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New U-Pb age constraints on the geological history of the Ganderian Bras d'Or terrane, Cape Breton Island, Nova Scotia

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ABSTRACT

The northern Appalachian orogen preserves evidence of a complex history of amalgamation of terranes with both Laurentian and Gondwanan affinities. The Ganderian Bras d'Or terrane of central Cape Breton Island is not well-represented elsewhere in the orogen and its relationship to other Ganderian terranes is enigmatic, particularly with respect to its pre-Neoproterozoic history. The Boisdale Hills and Kellys Mountain areas contain the oldest metamorphic rocks in the Bras d’Or terrane. Quartzite units in the Boisdale Hills have detrital zircon populations with ages ranging from 3.2 Ga to ca. 1 Ga. Paragneiss units from the Kellys Mountain area contain Mesozoic to Neoproterozoic detrital zircons, in which the youngest grains indicate that the maximum depositional age is <600 Ma. The detrital zircon populations of rocks from both areas are consistent with Gondwanan provenance for the protoliths, most likely the Amazonian craton. New U-Pb dates for subduction-related dioritic to granodioritic plutons in the Boisdale Hills yielded ages of 560 Ma to ca. 540 Ma. Sedimentary, bimodal volcanic and plutonic rocks from the Bourinot belt in the Boisdale Hills and related plutons in the Kellys Mountain area have ages of ca. 510 – 490 Ma and are interpreted to have formed during extension related to separation of Ganderia from Gondwana. The southeastern Bras d’Or terrane preserves rocks formed in Pan-African subduction zones on a former passive margin of Gondwana as well as rocks formed during the initial stages of rifting of Ganderia from Gondwana and the subsequent opening of the Rheic Ocean.

Key words: Cape Breton Island, detrital zircon, geochronology, tectonic evolution, Appalachians
Introduction

Cape Breton Island exposes a highly compressed cross-section of the northern Appalachian orogen, where geological components representing Laurentia and three accreted Gondwana-derived terranes are exposed across ca. 140 km (Fig. 1, inset). The Laurentian Blair River Inlier forms the northwesternmost component of the island, the Ganderian Aspy and Bras d’Or terranes form the central area, and the Avalonian Mira terrane forms the southern part (Fig. 1, inset; Barr et al. 1996; Hibbard et al. 2006, 2007). The Bras d’Or terrane is the most enigmatic of these terranes, particularly with respect to its Proterozoic history and affinity, and its relationship to other Ganderian and Avalonian parts of the northern Appalachian orogen (e.g., Barr and White 1996; Barr et al. 1996a; Dostal et al. 1996; Barr et al. 1998; Keppie and Dostal 1998; Murphy et al. 1999; Barr et al. 2014a, b). In contrast to other parts of Ganderia, which are dominated by lower Paleozoic rocks, the Bras d’Or terrane consists primarily of Neoproterozoic and Cambrian metamorphic and plutonic rocks, unconformably overlain by mainly Carboniferous sedimentary rocks (Fig. 1) (Raeside and Barr 1990; White et al. 2016). It has been correlated with rare Neoproterozoic inliers in Ganderian terranes in Newfoundland (Rogers et al. 2006; Zagorevski et al. 2007; Zagorevski et al. 2010), and with the Brookville terrane in southern New Brunswick to which it shows most geological similarity (Barr and Raeside 1989; Barr and White 1996; White and Barr 1996; Barr et al. 1998).

This study is focused on U-Pb dating of detrital and igneous zircon in metasedimentary and plutonic rocks in the Boisdale Hills and Kellys Mountain areas of the southeastern Bras d’Or terrane (Figs. 1, 2). The detrital zircon data presented here enhance the existing small detrital zircon database for the Bras d’Or terrane (Keppie et al. 1998; Barr et al. 2003; White et al. 2016) and enable more detailed comparison of high- and low-grade metasedimentary units in terms of
depositional age and provenance. These rocks are the oldest in the Bras d’Or terrane, and are useful to assess the provenance of pre-Appalachian-cycle rocks in Ganderia and the location of Ganderia prior to its accretion to Laurentia. In younger units, the proximity of Laurentia after the beginning of Pangaean amalgamation tends to obscure the smaller pre-Appalachian zircon populations by providing detrital material from a range of source areas. This study, therefore, does not have the challenge of discriminating between Laurentia-derived zircon of a particular age (e.g., Grenvillian) from zircon of similar age from other part of the same orogen. In addition to the detrital zircon data, this study includes U-Pb ages from five plutonic units which give evidence for a more protracted pre-Appalachian cycle plutonic history in the Bras d'Or terrane than previously recognized.

