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Further detrital zircon evidence for peri-Gondwanan blocks in the central Appalachian Piedmont Province, USA

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0. ABSTRACT

Evidence for exotic terranes in the central Appalachian Piedmont Province is fragmented between central Virginia, northern Maryland, and southeastern Pennsylvania. Here we present LA-ICPMS data from detrital zircon that supports the presence of an exotic terrane in this region. U/Pb dating of detrital zircon from new samples of the Storck quartzite (central Virginia) and the Hoods Mill rocks (northern Maryland) confirms the presence of a major age peak at ca. 630-610 Ma in these units. These ages are consistent with derivation from Gondwana, but not Ediacaran Laurentia. Further, modern εHf values of five of the ca. 670-580 Ma grains in these samples are inconsistent with derivation from the few plutons of this age in Ediacaran Laurentia. The Loch Raven Schist and a sedimentary xenolith in the Wilmington Complex contain a smaller proportion of ca. 670-580 Ma grains than the Storck quartzite and the Hoods Mill rocks, but more such grains than in sediment derived from Ediacaran Laurentia, so we tentatively conclude that these two units also received sediment from Gondwana. Detrital zircon ages from the type localities of the Piney Run Formation, Pleasant Grove Schist, Prettyboy Schist, and Wissahickon Formation indicate sediment provenance in Ediacaran Laurentia. We also present new U-Pb and Lu-Hf isotopic data from western Newfoundland plutons for comparison with such data from the detrital zircon. Intrusion ages of the Steel Mountain Anorthosite, Disappointment Hill Tonalite, and Round Pond Granite are 608±12, 600±8, and 590±9 Ma, respectively. None of these units was derived entirely from the depleted mantle.

1. INTRODUCTION

Successive accretion of magmatic arcs and ribbon continents to the eastern margin of Laurentia during Early Ordovician to Early Mississippian time caused pulses of orogeny in eastern Laurentia (van Staal et al., 2009; Pollock et al., 2012; Hibbard et al., 2012). In the northern and southern Appalachian Orogen, many of these accreted terranes were exotic to Laurentia, originally derived from the edges of Gondwana (Fig. 1; Pollock et al., 2012; Macdonald et al., 2014). In the central Appalachian Piedmont Province, Early Ordovician to Late Devonian deformation and metamorphism were widespread and locally intense (Drake, 1989; Bosbyshell et al., 1999; 2016; Kunk et al., 2005; Aleinikoff et al., 2006; Wintsch et al., 2010; Hughes et al., 2013), yet geologists have found only fragmentary evidence for terranes derived from Gondwana.

The strongest published evidence for continental crust with Gondwanan affinity in the central Appalachian Orogen consists of U/Pb isotopic ages of detrital zircon from Cambrian-Ordovician meta-sandstone samples taken from three Piedmont Province localities (Fig. 2; Hughes et al., 2014; Bosbyshell et al., 2015; Martin et al., 2015). The three sample locations are in central Virginia (1 sample), northern Maryland (1 sample), and southeastern Pennsylvania (4 samples). Some of the detrital zircon U/Pb ages from these samples are not easily explained as originating from Ediacaran Laurentia but are consistent with sediment derivation from a Gondwanan source. Most cogently, the existence of abundant ages between 670 and 580 Ma in all these samples suggests Gondwanan provenance. The 670-580 Ma ages are significant because felsic magmatism of this age is known from only two locations in probable Ediacaran Laurentia. The Goochland Terrane of central Virginia contains several small granitic plutons with crystallization ages between ca. 660 and 580 Ma (Owens and Tucker, 2003), and several

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granitic plutons in western Newfoundland crystallized between ca. 630 and 590 Ma (Williams et al., 1985; van Berkel and Currie, 1988; Currie et al., 1992; Lin et al., 2013). Further evidence for a Gondwanan sediment source to the sampled sandstone includes the following two considerations. First, in some samples there is an absence of a spike in ages at ca. 1200-950 Ma, the presence of which is a distinctive feature of Laurentia-derived sediment deposited on the eastern margin of the continent (e.g., Macdonald et al., 2014, Hughes et al., 2014; Martin et al., 2015). Second, some detrital zircon grains yielded U/Pb ages between 950 and 780 Ma, which also was a period of scarce metamorphism or felsic magmatism in Laurentia (Whitmeyer and Karlstrom, 2007). Bailey et al. (2008) reported detrital zircon U/Pb ages between 950 and 780 Ma from a sandstone from central Virginia, and likewise concluded that there was a Gondwanan sediment source to this sandstone (Shores melange sample shown in Hughes et al., 2014). The existence of only a few meta-sandstone samples with an apparent Gondwanan detrital zircon U/Pb age signature, and the 100 km that separates each of the central Virginia, northern Maryland, and southeastern Pennsylvania sample localities, challenges secure recognition and reconstruction of a putative peri-Gondwanan terrane in the Piedmont of the central Appalachian Orogen.

This paper investigates the possible presence of a Gondwana-derived terrane in the central Appalachian Piedmont Province using a three-pronged approach. First, we confirm the existence of sandstone that contains detrital zircon with a Gondwanan U/Pb age signature by dating detrital zircon from new samples collected near the sites of the first discoveries in central Virginia and northern Maryland (Hughes et al., 2014; Martin et al., 2015). Second, we test whether the 670-580 Ma detrital zircon is incompatible with derivation from Ediacaran Laurentia by comparing Hf isotope values in spots in the detrital zircon grains to Hf isotope values in spots in zircon from the two possible Laurentian

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sources, the granitoid in the Goochland Terrane and western Newfoundland. Third, we search for more locations in the central Appalachian Piedmont Province that expose sandstone with Gondwanan detrital zircon U/Pb age signatures.

2. TECTONIC SETTING

The Appalachian Orogen was part of a larger system of orogens that formed on the eastern edge of Laurentia during the Paleozoic Era (Scotese and Langford, 1995; Pollock et al., 2012). Geologists apply the term "Appalachian" to the portion of this larger orogen in the eastern United States and Canada between Alabama and Newfoundland (Fig. 1; Hibbard et al., 2006). In this article, we treat the southern Appalachians as that part of the orogen southwest of the northeastern limit of Carolinia in central Virginia, the northern Appalachians as the sector northeast of the southernmost exposure of Ganderia in southern Connecticut, and the central Appalachians as the portion between the northeastern limit of Carolinia and the southernmost exposures of Ganderia (Fig. 1).

Geologists use distinctions originally based on physiography to divide the central and southern Appalachian Orogen into four tectonic provinces (Hatcher, 1989). From west to east these are the Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain provinces. The focus of this article is the Piedmont Province. Dominated by metasedimentary rocks, the Piedmont Province is the formerly deepest and most outboard part of the orogen currently exposed (Hibbard et al., 2006). Meta-volcanic, meta-plutonic, and unmetamorphosed plutonic rocks also are present, particularly in eastern parts of the Piedmont Province (Hibbard et al., 2006). Deposition and intrusion mostly occurred during the Neoproterozoic and Paleozoic eras (Reinhardt, 1974; 1977; Fisher et al., 1979; Aleinikoff et al., 2002; 2006; Owens and Tucker, 2003; Horton et al., 2010; Owens et al.,

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2010; Pollock et al., 2010; Hughes et al., 2013; 2014; Bosbyshell et al., 2015; Martin et al., 2015). Piedmont Province rocks constitute a collage of fault-bounded terranes of varying origin (Fig. 2; Horton et al., 1989). The rocks in some terranes, such as the Westminster Terrane and most of the Potomac Terrane, intruded or were deposited on the eastern edge of Laurentia (Hughes et al., 2014; Martin et al., 2015). Others, such as the Carolinia Domain, intruded and were deposited on the periphery of Gondwana (Pollock et al., 2012). The depositional or intrusive origins of a few continental blocks are debated; examples include the Goochland Terrane and the Wilmington Complex and adjacent rocks (Farrar, 1984; Horton et al., 1989; Glover et al., 1997; Aleinikoff et al., 2006; Bosbyshell et al., 2015).

Geologists have assigned many names to and used shifting criteria to group the metasedimentary rocks of the Piedmont Province in the central Appalachian Orogen over the past 130 years (Williams, 1891; 1892; Bascom, 1902; 1905; Mathews, 1904; 1905; Mathews and Grasty, 1909; Knopf and Jonas, 1923; Virginia Geological Survey, 1928; Jonas and Stose, 1938; Hopson, 1964; Southwick and Fisher, 1967; Rodgers, 1970; Higgins, 1972; Crowley, 1976; Horton et al., 1989; Hibbard et al., 2006; Southworth et al., 2007; Bosbyshell et al., 2015; Martin et al., 2015). Neither detrital zircon U/Pb ages nor other provenance indicators were used in the assignations prior to approximately 2006. More recent U/Pb isotopic dating of detrital zircon made clear that some of the classical lithology-based correlations and groupings are not supported by the new dating (Hughes et al., 2014; Bosbyshell et al., 2015; Martin et al., 2015). It is beyond the scope of this article to discuss the history of formation names or to provide a resolution to naming conflicts in the central Appalachian Piedmont Province. Instead, we show sample locations in Figure 2 free of the biases produced by the old lithology-based formation names. In Table 1 we list

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the formation names as currently applied but emphasize that in some cases these formation names are not compatible with recent studies of detrital zircon U/Pb ages. One of the samples listed in Table 1 came from a metasedimentary xenolith in the Brandywine Blue Gneiss, which is a member of the Wilmington Complex. The Wilmington Complex is an Early Ordovician island arc metamorphosed to granulite facies during the Silurian Period (Aleinikoff et al., 2006).

