot for all analyses of sample HMB. (**b**) Enlargement of concordia plot for Neoproterozoic zircons (ellipses are 2σ). (**c**) Relative probability plot of Neoproterozoic zircons (ages and 2σ errors used are those labelled 'reported age' in Table 1).

Discussion

Recent analyses that have shown that detrital zircons can be transported considerable distances in fluviatile environments (e.g. Rainbird *et al*. 2001), implying laterally extensive drainage systems. The range in zircon populations in the Neoproterozoic clastic rocks would imply a extensive drainage system within

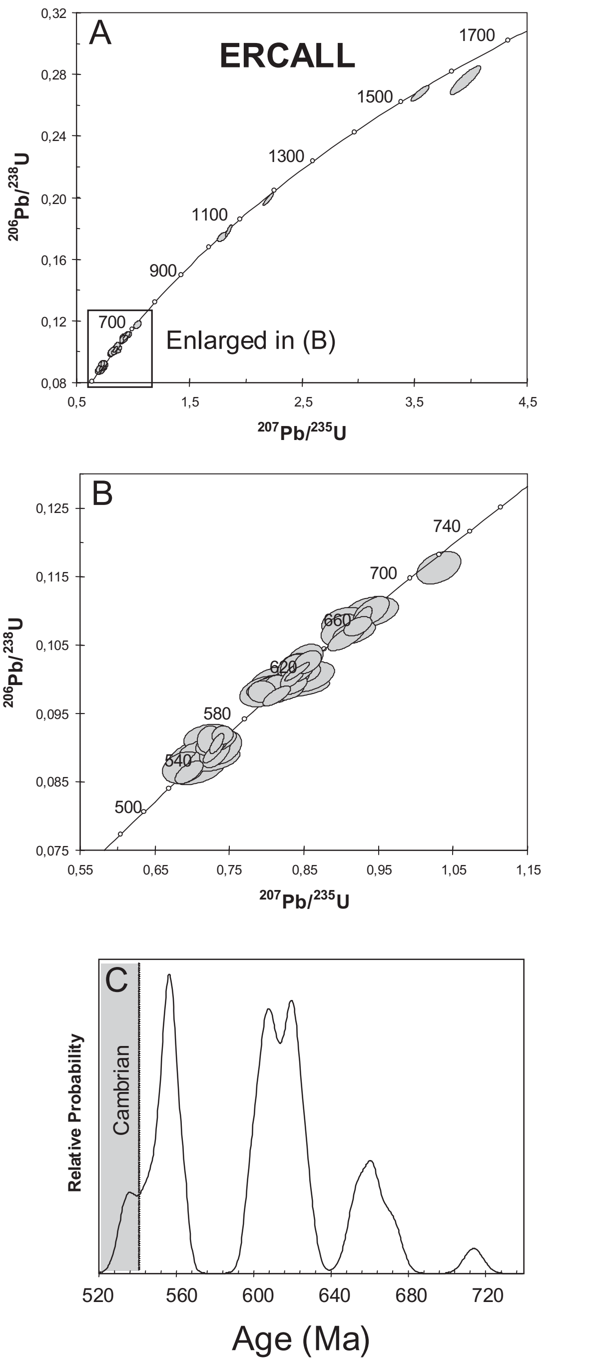

Fig. 7. (**a**) U–Pb concordia plot of sample ERCALL (one Archaean zircon not shown). (**b**) Enlargement of concordia plot for Neoproterozoic–Cambrian zircons (ellipses are 2σ). (**c**) Relative probability plot of Neoproterozoic–Cambrian zircons (ages and 2σ errors used are those labelled ‘reported age’ in Table 2).

Amazonia. In contrast, the vast majority of zircons in both HMB and ERCALL, however, can be readily derived from underlying Neoproterozoic Avalonian rocks. Both samples are dominated by zircons derived either from the main phase of Avalonian magmatism (*c*. 635–570 Ma), or from the early arc phase (750–670 Ma). In the case of the HMB sample, the lack of Cambrian zircons may reflect the fact that the Malignant Cove Formation underlies the oldest Cambrian volcanic units in the Antigonish Highlands. The Mesoproterozoic and Palaeoproterozoic zircons in both samples could readily be derived by recycling of such zircons from the underlying Neoproterozoic sedimentary units. In contrast to the late Neoproterozoic rocks, therefore, there is nothing in the new data that requires laterally extensive drainage systems.

The cause of the switch from extensive to localized drainage systems is uncertain at this stage and several hypotheses are possible. The switch could reflect rifting and isolation of Avalonia from Amazonia between *c*. 585 and 540 Ma. Such a hypothesis is consistent with the interpretation of faunal data, which indicate that Avalonia was an insular microcontinent by the end of the Precambrian (Landing 1996). Alternatively, the switch might reflect the creation of a topographical barrier along the northern Gondwanan margin, in a manner analogous to the rise of the Andes about 15 Ma ago, or the creation of a Basin-and-Range topography in the Western USA about 20 Ma ago. Prior to 15 Ma ago, the Amazon River flowed westward into the Pacific, its erosion able to keep pace with the rise of the Andes. However, an accelerated uplift some 15 Ma ago reversed its flow towards the Atlantic Ocean, thereby dramatically changing the drainage systems of South America. As a result, the modern western margin of the Andes is dominated by relatively local drainage systems. The origin of the US Basin-and-Range topography in uncertain, but most models relate it to directly or indirectly to the generation of the San Andreas Fault system. A similar tectonic environment has been proposed for the *c*. 590–540 Ma interval in Avalonia (Murphy *et al*. 2000; Nance *et al*. 2002; Keppie *et al*. 2003). Such an environment would provide the varied topography to focus drainage systems parallel to the axis of the mountains, and provide abundant access to local zircons and at the same time cut off supply from the cratonic hinterland.

McNamara *et al*. (2001) interpreted palaeomagnetic data that showed that the *c*. 580–570 Ma rocks in the Avalon terrane of southern Newfoundland were deposited at a palaeolatitude of 34° +8°/−7° to reflect proximity of West Avalonia to West Africa. There is no evidence in either the Neoproterozoic or Cambrian zircon data for any connection to West Africa. The West African craton is characterized by the absence of by 680–550 Ma Pan-African and 2.0 Ga Eburnian crust and an absence of tectonothermal events between *c*. 0.7 Ga and 2.0 Ga. The Meguma Group of southern Nova Scotia, on the other hand, is an example of a Cambro-Ordovician sequence that may be derived from the West African craton. Single-grain detrital zircon and titanite data from these rocks yield late Neoproterozoic dates (*c*. 680–566 Ma) and a lack of detritus between 680 and 2040 Ma (Krogh & Keppie 1990). Murphy *et al*. (2000) pointed out that interpretation of palaeomagnetic data for terranes such as West Avalonia is critically dependent upon the palaeolatitude of the continents at the time. The location of Gondwana in Neoproterozoic reconstructions (e.g. Dalziel *et al*. 1994) is based upon Laurentian palaeomagnetic poles and tacitly assumes a connection between Laurentia, Amazonia and West Africa. However, the data of Loewy *et al*. (2000) and Ramos & Aleman (2000), which describe a Neoproterozoic orogen (Marañon belt, Fig. 1) between the Peruvian Arequipa massif and the Amazon craton, call into question the connection between Laurentia and Amazonia. In the absence of reliable palaeomagnetic data for Amazonia and West Africa, the significance of the *c*. 34° palaeolatitude determination for West Avalonia relative to the Gondwanan margin is uncertain.

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