Geological setting

By the early 2000s, the 1970s' division of the Appalachian orogen into Humber, Dunnage, Gander, Avalon, and Meguma zones (Williams 1978) had been replaced by divisions that recognized their origins either in Laurentia or peripheral to Laurentia versus origins in Gondwana or peripheral to Gondwana (e.g., Hibbard et al. 2006). The former Dunnage zone was subdivided into peri-Laurentian and peri-Gondwanan parts, the latter peripheral to the Ganderian part of Gondwana that was interpreted to have been linked to Amazonia whereas in many reconstructions Avalonia and Meguma are linked to West Africa (e.g., Hibbard et al. 2007; van Staal and Barr 2012; van Staal et al. 2012). In the new interpretations, the Ordovician Taconic orogeny resulted from subduction and closures of seaways adjacent to Laurentia, whereas the Penobscottian orogeny in a similar time frame represented subduction and closure of seaways adjacent to Ganderia (Zagorevski et al. 2010; van Staal and Bar 2012). The Silurian Salinic
orogeny resulted from closure of the Iapetus Ocean and juxtaposed Ganderia with Laurentia and peri-Laurentian terranes. Subsequently, in the late Silurian and Devonian, closure of the Rheic Ocean and related seaways, which had formed when Ganderia, Avalonia, and Meguma separated from Gondwana in the early Paleozoic, resulted in the Acadian and Neoacadian orogenies and the construction of the composite Laurentian margin. This composite margin was subsequently deformed by collisional and transcurrent tectonics during closure of Rheic Ocean remnants in the Carboniferous Alleghanian orogeny to form the supercontinent Pangaea (e.g., van Staal and Barr 2012).

Unravelling the various Laurentian and Gondwanan components in the Appalachian orogen has been challenging, in large part because of limited exposures of their Precambrian infrastructure and overprinting by younger metamorphic, magmatic, and tectonic events. Hence areas such as the Bras d’Or terrane where such rocks are exposed with limited Paleozoic overprint are invaluable in interpreting provenance within Gondwanan terranes. The Bras d’Or terrane is also valuable because it has been independently linked with the Gondwanan margin as summarized by Pollock et al. (2012) and Domier (2015) through Cambrian Gondwanan faunal provinces which gradually shift towards Laurentian provinces during the Ordovician and Silurian as a result of the opening of the Rheic ocean (Cocks and Fortey 1982) and paleomagnetic data which have been interpreted to place the terrane close to the West African part of Gondwana during the Cambrian (Johnson and Van der Voo 1985).

The Neoproterozoic metamorphic rocks of the Bras d’Or terrane include small, isolated areas of low-pressure amphibolite-facies gneiss, and larger areas of greenschist-facies (and in places upper greenschist-facies to lower amphibolite-facies) quartzite, marble, meta-greywacke, and minor volcanic rocks (Fig. 1). Most of these rocks were included in the George River Series
or Group by early workers (e.g., Milligan 1970; Keppie 1979). As a result of regional mapping and petrological studies, Raeside and Barr (1990) divided these rocks into two assemblages based mainly on metamorphic grade: mainly lower grade units which were named the George River metamorphic suite and higher-grade units, including gneissic rocks, which were named the Bras d’Or metamorphic suite. These metamorphic rocks are generally separated by faults or by intrusive rocks and their relationships to each other are uncertain. However, recent dating and petrological studies have suggested that they are equivalent units at different metamorphic grades, for example in the Kellys Mountain area where the high-grade Kellys Mountain gneiss has been proposed to be equivalent to the lower-grade Glen Tosh Formation (Barr et al. 2013). Similarly in the Creignish Hills area, high-grade metasedimentary rocks of the Melford Formation and Chuggin Road complex are equivalent to the low-grade Blues Brook Formation, and in the North Mountain area, the Lime Hill gneissic complex is correlative with the lower grade Malagawatch Formation (White and Boehner 2008; White et al. 2016).

If the lower-grade metasedimentary units in the Bras d’Or terrane are age correlative, then their maximum depositional age (and that of their higher-grade equivalent units) is constrained at about 600 Ma, based on the youngest detrital zircon U-Pb age from the Blues Brook Formation in the Creignish Hills (White et al. 2016). Their minimum age is constrained by many 560-550 Ma U-Pb zircon ages from cross-cutting plutons throughout the terrane (see White et al. 2016 for a recent compilation). An additional age constraint is provided by an age of 576.5 ± 2.3 Ma for volcanic rocks of the Price Point Formation, one of the low-grade metamorphic units in the eastern part of the Bras d’Or terrane (Barr et al. 2018). The minimum age of the higher-grade Bras d’Or metamorphic suite is constrained by the igneous crystallization age of ca. 560-565 Ma for the Chuggin Road tonalitic orthogneiss in the Creignish Hills (White et al. 2016), and a ca.
586 Ma date for the Melford pluton reported by Keppie et al. (2000). Regional metamorphism likely occurred during the widespread plutonic activity at ca. 560 - 565 Ma (White et al. 2016), indicating an active tectonic environment where deposition of sediments at ca. 600 Ma was quickly followed by regional metamorphism, igneous activity, and rapid exhumation (White et al. 2016). Rapid exhumation is indicated by $^{40}$Ar/$^{39}$Ar ages between 550 and 540 Ma, interpreted to date cooling that closely followed intrusion of the plutonic rocks (Keppie et al. 1990, 2000; White et al. 1990, 2016).