From west to east, the island of Newfoundland consists of a Laurentian/peri-Laurentian domain and two peri-Gondwanan domains, Ganderia and Avalonia. Cawood et al. (1995) divided part of the Laurentian domain into several fault-bounded tectonic blocks with partially distinct geologic histories. Two of our Newfoundland samples come from a central block, the Corner Brook Lake block (Fig. 3; Table 2). In the Corner Brook Lake block, the oldest rocks are granulite facies gneiss and related rocks with protolith igneous crystallization ages of ca. 1500 Ma (Currie et al., 1992; Cawood et al., 1996; Lin et al., 2013). These Mesoproterozoic units were intruded by a suite of granitic magmas at ca. 600 Ma (Williams et al., 1985; van Berkel and Currie, 1988; Currie et al., 1992; Lin et al., 2013) as well as by bimodal magmas at ca. 555 Ma (Cawood et al., 1995). Our third Newfoundland sample comes from the Steel Mountain Anorthosite, which intruded the Mesoproterozoic Corner Brook Lake rocks in some locations and was thrust below the southern edge of the Corner Brook Lake block in others (Fig. 3; Lin et al., 2013). The intrusion age of the Steel Mountain Anorthosite heretofore was assumed to be Mesoproterozoic (Lin et al., 2013) but in this contribution is shown to be ca. 608 Ma. The Proterozoic rocks are unconformably overlain by Ediacaran to Ordovician clastic and carbonate deposits (Cawood and Nemchin, 2001). Lin et al. (2013) concluded that the Corner Brook Lake block, traditionally held to be the para-autochtonous former eastern

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margin of Laurentia, is in fact allochthonous, placed in its present position by motion on Paleozoic transcurrent faults.

Laurentia consisted of an Archean nucleus surrounded by Proterozoic and Paleozoic terranes, some of which originated far from Laurentia (Whitmeyer and Karlstrom, 2007). Regardless of their origin, after accretion to the continent these terranes became part of Laurentia. We therefore consider a Laurentian sediment source to be a source in Laurentia as the continent existed at the time of deposition. The sedimentary rocks considered in this article were deposited during or after the Ediacaran Period, so we refer to the continent as Ediacaran Laurentia when discussing sediment provenance. We use modern orientations to indicate compass directions, though it is important to consider that Laurentia rotated in map view during the Neoproterozoic and Paleozoic eras (Li et al., 2008; Pollock et al., 2012). Previous authors have referred to named high strain zones using the term “fault” or “shear zone” without careful attention to deformation mechanisms in some cases. We retain the historical uses of these words to ease comparison with previous publications and because deformation mechanisms are irrelevant for the conclusions in this article.

3. METHODS

3.1 Sample collection and zircon processing

Martin collected all samples. Each meta-sandstone sample came from the least micaceous, coarsest-grained part of the outcrop. Photomicrographs of thin sections from every sample are shown in Figure S1.

Martin et al (2015) reported Gondwanan zircon in a meta-sandstone in the Mather Gorge Formation of northern Maryland. In this paper we assign the informal name “Hoods Mill rocks” to these exotic rocks because their provenance is distinct from that of the

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Mather Gorge Formation near its type section, which was derived from Ediacaran Laurentia. For the current paper, Martin collected a new sample of the Hoods Mill rocks to verify the presence of Gondwanan detrital zircon (Table 1). The new sample was collected south of the south branch of the Patapsco River and east of Maryland State Route 97 whereas the sample reported in Martin et al. (2015) was located along the railroad tracks north of the river and directly west of the road. For the same purpose, Martin collected a new sample of the informally-named Storck quartzite of central Virginia near the location of the sample with Gondwanan zircon described by Hughes et al. (2014).

Zircon was separated and mounted in the laboratories in the Department of Geology at the University of Maryland. We isolated zircon from each sample by first crushing the rock using a mortar and pestle, then removing silt- and clay-sized particles by hand-panning in water, removing magnetic grains with a Frantz magnetic barrier separator, and removing less-dense grains in methylene iodide. We poured the now nearly-pure zircon onto double-sided tape and cast the grains in an epoxy disk together with shards or loose grains of reference zircon crystals. We then sanded and polished the disks by hand to expose the interiors of the grains. Prior to isotopic analysis, we imaged the grains using backscattered electrons and cathodoluminescence in the JEOL JXA-8900R electron probe microanalyzer at the University of Maryland. The images were used to avoid multiple cathodoluminescence zones, cracks, and inclusions during selection of spots for isotopic analysis.

3.2 Zircon mass spectrometry

Zircon from the western Newfoundland igneous rocks and all central Appalachian Piedmont Province meta-sandstone was analyzed in the Arizona LaserChron Center at the

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University of Arizona (Tables 1 and 2). Gehrels and Pecha (2014), Pullen et al. (2014), and Ibanez-Mejia et al. (2015) described the analytical procedures in detail; in this sub-section we briefly summarize these methods. We first analyzed spots in zircon grains for uranium and lead isotopes. We then selected zircon from samples 314002 (Storck quartzite) and 1213002 (Hoods Mill rocks) for in situ analysis of lutetium and hafnium isotopes in a different analysis session. We focused on grains from these samples with ages between ca. 670 and 580 Ma; we also analyzed some younger and older grains. The laser spot for the hafnium isotopic analyses was centered on the pit excavated by laser ablation for the uranium and lead isotope measurements. All uncertainties are reported at the 2-sigma level.

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3.2.1 Uranium-lead isotope measurements

A 20 μm-diameter spot was ablated in each zircon grain using a Photon Machines Analyte G2 excimer laser equipped with a HelEx ablation cell. The ablated zircon was carried in helium into the plasma source of a Thermo Element2 single-collector high resolution inductively coupled plasma mass spectrometer, which sequences rapidly through measurement of U, Th, and Pb isotopes. Each analysis consisted of 5 s of background measurement on peaks with the laser off, 10 s with the laser firing, and a 20 s delay to purge the previous sample and save files. The resulting ablation pits were approximately 12 μm deep. Analyses of reference zircon FC52 and SL bracketed every 5 analyses of sample zircon; these analyses were used to correct fractionation of the $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{238}U$ ratios, respectively. We also bracketed every 15 analyses of sample zircon with an analysis of reference zircon R33, treated as an unknown in this situation, to check the age determinations. Accepted ages for these standards are 1098.47±0.16, 563.5±3.2, and 420.53±0.16 Ma for FC, SL, and R33, respectively (Gehrels et al., 2008; Mattinson, 2010).

Data reduction was performed offline using an in-house Python decoding routine and an Excel program. Data reduction included the following steps. (1) Using the natural isotopic ratio $^{202}Hg/^{204}Hg = 4.3$, subtraction of the contribution from ^{204}Hg to the mass 204 signal to yield ^{204}Pb intensity. This mercury correction was not significant for most analyses because the mercury backgrounds were low. (2) Correction for common lead based on the measured ratio $^{206}Pb/^{204}Pb$ and the assumed composition of common lead from Stacey and Kramers (1975). (3) Correction for mass fractionation during analysis using the bracketing analyses of the reference zircon. (4) Calculation of U and Th concentrations using the measured intensity and known concentrations of reference zircon FC52. For detrital grains, we removed from consideration analyses with greater than 20% normal discordance, greater than 5% reverse discordance, or greater than 10% measurement (internal) uncertainty. We used $^{206}Pb/^{238}U$ dates for grains with $^{206}Pb/^{207}Pb$ dates younger than 900 Ma and $^{206}Pb/^{207}Pb$ dates for older grains.

3.2.2 Lutetium-hafnium isotope measurements

All Lu-Hf isotope data reported in this paper were acquired during a single analysis session. We used a Nu multi-collector high resolution inductively coupled plasma mass spectrometer to analyze hafnium isotopes. Instrument settings were established first by measurements of 10 ppb solutions of JMC475 and a Spex Hf solution followed by measurements of 10 ppb solutions containing Spex Hf, Yb, and Lu. These mixtures contained a range of concentrations of Yb and Lu, with ^{176}(Yb+Lu) up to 70% of the ^{176}Hf. After instrument tuning using the solutions, the settings on the mass spectrometer were optimized for laser ablation by a Photon Machines Analyte G2 excimer laser with a beam diameter of 40 µm. We then analyzed shards or loose grains of seven different zircon standards (R33, Temora, Mud Tank, Plesovice, 91500, FC52, and Sri Lanka) that were included in the epoxy disks with the sample zircon. After precision and accuracy were acceptable, we began analysis of zircon grains from the Appalachian samples using the same acquisition parameters. Each analysis consisted of background measurement via a single 40-second integration on peaks with the laser off followed by sixty 1-second integrations with the laser firing. The ablation rate was about 0.8 µm per second. Analysis of each standard bracketed about 20 analyses of sample zircon.

Data reduction was performed offline using an Excel program developed at the Arizona LaserChron Center. We corrected for mass fractionation during analysis following the method of Woodhead et al. (2004). All corrections were performed line-by-line. For each 60-second analysis, the mean and standard error of the ratio $^{176}Hf/^{177}Hf$ were calculated from the 1-second integrations after removing values more than two standard deviations from the mean. We calculated the ratio $^{176}Hf/^{177}Hf$ at the time of zircon crystallization using the measured $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ values and the ^{176}Lu decay constant of 1.867×10^{-11} year^{-1} (Scherer et al., 2001; Soderlund et al., 2004).

3.3 Uranium-lead data analysis and presentation

We prepared concordia, weighted mean, and relative age-probability diagrams using Isoplot version 4.15 (Ludwig, 2008). The weighted means were calculated with weighting according to the square of the internal uncertainties. The total uncertainty on the intrusion age determination for each western Newfoundland igneous sample was calculated by quadratic addition of the measurement (internal) and systematic (external) uncertainties.

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Age-probability diagrams for individual meta-sandstone samples show the age of each dated zircon and its measurement error as a normal distribution, summed into a single curve. Stacked age-probability plots from multiple meta-sandstone samples were prepared using an Excel program written at the Arizona LaserChron Center. This program normalizes the age-probability curves according to the number of constituent analyses such that each curve contains the same area, allowing direct comparison of multiple datasets, each composed of different numbers of analyses.

3.4 Determination of maximum depositional ages

Calculation of the maximum possible depositional age of a metasedimentary rock using its youngest detrital zircon grains commonly is complicated by lead loss, growth of metamorphic zircon, multiple age zones in a single grain, analytical error, and dating a very small fraction of the total zircon present in the sedimentary rock. Using the youngest single age from a set of detrital zircon U/Pb isotopic ages can result in a determination of maximum depositional age that is younger than the true depositional age (Dickinson and Gehrels, 2009). Instead, determining maximum depositional age using multiple analyses that overlap within uncertainty yields a more robust constraint on the maximum possible depositional age (Dickinson and Gehrels, 2009). We therefore calculate the maximum depositional age as the weighted mean of the two or more youngest analyses that overlap at the 1-sigma level plus the 2-sigma error on this weighted mean, rounded up to the nearest 10 M.y. interval.