The boundary between the Bras d’Or terrane and the mainly Early Paleozoic Aspy terrane to the north and west is the Eastern Highlands Shear Zone, a mylonitic high-strain zone (Lin 1993, 1995, 2001; Lin et al. 1994). Neoproterozoic rocks in the Bras d’Or terrane record $^{40}$Ar/$^{39}$Ar hornblende cooling ages of ca. 560 – 540 Ma, except those adjacent to the shear zone which have cooling ages of ca. 425 – 415 Ma, interpreted to be a result of partial resetting during the Aspy-Bras d’Or terrane collision (Reynolds et al. 1998; Lin 2001). The two terranes were juxtaposed by ca. 375 Ma, based on the age (U-Pb zircon, 375 ±5/-4 Ma and monazite, 372 to 373 Ma; Dunning et al. 1990) of the Black Brook Granitic Suite that intruded the shear zone and is largely undeformed. The Bras d’Or terrane may have been basement to the Aspy terrane (Chen et al. 1995; Lin et al. 2007), but the widespread Silurian to Devonian plutonism that characterizes the Aspy terrane (Barr et al. 2018 and references therein) is not present in the Bras d’Or terrane except within strands of the Eastern Highlands Shear Zone (Raeside and Barr 1990).

The Bras d’Or terrane is separated from the Avalonian Mira terrane to the south by a cryptic suture that is traced along the George River – MacIntosh Brook fault which experienced significant movement during the Carboniferous (Gibling et al. 1987). The McAdams Lake Formation, a Devonian conglomerate unit immediately to the south of this fault, contains clasts
from both Mira terrane and Bras d’Or terrane units indicating that the two terranes were juxtaposed before the Middle Devonian (White and Barr 1998). The Mira terrane is interpreted to have been thrust under the Bras d’Or terrane (to the NW in present-day co-ordinates, based on gravity and magnetic models of the boundary between them (King 2002). However, similarities in some fossiliferous Cambrian sedimentary units that overlie the Mira terrane and occur in a fault-bounded sliver in the Boisdale Hills of the Brans d’Or terrane (Fig. 1) continue to result in debate about the Ganderian vs Avalonian affinity of the Bras d’Or terrane (e.g., Landing and Fortey 2011).

Geology of the Boisdale Hills

Raeside (1989) assigned a narrow band of metamorphic rocks along the Georges Brook fault to the Frenchvale Road metamorphic suite, part of the regional Bras d’Or metamorphic suite of Raeside and Barr (1990), also known as the Bras d’Or gneiss (Keppie 2000). On its northwestern margin, the Frenchvale Road metamorphic suite was intruded by the Boisdale Hills pluton (Fig. 2). The suite comprises marble, quartzite, and psammitic with minor amphibolite and andalusite-bearing metapelitic rocks, and has been folded in an upright synform with limbs dipping moderately to steeply NE to SW (Raeside 1990). It is lithologically similar to the Lime Hill Gneissic Complex and the Melford Formation in the North Mountain and Creignish Hills areas, respectively (Fig. 2), where psammitic, semi-pelitic, marble and calc-silicate lithologies are common and metamorphic rocks are intruded by Neoproterozoic plutonic rocks (Raeside and Barr 1990; White et al. 1990, 2016). Peak metamorphic conditions in the Frenchvale Road metamorphic suite have been estimated at ca. 280 MPa at 580°C (Walker 1988) and 300 – 450 MPa at >600°C (Raeside 1990). Peak metamorphic conditions in the other high-grade areas are
<400 MPa with >650°C in the Lime Hill Gneiss (Raeside 1990), and 200 to 350 MPa at 525 to 650°C in the Whycocomagh Mountain Gneiss (Armitage 1989; Swanton et al. 2010).

The lower grade metamorphic rocks in the Boisdale Hills are assigned to the Benacadie Brook Formation which consists primarily of metasiltstone and metasandstone (Raeside 1989; Raeside and Barr 1990). Major igneous units in the Boisdale Hills are the Shunacadie pluton, which consists mostly of granodiorite dated at 564 Ma ± 3 (Barr et al. 1990) and associated tonalite dykes dated at 564.5 ± 5.1 Ma (Barr et al. 1999), and the more compositionally varied Boisdale Hills pluton (Barr and Setter 1986) for which a minimum age of ca. 530 Ma is indicated by \(^{40}\)Ar/\(^{39}\)Ar dating of hornblende by Keppie et al. (1990). These two plutons could be connected at depth, but at surface they are separated by an entirely fault-bounded belt of Cambrian volcanic and sedimentary rocks known as the Bourinot belt (White et al. 1994; Palacios et al. 2012). The plutons are intruded by mafic dykes which may have been feeders to the middle Cambrian mafic volcanic units of the Bourinot belt (Stevens 2010).