4. WESTERN NEWFOUNDLAND IGNEOUS ZIRCON SPOT U-PB AND LU-HF ISOTOPE DATA

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4.1 Western Newfoundland zircon U-Pb isotope data

We placed one 20 µm-diameter analysis spot in each zircon crystal because most crystals were small and many contained only one cathodoluminescence domain (Fig. 4). Table S1 and figure 5 present the results of these analyses. The dates of the standard zircon analyzed along with the unknowns mostly overlap the accepted ages within uncertainty (Table S2).

Analyses of spots in 50 zircon crystals from sample 1013002 produced $^{206}Pb/^{238}U$ ages between 627 and 581 Ma (Table S1, Figs. 4, 5). Analyses of spots in 16 zircon grains from sample 1013005 mostly yielded $^{206}Pb/^{238}U$ ages between 634 and 590 Ma plus one concordant analysis with a $^{206}Pb/^{207}Pb$ age of ca. 1140 Ma (Table S1, Figs. 4, 5). Spot analysis of 46 crystals from sample 1013006 yielded $^{206}Pb/^{238}U$ ages from 657 to 440 Ma (Table S1, Figs. 4, 5). Several of these grains are discordant with $^{206}Pb/^{207}Pb$ ages between ca. 1429 and 713 Ma.

4.2 Western Newfoundland zircon Lu-Hf isotope data

Repeated analysis of the seven zircon standards throughout the data acquisition session yielded the following weighted mean values of the measured $^{176}Hf/^{177}Hf$ ratios. R33: 0.282751±6, Temora: 0.282668±7, Mud Tank: 0.282540±5, Plesovice: 0.282500±6, 91500: 0.282316±7, FC52: 0.282179±6, Sri Lanka: 0.281684±5 (Fig. S2). These values mostly overlap the accepted values within uncertainty; note, however, that different articles report different values for some of the standards (Woodhead and Hergt, 2005; Kemp et al., 2006; Slama et al., 2008; Fisher et al., 2014).

In order to fit the 40 µm-diameter laser spot into a single cathodoluminescence domain while avoiding large cracks and inclusions, we were forced to analyze some

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slightly discordant zircon (Tables S1, S3). Analysis of fifteen spots in zircon from sample 1013002 of the Disappointment Hill Tonalite yielded a range of current εHf values between -13.0 and -16.5 (Fig. 6; Table S3). This range was +0.2 to -3.6 at the time of intrusion, ca. 600 Ma. Analysis of five spots in non-xenocrystic zircon from sample 1013005 of the Steel Mountain Anorthosite gave present-day εHf values from -10.4 to -13.7 (Fig. 6; Table S3). At 600 Ma, these values were +2.8 to -0.6. The modern εHf value of the ca. 1140 Ma crystal from sample 1013005 is -15.7; this value was +9.3 at 1140 Ma. The current εHf values of eight spots in non-xenocrystic zircon from sample 1013006 of the Round Pond Granite ranges from -7.8 to -12.2; these values were +5.1 to -0.1 at 600 Ma (Fig. 6; Table S3). These eight spots do not include the analysis from grain 31, which may be a xenocryst (see section 6.1). Including the analysis of this grain would not change our interpretation because its modern εHf value of -7.9 falls within the range of εHf values from the non-xenocrystic zircon extracted from sample 1013006.

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5. CENTRAL APPALACHIAN PIEDMONT DETRITAL ZIRCON U-PB AND LU-HF ISOTOPE DATA

5.1 Central Appalachian Piedmont detrital zircon U-Pb isotope data

We placed one 20 μm-diameter analysis spot in each zircon grain. Table S4 contains the U-Pb isotope data from these spots and Figure S3 shows the ages in histograms and relative probability plots. For analysis of Lu-Hf isotopes in zircon from samples 314002 and 1213002, we were forced to use six 5-16% reversely discordant analyses in order to fit the 40 μm-diameter laser spot into the zircon grains without intersecting multiple cathodoluminescence domains or large cracks or inclusions. These six U-Pb isotope analyses are listed in red in Table S4. We used these spots only for the Lu-Hf isotope analyses, we did not use the U-Pb isotope analyses for determination of sediment provenance or maximum depositional ages. The mean ages of the zircon standards analyzed with each sample overlap the accepted ages within uncertainty (Table S2).

Zircon from sample 314002 of the Storck quartzite (formal name: Mine Run Complex I) yielded 269 analyses with ages between ca. 3064 and 499 Ma. Similarly, zircon from sample 1213002 of the Hoods Mill rocks (formal name: Mather Gorge Formation) produced 252 analyses with ages between ca. 3034 and 521 Ma.

194 analyses of zircon in sample 1213003 of the Loch Raven Schist yielded ages from ca. 1801 to 397 Ma and one age of ca. 2601 Ma. Many grains younger than approximately 460 Ma had high U/Th ratios, up to 380 (Table S4). Zircon from sample 114002 of the Piney Run Formation yielded 166 analyses with ages between ca. 2775 and 1033 Ma plus one analysis at ca. 514 Ma (167 analyses total). Sample 114003 of the Pleasant Grove Schist yielded 271 ages between ca. 3005 and 955 Ma plus one analysis at ca. 629 Ma and one at ca. 518 Ma (273 analyses total). Analyses of zircon from sample 314001 of the Prettyboy Schist yielded 284 ages from ca. 1915 to 910 Ma plus additional ages at ca. 2478, 561, and 536 Ma (287 analyses total). 245 analyses in zircon from sample 314003 of the sedimentary xenolith in the Brandywine Blue Gneiss yielded ages between ca. 1993 and 423 Ma. Finally, zircon from sample 114005 of the Wissahickon Formation yielded 207 analyses with ages from ca. 2848 to 939 Ma plus two analyses at ca. 540 Ma (209 analyses total).

5.2 Central Appalachian Piedmont detrital zircon Lu-Hf isotope data

We analyzed spots in 40 zircon grains from sample 314002 of the Storck quartzite with crystallization ages between ca. 927 and 513 Ma (Tables 1; S3). The range of present-

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day εHf values in these crystals is -4 to -27 (Fig. 7, Table S3). We analyzed spots in 22 crystals from sample 1213002 of the Hoods Mill rocks with crystallization ages between ca. 911 and 541 Ma (Tables 1; S3). The modern εHf values in these grains range from -1 to -40 (Fig. 7, Table S3). There is no correlation between zircon crystallization age and modern εHf value (Fig. 7).

6. DISCUSSION

6.1 Intrusion ages of western Newfoundland plutons

For zircon from sample 1013002 of the Disappointment Hill Tonalite, removing from further consideration analyses more than 10% normally discordant or 5% reverse discordant leaves 30 analyses. The weighted mean $^{206}Pb/^{238}U$ age of these 30 analyses is 600±8 Ma (MSWD = 0.7) including systematic errors (Fig. 8). We take this as the intrusion age of the tonalite. This age overlaps within uncertainty the 606±2 Ma intrusion age published by Lin et al. (2013).

Zircon grain 13 in sample 1013005 of the Steel Mountain Anorthosite yielded a $^{206}Pb/^{207}Pb$ age of 1141±64 Ma, which is more than 500 M.y. older than the other ages from this sample. We interpret this grain to be a xenocryst inherited from the Mesoproterozoic rocks of the Corner Brook Lake block. Excluding the analysis of this xenocryst as well as analyses more than 10% normally discordant or 5% reverse discordant leaves 11 analyses. The weighted mean of these 11 analyses is 608±12 Ma (MSWD=0.6) including systematic errors (Fig. 8). We take this as the intrusion age of the anorthosite. The Ediacaran intrusion age of the Steel Mountain Anorthosite is considerably younger than the Mesoproterozoic intrusion age assumed in the absence of radiometric dating (Lin et al., 2013). Based on our new dating, we now recognize that intrusion of the anorthosite was

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broadly coeval with ca. 600 Ma intrusion of a granitic suite including the Disappointment Hill Tonalite and the Round Pond Granite. Because of the similarity in intrusion ages, the Steel Mountain Anorthosite perhaps should be considered part of the Corner Brook Lake block, as is this granitic suite.

Analysis of spot 42 in sample 1013006 of the Round Pond Granite was 4.5% reverse discordant and its $^{206}Pb/^{238}U$ age of 657 Ma is about 50 M.y. older than the $^{206}Pb/^{238}U$ age of the next oldest concordant analysis. We interpret this grain to be a xenocryst and do not use it for calculating the intrusion age of the granite. The $^{206}Pb/^{238}U$ age from spot 31 of 479 Ma is about 90 M.y. younger than the next youngest concordant analysis. Crystals 12, 30, and 11 have $^{206}Pb/^{238}U$ ages of ca. 440, 555, and 557 Ma and corresponding $^{206}Pb/^{207}Pb$ ages of 801, 713, and 739 Ma, respectively, and thus we recognize these grains as xenocrysts. Based on the results from grains 12, 30, and 11, we suggest grain 31 also is a xenocryst and do not use it in the calculation of the intrusion age. Excluding spots 42 and 31 as well as analyses more than 10% normally discordant or 5% reverse discordant leaves 21 analyses. The weighted mean of these 21 analyses is 590±9 Ma (MSWD=0.8) including systematic errors (Fig. 8). We take this as the intrusion age of the granite. Although this age overlaps with the multi-crystal thermal ionization mass spectrometer (TIMS) age of 602±10 Ma published by Williams et al. (1985) because of the large uncertainties on both ages, the central value of the TIMS age is 12 M.y. older than the central value of our laser ablation spot age. We now identify inherited zircon in this sample, leading us to suggest that the TIMS age may be slightly too old because Williams et al. (1985) did not recognize that some parts of the grains they analyzed were xenocrysts.

6.2 Sources of magma to western Newfoundland plutons

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The main goal of this paper is not to elucidate the sources of melt for the Ediacaran western Newfoundland plutons. Nevertheless, the zircon spot U-Pb and Lu-Hf isotope data allow us to recognize that none of the three studied plutons was derived solely from the depleted mantle. This conclusion is based on two types of data. First, the presence of xenocrystic zircon in samples 1013005 and 1013006 requires assimilation of preexisting crust into the Steel Mountain Anorthosite and Round Pond Granite magmas. Second, the εHf values of zircon in all three plutons were -7.8 to -16.5 at 600 Ma whereas the depleted mantle εHf value at this time was approximately +13 (Martin et al., 2018). The much more negative values of all the analyzed zircon in the western Newfoundland plutons rule out magma derivation purely from the depleted mantle.