The Bourinot belt consists of the Bourinot Group, including middle Cambrian basaltic and rhyolitic volcanic flows and tuffs of the Eskasoni Formation, mainly quartz-rich siltstone and shale of the Dugald Formation, and tuff and siltstone of the Gregwa Formation. The Bourinot Group is overlain by middle Cambrian shale and siltstone of the MacMullin Formation, shale and minor black limestone of the upper Cambrian MacNeil Formation, and light grey to black shale of the lower Ordovician McLeod Brook Formation (Hutchinson 1952; White et al. 1994; Landing et al. 1997). Landing (1996), Landing et al. (1997) and Landing and Fortey (2011) used regional names for these units, rather than the traditional terminology of previous authors. The Mount Cameron syenogranite in the northern of the Boisdale Hills yielded a Cambrian age of 509.3 ± 1.4 Ma and is considered related to the volcanic rocks of the Bourinot Group, of which
rhyolite on Long Island yielded an age of 505 Ma ± 3 Ma (White et al. 1994). Difficulties in reconciling paleontological and absolute ages as discussed by White et al. (1994) were resolved in subsequent iterations of the geological time scale (Palacios et al. 2012; Barr and White 2017a, b). Paleomagnetic studies in the volcanic and associated sedimentary rocks in the Bourinot Group have suggested that the Bras d’Or terrane (as basement to the Bourinot belt) was located proximal to the West African craton in Gondwana during the Middle Cambrian (Johnson and Van der Voo 1985). This is consistent with earlier interpretations of the faunal assemblages in the same rocks which linked the Bras d’Or terrane with Gondwanan (specifically Acado-Baltic) faunal provinces during the Cambrian (Cocks and Fortey 1985).

**Geology of the Kellys Mountain area**

Kellys Mountain consists mainly of leucogranitic rocks of the Kellys Mountain pluton which includes a varied suite of dioritic to granodioritic rocks, and a younger suite of granitic rocks, all of which intruded the Kellys Mountain migmatitic paragneiss and lower-grade metasedimentary rocks of the Glen Tosh Formation (Fig. 3; Barr et al. 1982, 2013; Jamieson 1984). The gneiss contains the mineral assemblage cordierite-biotite-K-feldspar-plagioclase-quartz with accessory apatite, tourmaline, and Fe-Ti oxides and has an inferred semi-pelitic to pelitic protolith (Jamieson 1984). It is heterogeneous and locally contains deformed and boudinaged amphibolite sheets concordant with the steeply dipping N-NW foliation in the gneissic units (Jamieson 1984). Marble, calc-silicate rocks, and quartzite typical of other high-grade metamorphic units of the Bras d’Or terrane (Raeside and Barr 1990) are not present in the Kellys Mountain area (Jamieson 1984; Barr et al. 2013). The Kellys Mountain gneiss records peak metamorphic conditions of 100–350 MPa and 580–700°C, attributed to low-pressure
contact metamorphism (Jamieson 1984). The protolith and metamorphic ages for the Kellys Mountain gneiss have been difficult to determine. A Rb-Sr isochron age of 701 ± 66 using an initial Sr ratio of 0.7056 ± 0.0030 was reported by Olszewski et al (1981). Keppie et al. (1998) assigned an age of 515 ± 1 Ma based on U-Pb monazite ages from the Kellys Mountain gneiss. However, that age may be partially reset (Barr et al. 2013) and the metamorphic age could be similar to the ca. 550 cooling ages from muscovite in the Barachois River and MacMillan Flowage metamorphic units of the eastern Cape Breton Highlands (Dallmeyer and Keppie 1993).

The Glen Tosh Formation forms the southern part of Kellys Mountain. It consists mainly of metasiltstone and metagreywacke and lacks the marble-quartzite components that characterize other areas of the George River metamorphic suite (Raeside and Barr 1990). The Glen Tosh Formation is thought to correlate with the Kellys Mountain gneiss based on isotopic and major element geochemistry (Barr et al. 2013) but this is uncertain as the ages of the protoliths are not known. Monazite in the Glen Tosh Formation shows evidence for recrystallization in the contact aureole of the Kellys Mountain granite at ca. 480 Ma (Shawwa et al. 2017), suggesting that at least part of the metamorphism in the lower grade rocks might be attributed to an unknown younger intrusion. Shawwa et al. (2017) also showed that the regional metamorphic fabric developed earlier than the overprinting contact metamorphism associated with the intrusive rocks.

The plutonic rocks in the Kellys Mountain area are mainly the Kellys Mountain granite, intruded into a less extensive but more varied suite of dioritic to granodioritic rocks (Barr et al. 1982). The granitic rocks were dated at 498 ± 2 Ma (U-Pb, zircon; Barr et al. 1990) and the dioritic rocks were assumed to be older (ca. 560 Ma) like other dioritic plutons of the Bras d'Or terrane (Raeside and Barr 1990; Dunning et al. 1990). A Rb-Sr whole-rock isochron was
proposed for the dioritic rocks suggesting an age of 636 ± 69 Ma (Gaudette et al. 1985) but this
isochron was poorly defined and reported only in an abstract without sample details and the
initial Sr ratio.

METHODS

With the exception of sample SMB06-110 for which methods are described at the end of
this section, samples for the present study were sent to Overburden Drilling Management (ODM)
in Ottawa, Ontario, for electro-pulse disaggregation and zircon separation. Zircon grains were
then picked (at Cape Breton University), mounted in an epoxy-covered thin section (this and all
subsequent steps at the University of New Brunswick Fredericton), polished to expose the
centres of the zircon grains, and imaged using cold cathodoluminescence to identify internal
zoning and inclusions. These images were used to select ablation points (30 µm diameter),
avoiding any visible inclusions, cracks, or other imperfections.