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6.3 Maximum possible depositional ages of central Appalachian Piedmont sandstone

In sample 314002 of the Storck quartzite, the two youngest analyses came from grain 238 (499±44 Ma) and grain 76 (513±28 Ma) (Table S4). The weighted mean of these two analyses is 509±23 Ma, which gives a maximum possible depositional age of 540 Ma. If instead we reject grain 238 as too young and use the ages from grain 76 and grain 299 (524±22 Ma), the weighted mean is 520±17, which again yields a maximum depositional age of 540 Ma. Accordingly, we take 540 Ma as the maximum possible depositional age of the Storck quartzite. Hughes et al. (2014) similarly found that the maximum depositional age of their sample of the Storck quartzite (their sample KSH-11-40) was Cambrian.

In sample 1213002 of the Hoods Mill rocks, grains 151 and 307 yielded the two youngest $^{206}Pb/^{238}U$ ages, 521±40 and 529±22 Ma, respectively (Table S4). The weighted mean of these ages is 528±19 Ma, which gives a maximum depositional age of 550 Ma. Adding grains 92 (531±30 Ma) and 144 (531±30 Ma), the weighted mean of the four youngest analyses is 529±14 Ma, which likewise gives a maximum depositional age of 550 Ma. We thus take 550 Ma as the maximum depositional age of the Hoods Mill rocks based on this sample. The youngest detrital zircon in the Hoods Mill rocks sample studied by Martin et al. (2015) (their sample 1010002) had similar ages and the maximum depositional age determined from their sample was comparable at 540 Ma.

Interpretation of the zircon ages in sample 1213003 of the Loch Raven Schist is complicated by post-depositional growth of metamorphic zircon as well as lead loss from detrital grains. Grains 253 through 165 yielded the youngest $^{206}Pb/^{238}U$ ages from this sample and most of these crystals had U/Th ratios between 380 and 102 (Table S4). Because of their youth and high U/Th ratios (see Hoskin and Schaltegger, 2003), we interpret these 17 grains to have crystallized during metamorphism after deposition; therefore we do not use these grains for determining maximum depositional age or provenance. Grains 232 through 288 are older and had lower U/Th ratios than these 17 metamorphic crystals (Table S4). However, most of these grains were only 86-91% concordant, and grain 324 was 4% reverse discordant with an age uncertainty of 100 M.y. It is possible that these 8 grains are detrital grains that actually crystallized between ca. 488 and 459 Ma. However, the discordance of the analyses suggests that these could be detrital grains with older crystallization ages. We conservatively choose not to use these 8 grains for determination of the maximum depositional age or provenance in order to avoid erroneously young ages. The next two youngest analyses came from grain 203 (507±22 Ma; 97% concordant) and grain 213 (510±44 Ma; 96% concordant). The weighted mean of these two ages is 507±20 Ma, which gives a maximum depositional age of 530 Ma. Adding spot 310 (526±24 Ma), the weighted mean of these three analyses is 515±15 Ma,

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which likewise gives a maximum depositional age of 530 Ma. We therefore take 530 Ma as the maximum depositional age of the Loch Raven Schist.

With a $^{206}Pb/^{238}U$ age of 514±28 Ma, grain 180 produced the youngest analysis from sample 114002 of the Piney Run Formation (Table S4). However, no other ages from this sample overlap the age of grain 180 within uncertainty, so we do not use the age of grain 180 to determine the maximum depositional age of this formation. Grain 185 (1033±46 Ma), grain 228 (1036±38 Ma), and grain 148 (1037±52 Ma) are the next three youngest grains in sample 114002. The weighted mean of their ages is 1035±25 Ma, which gives a maximum depositional age of 1060 Ma for the Piney Run Formation.

Sample 114003 of the Pleasant Grove Schist produced two young grains with $^{206}Pb/^{238}U$ ages that do not overlap with any other analyses within uncertainty: grain 10 at 519±32 Ma and grain 309 at 629±24 Ma (Table S4). The four youngest grains with ages that do overlap within uncertainty are grain 165 (955±132 Ma), grain 187 (969±100 Ma), grain 206 (988±62 Ma) and grain 186 (989±146 Ma). The weighted mean of these four ages is 980±46 Ma, which results in a maximum depositional age of 1030 Ma.

The ages of the two youngest grains in sample 314001 of the Prettyboy Schist, grain 124 (536±22 Ma) and grain 240 (561±28 Ma) overlap within uncertainty. The weighted mean of these two ages is 546±17 Ma. We therefore use 570 Ma as the maximum depositional age of the Prettyboy Schist.

Interpretation of the ages of the zircon extracted from sample 314003 of the sedimentary xenolith in the Brandywine Blue Gneiss is complicated by the presence of metamorphic zircon (see also Aleinikoff et al., 2006). The youngest 37 zircon crystals, from grain 45 to grain 183, have $^{206}Pb/^{238}U$ ages that overlap the intrusion age of the Brandywine Blue Gneiss protolith (476±6 Ma; Aleinikoff et al., 2006), considering

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uncertainties (Table S4). We conservatively choose not to use these 37 ages for interpretation of maximum depositional age or provenance in order to avoid inclusion of grains with an age that is incorrectly too young. The two youngest grains with $^{206}Pb/^{238}U$ ages that do not overlap the gneiss protolith intrusion age within uncertainty are grain 242 (515±24 Ma) and grain 162 (515±34 Ma). The weighted mean of these two ages is 515±19 Ma, which produces a maximum depositional age of 540 Ma. Adding the next youngest analysis, 517±24 Ma from grain 50, the weighted mean of the three ages becomes 516±15 Ma, for a maximum depositional age of 540 Ma. We thus take 540 Ma as the maximum depositional age of the sedimentary xenolith in the Brandywine Blue Gneiss.

The two youngest analyses from sample 114005 of the Wissahickon Formation produced $^{206}Pb/^{238}U$ ages of 537±48 Ma (grain 114) and 542±34 (spot 23) (Table S4). The weighted mean of these ages is 540±28 Ma. The maximum depositional age of the Wissahickon Formation therefore is 570 Ma.

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6.4 Central Appalachian Piedmont sandstone sediment provenance

The tallest age peak in samples 114002, 114003, and 114005 of the Piney Run Formation, Pleasant Grove Schist, and Wissahickon Formation lies at ca. 1460-1380 Ma (Fig. S3). Each sample also has a major peak at ca. 1200-1170 Ma, a smaller Neoarchean peak, a continuum of ages between ca. 1800 and 950 Ma, and one or two grains between 550 and 500 Ma. The results from sample 314001 of the Prettyboy Schist are similar, with a main age peak at ca. 1050 Ma, one analysis at ca. 2500 Ma, a continuum of ages between ca. 1500 and 950 Ma, and two analyses between ca. 560 and 530 Ma (Fig. S3). The Mesoproterozoic main age peak in all four samples also is present in late Ediacaran-Cambrian quartzite from the Blue Ridge Province directly to the west (Fig. 9; Satkoski, 2013). The source of the Blue Ridge sediment was Ediacaran Laurentia (Satkoski, 2013; Smoot and Southworth, 2014). The spectrum of detrital zircon ages from the four new samples also is similar to the age spectrum from many other Ediacaran-Cambrian quartzite samples from the Piedmont Province of the central part of the Appalachian Orogen (Fig. 9). Hughes et al. (2014) and Martin et al. (2015) showed that the sources of the zircon to these Piedmont meta-sandstone samples could have been rocks in Ediacaran Laurentia. The abundant ca. 1550-950 Ma grains could have come from the Granite-Rhyolite and Grenville provinces directly west of the Appalachian Piedmont Province, whereas most of the grains with other ages may have originated farther west (Whitmeyer and Karlstrom, 2007; Martin et al., 2015). This analysis holds for our four new samples as well. Because of the viable sources in Ediacaran Laurentia and the similarity of the new ages to those from the Blue Ridge Province, we interpret Ediacaran Laurentia as the source of sediment to the type localities of the Piney Run Formation, Pleasant Grove Schist, Prettyboy Schist, and Wissahickon Formation.

One motive for analyzing a new sample of the Storck quartzite and the Hoods Mill rocks is to verify the detrital zircon age spectra reported by Hughes et al. (2014) and Martin et al. (2015). Figure 10 confirms that the detrital zircon age spectrum from each of our new samples is nearly identical to the previously reported age spectrum from each unit. Figure 10 also highlights the similarities in ages of detrital zircon from the Storck quartzite and the Hoods Mill rocks. In both units, the main age peak is at ca. 630-600 Ma. Each unit additionally contains zircon with ages both younger and older than this spike, with no large gaps between ca. 2200 and 530 Ma.

Hughes et al. (2014) and Martin et al. (2015) concluded that Ediacaran Laurentia was an unlikely source for the detrital zircon in the Storck quartzite and Hoods Mill rocks,

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respectively, for two reasons. First, the main detrital zircon age peak in these samples is at ca. 630-610 Ma, but Ediacaran Laurentia contained few felsic rocks with crystallization ages between ca. 670 and 580 Ma (Whitmeyer and Karlstrom, 2007). Second, the ages of detrital zircon from the Storck quartzite and Hoods Mill rocks do not form a prominent Mesoproterozoic peak, but a major Mesoproterozoic age peak is a key signature of detrital zircon derived from Ediacaran Laurentia. Hughes et al. (2014) and Martin et al. (2015) instead proposed that Gondwana was the most likely source of the sediment to these units. Figure 9 emphasizes that the ages of detrital zircon from the Storck quartzite and Hoods Mill rocks are similar to detrital zircon ages from known peri-Gondwanan terranes but are dissimilar to detrital zircon ages from sediment derived from Ediacaran Laurentia, such as the late Ediacaran-Cambrian sandstone of the central Blue Ridge Province. Based on the detrital zircon ages, we concur with the previous interpretations: Gondwana is a plausible source of the sediment to the Storck quartzite and Hoods Mill rocks but Ediacaran Laurentia is not.