U and Pb isotopic compositions were measured using the Resonetics S-155-LR 193 nm
Excimer laser ablation system connected to an Agilent 7700x quadrupole inductively coupled
plasma – mass spectrometer in the Department of Earth Sciences at the University of New
Brunswick, following the procedure outlined by McFarlane and Luo (2012) and Archibald et al.
(2013). Data reduction was done in-house using Iolite software (Paton et al. 2011) to process the
laser output into data files, and further reduced for U–Pb geochronology using VizualAge (Petrus
and Kamber 2012). VizualAge outputs include uncorrected U–Pb ratios that were used to model
$^{204}\text{Pb}$-based corrections (Andersen 2002) and $^{208}\text{Pb}$-based corrections. Data were filtered using
$^{204}\text{Pb}$ as a monitor. As described in Barr et al. (2018) we use the following procedure: for grains
with <80 counts/s $^{204}\text{Pb}$, data are uncorrected; and for grains where the % error on the $^{204}\text{Pb}$
counts per second was <20%, we used a $^{204}\text{Pb}$-based correction (Andersen 2002), and for grains where the % of radiogenic Pb (PB* in file) is less than 98.5% we used a $^{208}\text{Pb}$-based correction (Petrus and Kamber 2012). After these corrections were applied, data were sorted by % concordance ($^{206}\text{Pb}/^{238}\text{U}$ versus $^{207}\text{Pb}/^{235}\text{U}$), and by the % of radiogenic Pb in the grains as calculated using VizualAge. All analytical data are presented in Appendix A.

Concordia ages for igneous units were calculated for clusters of three or more near-concordant points using Isoplot versions 3.75 and 4.15 (Ludwig 2003, 2012). Data points included in the concordia calculations and reported here are grains that are 98%–101% concordant and do not require a correction for common Pb ($^{204}\text{Pb}$ counts/s < 80). In all cases concordia ages are calculated with as many grains as possible, and therefore the MSWD values and reported probability of concordance could in some cases be improved by using fewer grains. However, in this paper we follow the approach of including as many grains as possible in order to get a representative concordia age and avoid selecting grains only to improve the MSWD. In all cases the concordia ages overlap with the weighted mean ages for the samples using all near-concordant data ($^{206}\text{Pb}/^{238}\text{U}$) for most samples and $^{207}\text{Pb}/^{206}\text{Pb}$ ages for the samples older than 1Ga. We report concordia ages instead of the weighted mean ages because the weighted mean ages include more of the grains on the outer edges of the spreads of data.

For detrital zircon samples we present probability distribution histograms based on $^{207}\text{Pb}/^{206}\text{Pb}$ ages, for grains between 95 and 101% concordant. To determine the youngest age represented in each sample we use only clusters of more than 3 grains with ages that overlap within error and are 98-101% concordant. Using only near-concordant grains that overlap within error is a conservative approach which serves to reduce the possibility of misrepresenting the
maximum depositional age as too young by using single grains that may have experienced Pb loss (Dickenson and Gehrels 2010).

Concordia ages for FC1 during 9 separate runs were 1098.4 ±3.9 Ma, 1098.8 ±4.1 Ma, 1098.6 ±3.6 Ma, 1099.1 ±2.7 Ma, 1099.0 ±3.7 Ma, 1099.4 ±3.0 Ma, 1098.8 ±2.2 Ma, 1098.9 ±2.6 Ma, and 1098.9 ±2.9 Ma. Concordia ages for 91500 during 4 separate runs were 1059.9 ±5.1 Ma, 1051.5 ±15 Ma, 1069.5 ±7.2 Ma, and 1048.1 ±4.8 Ma. Concordia ages for Tanzania in two separate runs were 694.4 ±7.6 Ma and 696.6 ±4.0 Ma. Concordia ages for Plesovice during 6 separate runs were 335.7 ±2.0 Ma, 337.1 ±1.9 Ma, 336.1 ±2.0 Ma, 334.8 ±1.0 Ma, 340.4 ±1.5 Ma, and 339.0 ±1.4 Ma. The concordia age of the LaserChron standard SL was 565.3 ±2.2 Ma. NIST610 glass was used as a concentration standard. All data for standards are compiled in a separate file and presented in Appendix B.