To test whether the Neoproterozoic plutons in the Goochland Terrane or western Newfoundland could have provided detrital zircon to the Storck quartzite or Hoods Mill rocks, we compare the modern εHf values of spots in zircon in Neoproterozoic plutons from each area to the modern εHf values of spots in the detrital zircon in samples 314002 and 1213002 that overlap the age range 670-580 Ma within uncertainty (Fig. 11). Most of the εHf values of the detrital zircon overlap the εHf values of the zircon from the plutons. However, one detrital grain from the Hoods Mill rocks has an εHf value less negative than the pluton zircon and three grains from the Hoods Mill rocks and one grain from the Storck quartzite have an εHf value more negative than the pluton zircon, outside uncertainty. It is impossible to rule out the Goochland Terrane or western Newfoundland as sources of the

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detrital zircon based on εHf values because it is possible that a magmatic rock bearing zircon with the appropriate Lu-Hf isotopic composition existed at the time of deposition of the Storck quartzite or Hoods Mill rocks but that magmatic rock has since been eroded away, leaving it unavailable for sampling. Nevertheless, the presence of detrital zircon with modern εHf values both less and more negative than any of the values measured in zircon from the Neoproterozoic plutons is consistent with the derivation of Storck and Hoods Mill sediment from a source other than the Goochland Terrane or western Newfoundland. Moreover, the present-day εHf values of the detrital zircon in the Storck quartzite and Hoods Mill rocks mostly overlap the modern εHf values of ca. 670-580 Ma detrital zircon from a Ganderian sandstone, which range from -7 to -30 (Willner et al., 2014).

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Neither the U/Pb ages nor the present-day εHf values of detrital zircon in the Storck quartzite and Hoods Mill rocks are consistent with sediment derivation from Ediacaran Laurentia. Further, the U/Pb ages of detrital zircon from these units are similar to the ages of detrital zircon from late Ediacaran-Cambrian sandstone in known peri-Gondwanan terranes. We therefore conclude that Gondwana was the most likely source of sediment to the Storck quartzite and the Hoods Mill rocks. The Storck quartzite lies directly west of the Chopawamsic Fault in northern Virginia and the Hoods Mill rocks crop out directly west of the Plummers Island Fault in northern Maryland (Fig. 2). Based on the occurrence of these exotic rocks directly west of these two faults, we speculate that the faults might be correlative.

In contrast to the other samples, interpretation of the provenance of the Loch Raven Schist (sample 1213003) and the sedimentary xenolith in the Brandywine Blue Gneiss (sample 314003) is not clear-cut. These units have late Mesoproterozoic to earliest

Neoproterozoic major age peaks, broadly similar to sediment derived from Ediacaran Laurentia (Fig. 9). However, both samples also contain multiple detrital grains with U/Pb ages between 670 and 580 Ma (Fig. S3; Table S4). The quantities of grains of this age are intermediate between the numbers of such grains in the Storck quartzite and Hoods Mill rocks and the quantities in samples with sediment derived from Ediacaran Laurentia. 24% and 37% of the detrital zircon in the Storck quartzite and the Hoods Mill rocks, respectively, have ages that overlap the range 670 to 580 Ma including uncertainties. These proportions are 6% and 5% in the Loch Raven Schist and the sedimentary xenolith, respectively, but fall to 1% and 0.4% in most central Piedmont quartzite of the same age and central Blue Ridge late Ediacaran-Cambrian quartzite, respectively. Many central Piedmont samples contain zero 670-580 Ma grains. Excluding the Storck quartzite, Hoods Mill rocks, Loch Raven Schist, and the sedimentary xenolith, the central Piedmont sample with the most grains in this age range is sample 909001 of the northern Sykesville Formation, with 3% (Martin et al., 2015).

There are two plausible interpretations of the provenance of the detrital zircon in the Loch Raven Schist and the sedimentary xenolith. One possibility is sediment derivation from Ediacaran Laurentia. In this scenario, the ca. 670-580 Ma grains came from the Goochland Terrane, western Newfoundland, or an unrecognized source in Ediacaran Laurentia. The second option is sediment derivation from Gondwana. In this scenario, the Loch Raven Schist and the sedimentary xenolith received more ca. 1200-900 Ma zircon than is present in most other Gondwana-derived late Ediacaran-Cambrian sandstone due to normal variations in the proportions of sediment transported by separate networks that crossed large areas of a continent.

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A challenge to option 1 is that no other units unequivocally derived from Ediacaran Laurentia have so many ca. 670-580 Ma detrital grains. Sykesville Formation sample 909001 contains 3% detrital zircon of this age (Martin et al., 2015), but this remains a lower percentage than in the Loch Raven Schist or the sedimentary xenolith. Further, the Laurentian provenance of the Sykesville Formation is not unimpeachable. One point in favor of option 2 is that there are examples of Gondwanan late Ediacaran-Cambrian sandstone with age spectra similar to those in the Loch Raven Schist and the sedimentary xenolith. For example, the Puncoviscana Formation in northwestern Argentina contains many detrital grains with ages between ca. 1200-900 Ma (Fig. 9), including sample PMXX-2 in Adams et al. (2011), which has a prominent ca. 1200 Ma age spike and no zircon younger than 900 Ma. Schwartz and Gromet (2004) likewise found a metamorphosed equivalent of the Puncoviscana Formation with a major age peak at ca. 1000 Ma; this peak is larger than the ca. 600 Ma peak in this unit. Option 2 also has the advantage that other units geographically near and geologically related to the Wilmington Complex contain Gondwana-derived zircon. These units include the Chester Park Gneiss and rocks labeled as the Wissahickon Formation (Bosbyshell et al., 2015). The latter unit is intercalated with rocks of the Wilmington Complex. Based on the problem with option 1 and the merits of option 2, we tentatively conclude that option 2 is the best interpretation. That is, the Loch Raven Schist and the sedimentary xenolith might contain Gondwana-derived zircon, but this conclusion is less certain for these units than for the Storck quartzite and the Hoods Mill rocks. If the sedimentary xenolith in the Brandywine Blue Gneiss does contain Gondwanan zircon, the Wilmington Complex island arc intruded sedimentary rocks that were derived from Gondwana.

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7. CONCLUSIONS

Our new U-Pb and Lu-Hf isotope data from spots in zircon support the following conclusions.

1. Intrusion of the Steel Mountain Anorthosite, Disappointment Hill Tonalite, and Round Pond Granite in western Newfoundland occurred at 608±12, 600±8, and 590±9 Ma, respectively. Intrusion of the Steel Mountain Anorthosite is now recognized to have been broadly coeval with intrusion of a granitic suite in western Newfoundland at ca. 630-590.
2. The source of magma to the Steel Mountain Anorthosite, Disappointment Hill Tonalite, and Round Pond Granite was not solely depleted mantle.
3. The maximum depositional age for most of our central Appalachian Piedmont Province quartzite samples is late Ediacaran or Early Cambrian.
4. Sediment in our samples from the type localities of the Piney Run Formation, Pleasant Grove Schist, Prettyboy Schist, and Wissahickon Formation was derived from Ediacaran Laurentia.
5. Sediment in the Storck quartzite and the Hoods Mill rocks was derived from Gondwana. We confirm the presence of a ca. 630-610 Ma peak in detrital zircon ages in these units. The large proportions of detrital grains with ages between 670 and 580 Ma in these units is not consistent with derivation from Ediacaran Laurentia but is similar to the age spectra of detrital zircon in much late Ediacaran-Cambrian sandstone with a Gondwanan provenance. Modern εHf values of some of the 670-580 Ma detrital zircon likewise are inconsistent with derivation from the scarce Neoproterozoic plutons in Ediacaran Laurentia.

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6. The provenance of the sediment in the Loch Raven Schist and a sedimentary xenolith in the Brandywine Blue Gneiss is less certain. However, these units contain more ca. 670-580 Ma detrital zircon than any late Ediacaran-Cambrian sandstone unequivocally derived from Ediacaran Laurentia, so we tentatively conclude that Gondwana was the source of zircon to these units. If correct, this conclusion means that the Brandywine Blue Gneiss, which is part of the Wilmington Complex island arc, intruded sedimentary rocks derived from Gondwana.

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FIGURE CAPTIONS

1. Generalized geologic map of the Appalachian Orogen. Modified from Hibbard et al. (2006).
2. Geologic map of part of the central Appalachian Piedmont Province. Modified from Hibbard et al. (2006), Southworth et al. (2007), Hughes et al. (2014), and Martin et al. (2015).
3. Geologic map of part of western Newfoundland. Modified from Brem et al. (2006) and Lin et al. (2013).
4. Backscattered electron (left column) and cathodoluminescence (right column) images of zircon from the three samples of western Newfoundland intrusive rocks. The circles show the locations of 20 μm-diameter laser spots that yielded the indicated $^{206}Pb/^{238}U$ ages.
5. Concordia diagrams for U/Pb isotope analyses of spots in zircon from the three samples of western Newfoundland intrusive rocks.
6. Modern εHf values of spots in zircon from the three samples of western Newfoundland intrusive rocks.
7. Modern εHf values versus crystallization age for detrital zircon from the Storck quartzite and the Hoods Mill rocks. There is no correlation between zircon crystallization age and modern εHf value.
8. Plots of concordant, non-xenocrystic U-Pb isotope analyses (vertical red bars) from each sample of western Newfoundland intrusive rocks showing the weighted mean $^{206}Pb/^{238}U$ age (horizontal green bar). The reported uncertainty includes both measurement and systematic errors.

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9. Normalized relative probability plots of detrital zircon ages from our samples compared to detrital zircon ages from other late Ediacaran-Cambrian Laurentian and peri-Gondwanan sandstone. Data were normalized so that the area under each curve is the same. Data sources and processing details are given in Table S5 and the ages and corresponding errors are in Table S6. The sample numbers for the Piney Run Formation, Pleasant Grove Schist, Prettyboy Schist, and Wissahickon Formation are 114002, 114003, 314001, and 114005, respectively.
10. Normalized relative probability plots of detrital zircon ages from the Storck quartzite and the Hoods Mill rocks. The detrital zircon age spectra from our new samples are nearly identical to the previously-published spectra from these units. Data were normalized so that the area under each curve is the same. Data processing is described in Table S5.
11. Comparison of present-day εHf values of 670-580 Ma detrital zircon from the Storck quartzite and the Hoods Mill rocks with modern εHf values of zircon in Neoproterozoic plutons in the Goochland Terrane and western Newfoundland. The present-day εHf values of the detrital zircon extend to values both less and more negative than the zircon in the plutons, outside uncertainty. The plot shows only detrital grains with ages that overlap the age range 670-580 Ma within uncertainty. These are grains 131 to 218 in sample 314002 and 69 to 266 in sample 1213002 (Table S3). The range of εHf values for the zircon in the plutons includes uncertainties. The bands of values for the plutons are shown stretching horizontally across the entire diagram to ease viewing, but the actual range of intrusion ages is 630-590 and 660-580 Ma for the western Newfoundland and Goochland plutons, respectively. εHf values for the Goochland Terrane zircon from Martin et al. (2018).

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TABLES

1. Central Appalachian Piedmont meta-sandstone sample summary.
2. Western Newfoundland igneous rocks sample summary.

ELECTRONIC SUPPLEMENT

FIGURES

Figure S1: Photomicrographs of thin sections of each sample. The scale is the same for each image. In (B), all minerals in the field of view are plagioclase feldspar. Abbreviations: amp-amphibole, bt-biotite, chl-chlorite, fsp-feldspar, grt-garnet, ms-muscovite, q-quartz.

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Figure S2: Measured $^{176}Hf/^{177}Hf$ ratios of spots in the seven zircon standards acquired throughout the Lu-Hf isotope analysis session. The horizontal green bar indicates the weighted mean.

Figure S3: Histograms and relative probability plots of the U/Pb isotopic ages of detrital zircon from each central Appalachian Piedmont meta-sandstone sample. Best age is the $^{206}Pb/^{238}U$ date for grains with a $^{206}Pb/^{207}Pb$ date younger than 900 Ma and $^{206}Pb/^{207}Pb$ date for older grains.

TABLES

Table S1: Western Newfoundland igneous zircon spot U-Pb isotope data.

Table S2: Summary of U/Pb ages of standard zircon analyzed along with zircon from the samples.

Table S3: Zircon spot Lu-Hf isotope data.

Table S4: Central Appalachian Piedmont detrital zircon spot U-Pb isotope data.

Table S5: Data sources and processing details for Figure 9.

Table S6: Data used to make Figure 9.

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TABLE 1. SUMMARY OF META-SANDSTONE SAMPLES FROM THE CENTRAL APPALACHIAN PIEDMONT

Sample number	Formation name	Informal name	Latitude °N	Longitude °W	Number of U/Pb analyses kept	Max depo age (Ma), this study	U/Pb ages of individual zircon analyses used to determine max depo age (Ma)	Number of Hf analyses	Reference
Central Virginia									
314002	Mine Run Complex I	Storck quartzite	38.41843	77.63513	269	540	499, 513	40	Hughes et al., 2014
Northern Maryland									
1213002	Mather Gorge	Hoods Mill rocks[b]	39.35212	77.01553	252	550	521, 529	22	Martin et al., 2015
1213003[a]	Loch Raven Schist	-	39.50111	76.62347	169	530	507, 510	not analyzed	Crowley, 1976
114002[a]	Piney Run	-	39.53998	76.77674	167	1060	1033, 1036, 1037	not analyzed	Crowley, 1976
114003[a]	Pleasant Grove Schist	-	39.54285	76.80614	273	1030	955, 969, 988, 989	not analyzed	Crowley, 1976
314001[a]	Prettyboy Schist	-	39.61900	76.70773	287	570	536, 561	not analyzed	Crowley, 1976
Northern Delaware									
314003	Brandywine Blue Gneiss	sedimentary xenolith[b]	39.77823	75.50748	208	540	515, 515	not analyzed	Plank et al., 2000
Southeastern Pennsylvania									
114005[a]	Wissahickon	-	40.05671	75.21819	209	570	537, 542	not analyzed	Bascom, 1905
				Totals:	**1834**	**analyses from 8 samples**		**62**	**analyses from 2 samples**

[a]Type locality.

[b]Informal name assigned in this study.

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TABLE 2. SUMMARY OF WESTERN NEWFOUNDLAND IGNEOUS SAMPLES

Sample number	Unit name	Latitude °N	Longitude °W	Number of zircon Hf analyses	Igneous crystallization age (Ma)	Igneous crystallization age reference
1013002	Disappointment Hill Tonalite	48.58884	58.14222	15	606 ± 2	Lin et al., 2013
1013005	Steel Mountain Anorthosite	48.55948	58.15767	6	608 ± 12	this study
1013006	Round Pond Granite	49.06184	57.70439	9	590 ± 9	this study
			Total:	**30**	**analyses from 3 samples**	

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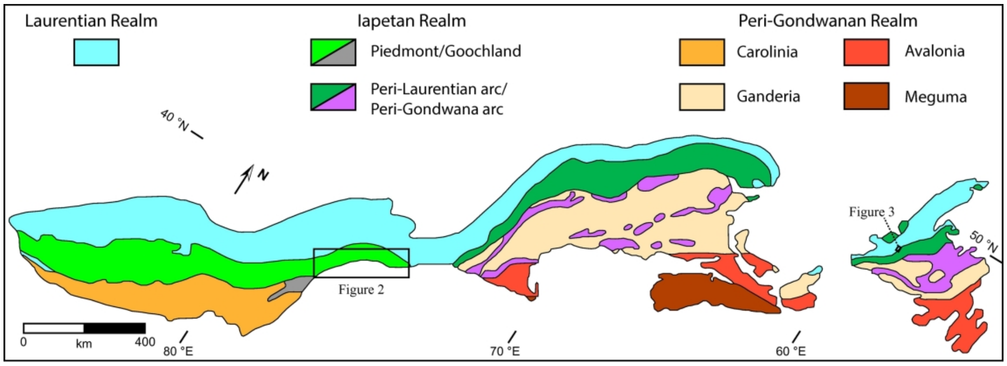

Figure 1 (Martin and Bosbyshell)

Generalized geologic map of the Appalachian Orogen. Modified from Hibbard et al. (2006).

231x119mm (300 x 300 DPI)

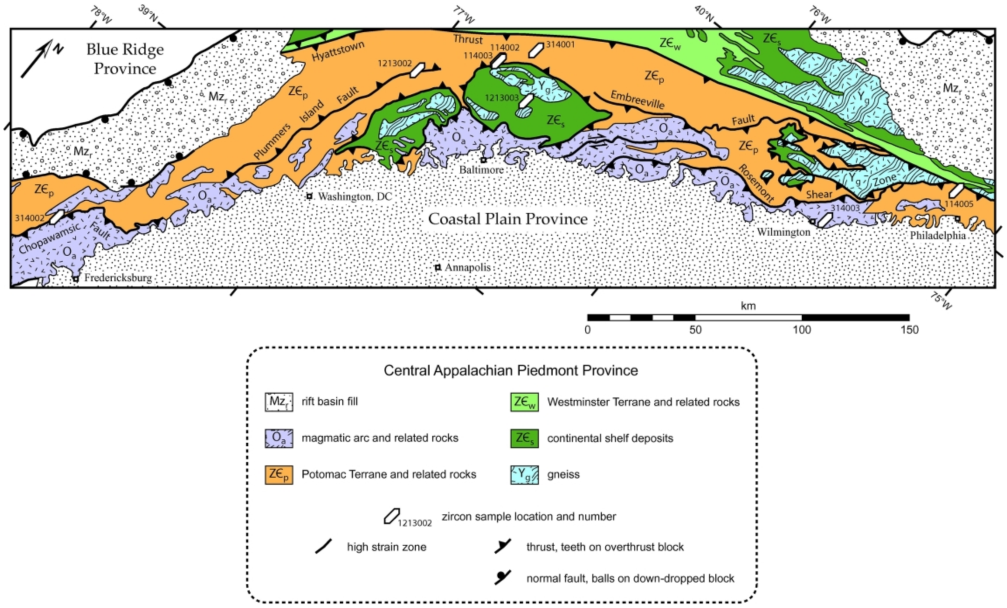

Figure 2 (Martin and Bosbyshell)

Geologic map of part of the central Appalachian Piedmont Province. Modified from Hibbard et al. (2006), Southworth et al. (2007), Hughes et al. (2014), and Martin et al. (2015).

219x163mm (300 x 300 DPI)

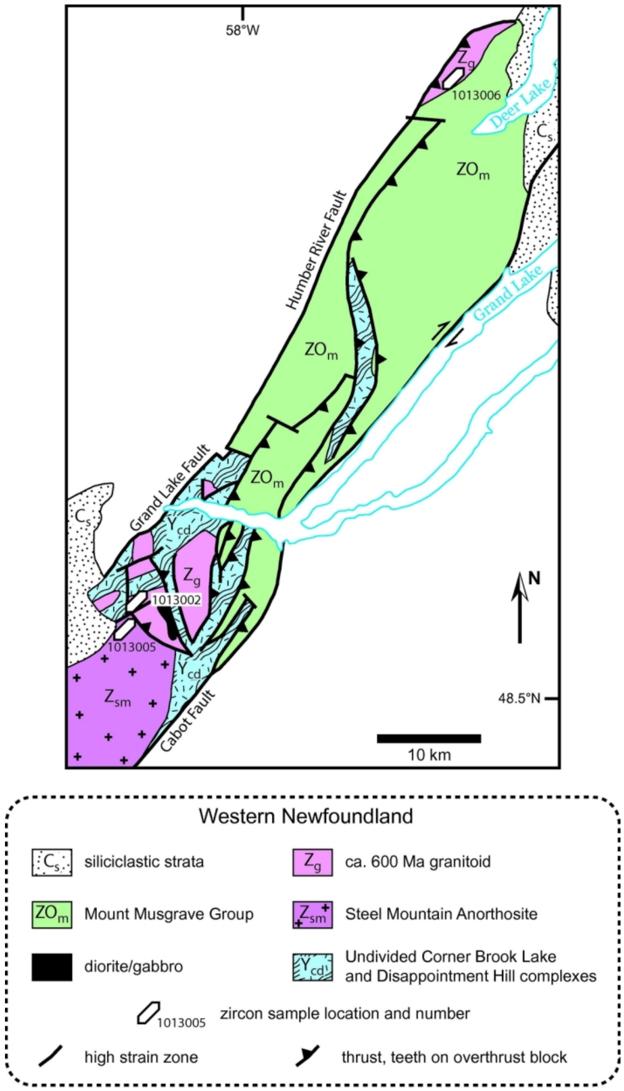

Figure 3 (Martin and Bosbyshell)

Geologic map of part of western Newfoundland. Modified from Brem et al. (2006) and Lin et al. (2013).