Sample SMB06-110 was analyzed at the LaserChron facility of the University of Arizona. Zircon grains were recovered from about 20 lbs of clastic sediment using standard mineral separation procedures, including jaw crushing, disk milling, Wilfley table separation, and heavy liquid and Frantz magnetic separation. Zircon concentrates were mounted in epoxy and polished to their approximate mid-sections to expose the interiors of most zircon grains. Laser ablation analyses were acquired using a Micromass (GV) Isoprobe multicollector ICP-MS equipped with 9 Faraday collectors, and axial Daly detector, and 4 ion-counting channeltrons. The instrument uses a NewWave excimer laser with an emission wavelength of 193 nm. The collector arrangement permits measurement of $^{204}$Pb in an ion-counting channel while $^{206}$Pb, $^{207}$Pb, $^{208}$Pb, $^{232}$Th and $^{238}$U are simultaneously measured using Faraday detectors. All analyses were conducted in static mode using a laser beam diameter of 35 microns at an output energy of ~32 mJ and a repetition rate of 8 Hz. Each analysis consisted of one 20-second integration on
backgrounds (no laser firing) and twenty 1-second integrations on peaks with the laser firing. Any Hg contribution to the $^{204}$Pb mass position was removed by subtracting the background values; such contributions from the Ar plasma gas were minimal. A 30-s delay was required for peak signal intensity to return to background values. The depth of each excimer ablation pit is approximately 15-20 microns. Inter-element fractionation during the analysis was monitored by analyzing fragments of a large, concordant zircon crystal standard having a precisely known ID-TIMS age (564 ± 4 Ma, 2σ). This reference zircon was analyzed once every 5 unknowns. Measured isotopic ratios were corrected against the standard calibration, and a common Pb correction was made using the measured $^{204}$Pb, assuming an initial Pb composition according to Stacey and Kramers (1975). Analyzed zircons were selected randomly except for avoidance of grains with visible cracks, inclusions or compositional zoning (cores). Reported ages are based primarily on $^{207}$Pb/$^{206}$Pb ratios for grains >1Ga and $^{206}$Pb/$^{238}$U ratios for grains <1Ga (in this study there are no grains between 800 Ma and 1 Ga). Concordia plots and probability distributions were constructed using the same filters and procedures as the samples described above. All analytical data are presented in Appendix A with analyses that are included in concordia calculations highlighted in grey.

**Results**

**Detrital zircon results**

**Frenchvale Road Metamorphic Suite - Sample BH036**

Sample BH036 from the Frenchvale Road metamorphic suite in the Boisdale Hills (Fig. 2) is massive, white, medium-grained quartzite. It consists of 80% quartz, 10% plagioclase, 10% mica (mostly muscovite), and trace amounts of apatite, calcite, zircon, and opaque phases.
mostly pyrite). The zircon grains separated from the sample are small (20 to 100 µm), rounded, and anhedral, indicating extensive transport and/or reworking. In CL the crystals fluoresce poorly but some have oscillatory zoning in their centres typical of magmatic zircons. The 119 95-101% concordant grains (out of 160 analysed) gave a wide range of Archean to Paleoproterozoic ages (Fig. 4a). The major populations are 3.1 to 2.5 Ga, 2.2 to 1.9 Ga, and 1.7 to 1.6 Ga. A few grains are in the 1.35 to 1.2 Ga age range, but none of them overlap to provide a good estimate of the maximum depositional age, which is likely younger than that age range.

**Frenchvale Road Metamorphic Suite - Sample BH017**

A second quartzite sample BH017 is from the Levatte quarry in the northern part of the Frenchvale Road metamorphic suite (Fig. 2). It is grey and medium-grained, composed of 85% quartz, 10% mica (mostly muscovite with minor biotite), 5% or less plagioclase, and trace amounts of apatite, calcite, zircon, and opaque phases (mostly pyrite). Zircon grains from this sample range in size from 50 to 250 µm. They are rounded and most are anhedral, although some grains are subhedral with bipyramidal terminations preserved, and some broken grains are also present. In CL the crystals fluoresce poorly but some have visible oscillatory zoning in their centres.

The zircon grains in sample BH017 display an age pattern different from that in sample BH036. One hundred and twelve 95-101% concordant grains (out of 113 analysed) show ages that are mainly between 1.6 Ga and 1.0 Ga, with major peaks at 1.2 Ga and 1.6 Ga, and also smaller populations of ages around 3.2, 2.6, 2.5, 2.0, and 1.7 Ga (Fig 4b). The youngest three overlapping grains produce a concordia age of 967.4 ± 7.4 Ma; the weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$
ages for these three grains is $956 \pm 19$. These data may provide a constraint on the maximum depositional age of the quartzite protolith.

**Kellys Mountain paragneiss – sample KM10-04**

Sample KM10-04 is migmatitic paragneiss from near the base of Kellys Mountain (Fig. 3). It consists of fine- to medium-grained quartz, plagioclase, and biotite, and minor epidote. The quartz grains are sutured, and plagioclase is euhedral with faint zoning visible in thin section. Accessory minerals include zircon, apatite, and fine-grained oxides and sulphides. Zircon grains separated from this sample are small and range in size from 20 to 100 µm. They are rounded and all are anhedral. In CL most of the crystals fluoresce poorly but some have oscillatory zoning typical of igneous rocks, without visible metamorphic overgrowths.

The age distribution from 107 95-101% concordant grains (out of 121 analysed) shows major peaks between about 0.6-0.8 Ga and an almost continuous range of Mesoproterozoic ages between about 1.0 and 2.2 Ga, with minor peaks at 1.8 Ga and 1.3 Ga, and no evidence for Archean grains (Fig. 4c). The Neoproterozoic grains have two major populations between 680 to 660 Ma, and 625 to 600 Ma. The youngest four grains that overlap within error give a concordia age of $622.3 \pm 4.2$ Ma. The weighted means of the $^{238}\text{U}/^{206}\text{Pb}$ ages for the two Neoproterozoic populations are $671.0 \pm 8.3$ Ma for the older group of 7 grains and $614.6 \pm 7.3$ Ma for the younger group of 9 grains. Based on the youngest population this rock has a maximum depositional age of about 615 Ma. A single grain with an age of 550 Ma is not considered as a maximum depositional age as it is not possible to rule out that it is a result of Pb-loss, and there is only one grain with that age instead of an overlapping group of ages from several grains (Dickenson and Gehrels 2009).
**Kellys Mountain paragneiss - sample DB002**

Sample DB002 is migmatitic paragneiss from the top of Kellys Mountain (Fig. 3). It is an equigranular, weakly foliated gneiss that contains quartz, plagioclase, and biotite (partially chloritized), with accessory zircon, sulphide phases, and apatite. The plagioclase is saussuritized, and epidote is present in veins and around plagioclase crystals. This sample contained a limited number of zircons grains that range in size between 20 to 200 µm. They are variable in shape, some are rounded and anhedral whereas others are tabular and euhedral with bipyramidal terminations, and yet others are blocky and equant. In CL the crystals fluoresce poorly but many show faint oscillatory zoning typical of igneous rocks, without visible metamorphic overgrowths.

Forty-one grains (out of 48 analysed in this relatively zircon-poor sample) are 95-101% concordant and yielded ages between ca. 590 and 700 Ma (Fig. 4d). Only a few grains have ages between 1.1 and 1.4 Ga, and between 1.5 and 1.6 Ga. The youngest five overlapping grains give a concordia age of 595.4 ± 8.9 Ma. The weighted mean of the same 5 grains is 595 ± 15 at 95% confidence level suggesting that the maximum depositional age of the protolith of this rock is 595 Ma.

Although samples DB002 and KM04-10 are petrographically similar, their detrital zircon patterns are quite different in the relative lack of Mesoproterozoic grains in sample DB002. However both samples show major Neoproterozoic populations (Fig. 5a, b).

**Eskasoni Formation, Bourinot Group – sample SMB06-110**

Quartz arenite sample SMB06-110 is from the lower part of the Eskasoni Formation, the lowermost formation in the Bourinot Group in the Boisdale Hills (Fig. 2). The sample contains
mainly quartz with minor opaque minerals and white mica. Zircon grains separated from this sample are subhedral and mostly clear, ranging in size from 30 to 80 µm.

The main age population (Fig. 4e) spans the Late Proterozoic and early Cambrian, with sparse Neoproterozoic to Archean ages from 82 grains that are 95-101% concordant (out of 99 analysed). The youngest group of 11 overlapping grains has a concordia age of $518.0 \pm 2.9$ Ma with an MSWD of 0.18, and a probability of concordance of 0.67. This age overlaps with the weighted mean of the same grains, at $517.9 \pm 2.9$ Ma at 95% confidence level with an MSWD of 0.58 and a probability of 0.83, suggesting a maximum depositional age of 515 Ma. This age is consistent with the age of $505\pm3$ Ma obtained for rhyolite in the Eskasoni Formation in the northern part of the Bourinot belt, and with the age of $509\pm2$ Ma for the Mount Cameron syenogranite pluton that occurs in faulted contact with the Bourinot Group but is inferred to be co-magmatic with the volcanic rocks based on petrological characteristics and age (White et al. 1994).

Igneous crystallization age results

Boisdale Hills pluton – sample BH040

Sample BH040 is medium-grained equigranular granodiorite from the northern part of the Boisdale Hills pluton in the unit mapped as biotite granodiorite by Barr and Setter (1986) (Fig. 2). It contains plagioclase, microcline, quartz, hornblende, and biotite with accessory rutile, zircon, magnetite, and sulphide minerals. Zircon grains from this sample are generally euhedral. They are mostly long and tabular and range in size from 50 to 150 µm. In CL they show oscillatory zoning typical of magmatic zircon.
The full dataset for this sample (Figure 5a) shows that the data are distributed along the concordia line with all but one of the grains < 600 Ma. The one exceptional grain is near concordant (100.2%) with a $^{206}\text{Pb}/^{238}\text{U}$ age of 659 ± 10 Ma suggesting that inheritance is not a major factor in this unit. There is no evidence for a clear discordia line that can be used to make unambiguous interpretations of Pb loss. No physical differences are apparent between the zircon grains with the older ages or those with younger ages so there are no external criteria to pick which group is the more appropriate to use in age interpretations. The probability distribution for all 31 grains between 98 and 101% concordant (Fig. 5b) shows two peaks in the age distribution with a gap between them. Thirteen of the analyzed grains are between 98 and 101% concordant and yield a concordia age of 562.1 ± 2.2 Ma, (Fig. 5c) and the five youngest overlapping grains in that distribution have a concordia age of 541.5 ± 3.0 Ma (Fig. 5c). There are no physical differences (size, shape, CL fluorescence) between the zircons with the older ages or those with younger ages so there are no external criteria to pick which group is the more appropriate to use in age interpretations, and therefore all the concordant grains have to be taken into account. The plot of the same 31 $^{206}\text{Pb}/^{238}\text{U}$ ages in Figure 5d shows the same gap between the group of grains overlapping ca. 560 Ma, and the group ca. 540 Ma. The weighted mean of the 98 and 101% concordant grains < 600 Ma is 552.3 ± 6.5 Ma at 95% confidence level with one grain out of 31 rejected; however, the MSWD is 14 so we do not interpret the weighted mean as a robust estimate of crystallization age.