94x183mm (300 x 300 DPI)

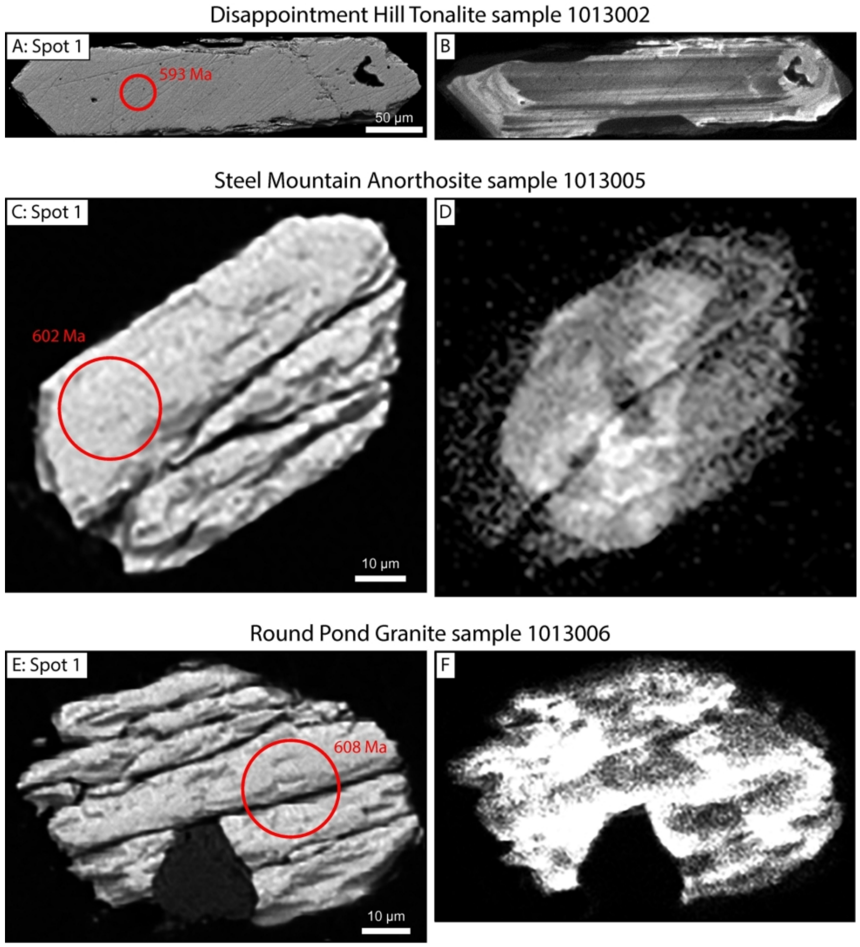

Figure 4 (Martin and Bosbyshell)

Backscattered electron (left column) and cathodoluminescence (right column) images of zircon from the three samples of western Newfoundland intrusive rocks. The circles show the locations of 20 µm-diameter laser spots that yielded the indicated 206Pb/238U ages.

154x217mm (300 x 300 DPI)

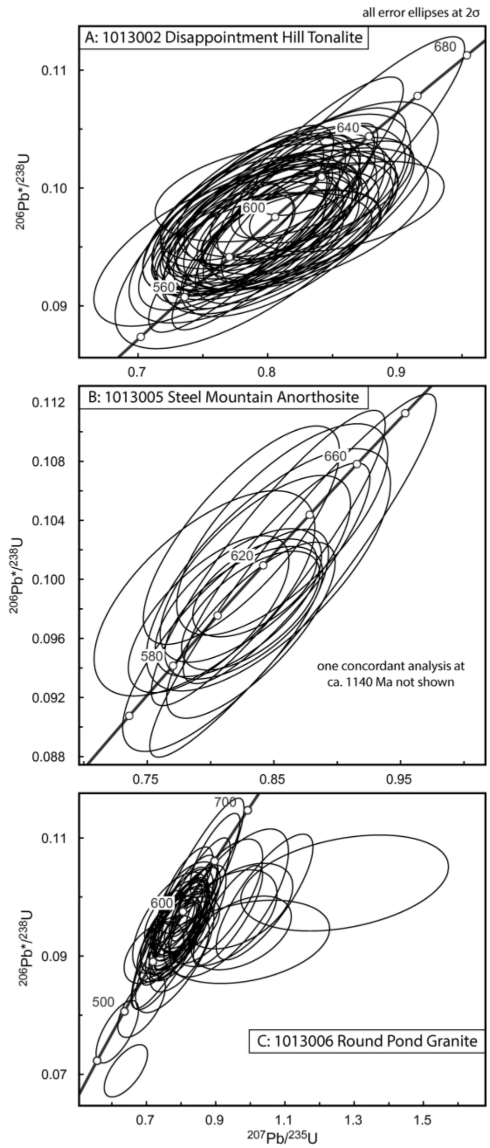

Figure 5 (Martin and Bosbyshell)

Concordia diagrams for U/Pb isotope analyses of spots in zircon from the three samples of western Newfoundland intrusive rocks.

101x253mm (300 x 300 DPI)

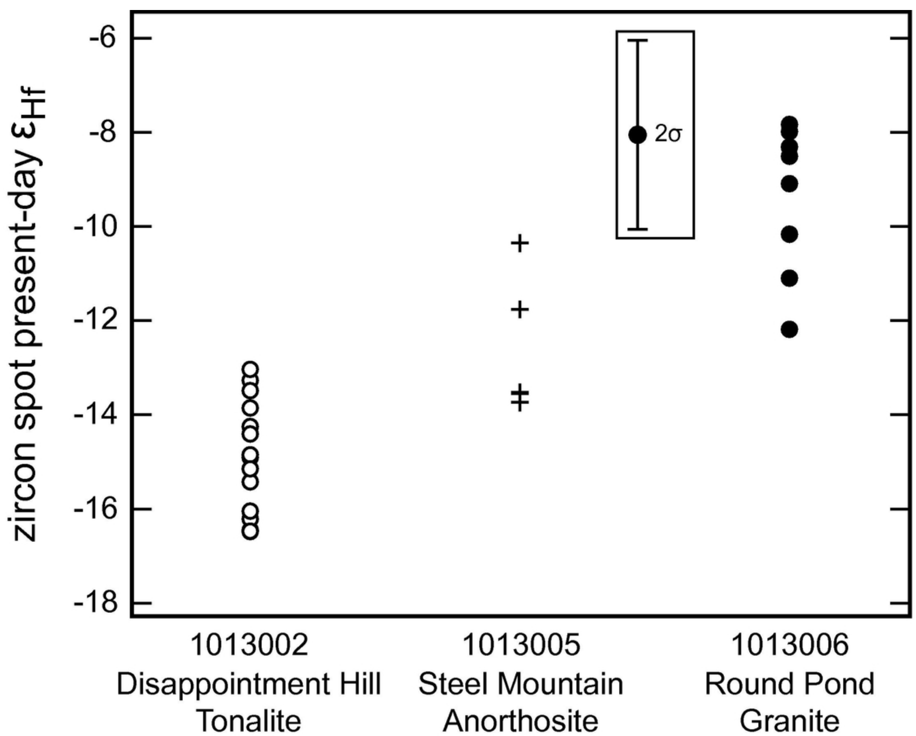

Figure 6 (Martin and Bosbyshell)

Modern εHf values of spots in zircon from the three samples of western Newfoundland intrusive rocks.

94x123mm (300 x 300 DPI)

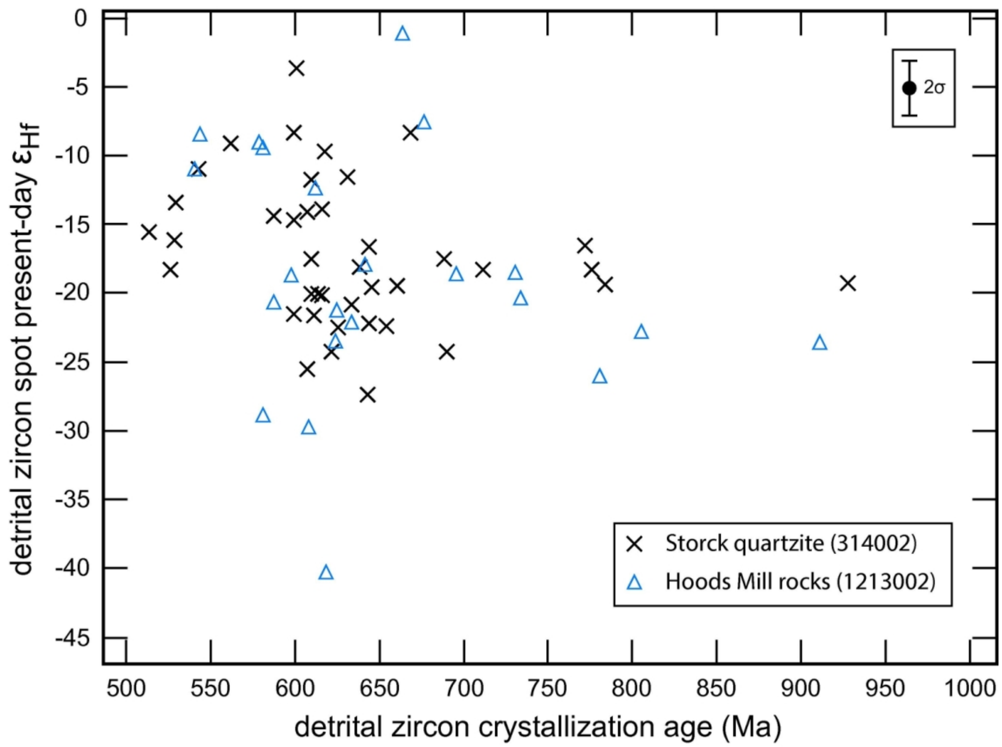

Figure 7 (Martin and Bosbyshell)

Modern εHf values versus crystallization age for detrital zircon from the Storck quartzite and the Hoods Mill rocks. There is no correlation between zircon crystallization age and modern εHf value.

131x157mm (300 x 300 DPI)

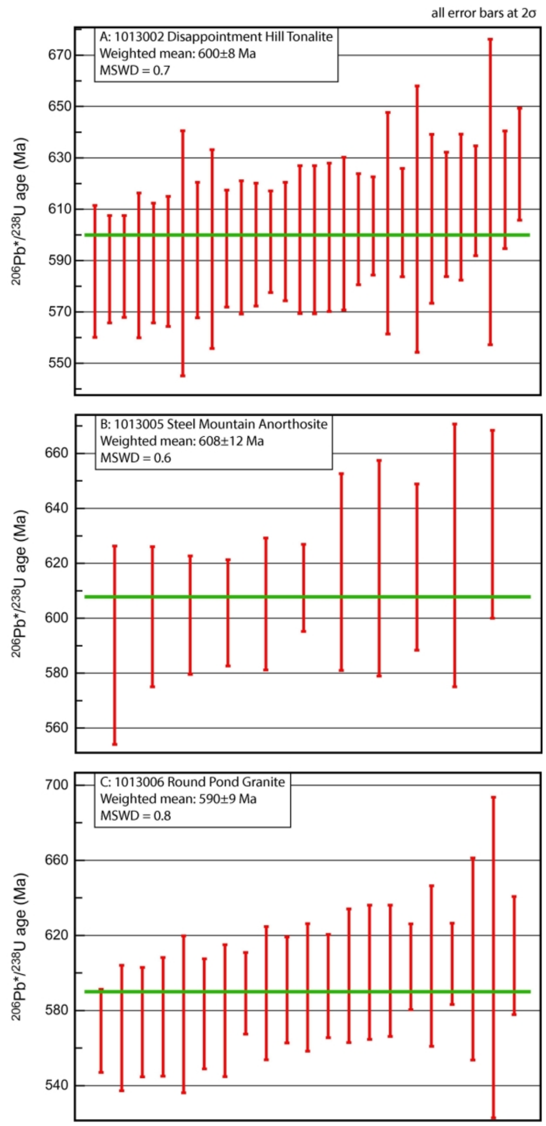

Figure 8 (Martin and Bosbyshell)

Plots of concordant, non-xenocrystic U-Pb isotope analyses (vertical red bars) from each sample of western Newfoundland intrusive rocks showing the weighted mean 206Pb/238U age (horizontal green bar). The reported uncertainty includes both measurement and systematic errors.

108x241mm (300 x 300 DPI)

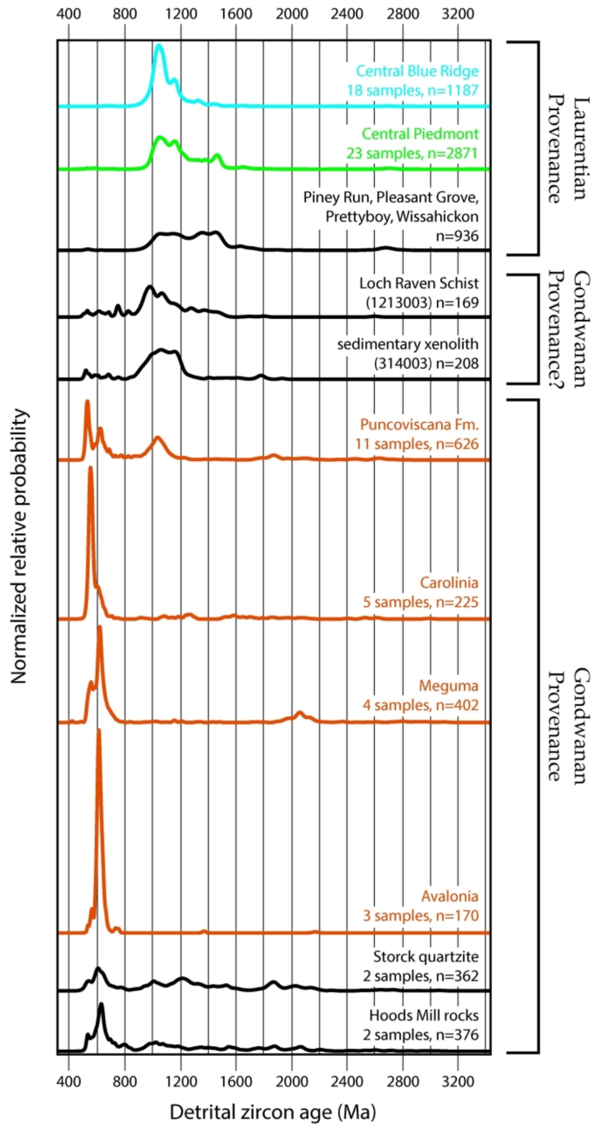

Figure 9 (Martin and Bosbyshell)

Normalized relative probability plots of detrital zircon ages from our samples compared to detrital zircon ages from other late Ediacaran-Cambrian Laurentian and peri-Gondwanan sandstone. Data were normalized so that the area under each curve is the same. Data sources and processing details are given in Table S5 and the ages and corresponding errors are in Table S6. The sample numbers for the Piney Run Formation, Pleasant Grove Schist, Prettyboy Schist, and Wissahickon Formation are 114002, 114003, 314001, and 114005, respectively.

115x236mm (300 x 300 DPI)

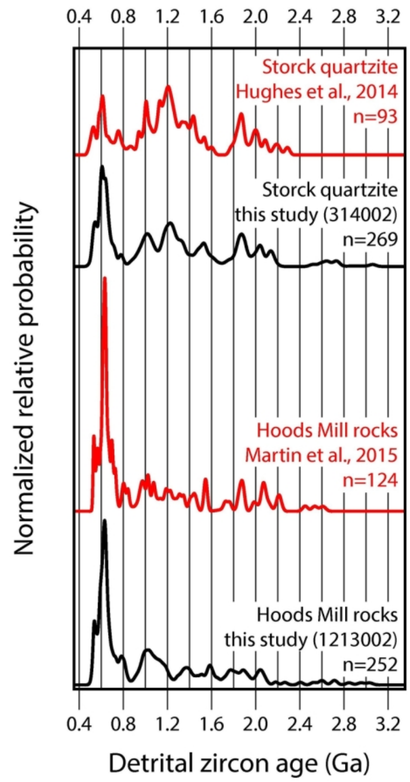

Figure 10 (Martin and Bosbyshell)

Normalized relative probability plots of detrital zircon ages from the Storck quartzite and the Hoods Mill rocks. The detrital zircon age spectra from our new samples are nearly identical to the previously-published spectra from these units. Data were normalized so that the area under each curve is the same. Data processing is described in Table S5.

67x184mm (300 x 300 DPI)

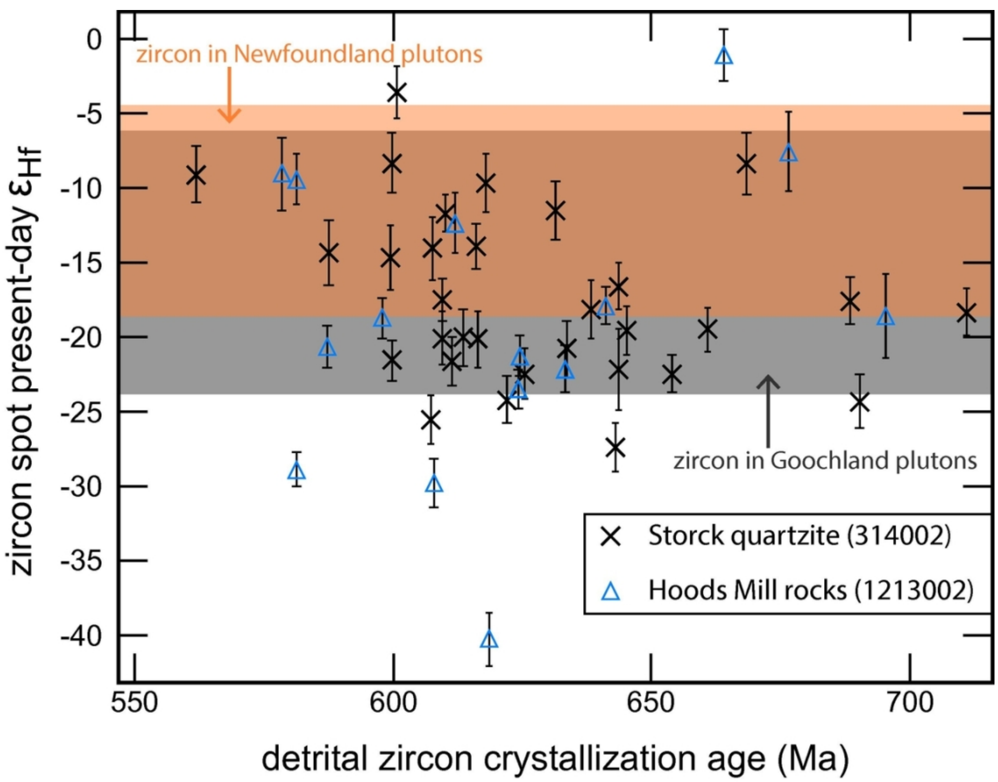

Figure 11 (Martin and Bosbyshell)

Comparison of present-day εHf values of 670-580 Ma detrital zircon from the Storck quartzite and the Hoods Mill rocks with modern εHf values of zircon in Neoproterozoic plutons in the Goochland Terrane and western Newfoundland. The present-day εHf values of the detrital zircon extend to values both less and more negative than the zircon in the plutons, outside uncertainty. The plot shows only detrital grains with ages that overlap the age range 670-580 Ma within uncertainty. These are grains 131 to 218 in sample 314002 and 69 to 266 in sample 1213002 (Table S3). The range of εHf values for the zircon in the plutons includes uncertainties. The bands of values for the plutons are shown stretching horizontally across the entire diagram to ease viewing, but the actual range of intrusion ages is 630-590 and 660-580 Ma for the western Newfoundland and Goochland plutons, respectively. εHf values for the Goochland Terrane zircon from Martin et al. (2018).

108x118mm (300 x 300 DPI)