Two interpretations are possible for the age of this sample. One is that the main crystallization age is 562.1 ± 2.2 Ma as indicated by the larger group of overlapping grains, and that the younger group at ca. 540 Ma represents a later phase of crystallization or Pb loss that did not disturb the $^{207}\text{Pb}/^{206}\text{Pb}$ systematics. In this interpretation the Boisdale Hills pluton as sampled
here would be linked to the Shunacadie pluton to the northwest which is dated at $564 \pm 3/-2$ Ma and $565 \pm 5$ Ma for granodiorite and tonalite, respectively (Barr et al. 1990, 1999). The second interpretation is that the older group represents inherited ages and that the crystallization age for the sample is $541.5 \pm 3.0$ Ma. The ca. 540 Ma age agrees well with the next sample to be discussed, BH035G, and the older ages could represent inheritance from a source similar in age to the Shunacadie pluton (or that pluton itself).

Boisdale Hills pluton – sample BH035

Sample BH035 is from the southern part of the Boisdale Hills pluton in an area mapped as biotite-hornblende granodiorite by Barr and Setter (1986). However, access and outcrop in that area are limited, and the dated sample is from outcrops on new logging roads not available in that earlier work. The dated sample is medium-grained biotite-hornblende tonalite with abundant finer-grained dioritic xenoliths; both rock types were included in the inferred oldest component of the pluton by Barr and Setter (1986). The dominant tonalitic part of the dated sample contains plagioclase, quartz, hornblende and biotite with minor microcline. Accessory minerals include titanite, apatite, and zircon.

Zircon grains from this sample vary considerably in size, ranging from 20 to 200 µm. The smaller crystals are generally short and stubby whereas larger grains are tabular. In CL most of the grains show oscillatory zoning typical of magmatic zircons. The full dataset shown in Figure 5e shows that all the data are clustered in the same area. Using the twenty analyzed grains that are 98-101% concordant, this sample has a concordia age of $540.5 \pm 1.6$ Ma, interpreted as the igneous crystallization age (Fig. 5f). There is no evidence for any older inherited grains in this sample. As noted, this age is similar to the younger concordia age from sample BH040; taken
together the data suggest that the Boisdale Hills pluton likely crystallized at around 540 Ma and hence is 20-25 million years younger than the Shunacadie pluton.

**Kellys Mountain diorite – sample SMB16-219**

SMB16-219 is medium-grained diorite from the south side of Kellys Mountain (Fig. 3). This sample is from an area mapped as undivided quartz diorite, tonalite, diorite, granodiorite, quartz monzonite, and hornblendite, and assumed to be the oldest plutonic unit on Kellys Mountain (Barr et al. 1982). The dated diorite sample consists mostly of plagioclase and hornblende, the latter with relict cores of clinopyroxene. Quartz and biotite are minor interstitial components. The sample is zircon poor, and every grain that could be picked was analysed. The zircon grains are subhedral to anhedral grains in the 20 to 100 µm range. In CL most grains show oscillatory zoning typical of magmatic zircons. The full dataset contains very few concordant grains (Fig. 6a), and the concordia age of 515.2 ± 5.7 Ma is based on only three grains but they overlap (Fig. 6b) and make a peak in the frequency distribution. This age is interpreted as the igneous crystallization age.

**Kellys Mountain biotite granodiorite – sample SMB16-220**

SMB16-220 is from a newly exposed roadside outcrop in an area mapped as leucogranite by Barr et al. (1982) but no outcrop was seen in the area at that time (Fig. 3). Unlike the leucogranite that forms most of Kellys Mountain, sample SMB16-220 is granodiorite and contains 10 to 15% biotite and minor hornblende. Plagioclase is the most abundant mineral, with quartz and perthitic orthoclase mainly interstitial. Zircon grains are euhedral and small, in the range of 20 to 100 µm. Black rounded inclusions and red/orange staining is typical. In CL most
grains show oscillatory zoning. The full dataset shown in Figure 6c shows that all the data are clustered together. Nine concordant grains yield a concordia age of 510.1 ± 3.6 Ma (Fig. 6d) interpreted as the main age of crystallization. The age overlaps within error that of dioritic sample SMB16-219 but the field relations between the two rock types are unknown.

Kellys Mountain granite – sample DB006

Sample DB006 is from a granitic dyke in the Kellys Mountain paragneiss from the summit of Kellys Mountain. This granite forms most of the Kellys Mountain pluton (Fig. 3) and a sample dated previously by Barr et al. (1990) yielded an age of 498 ± 2 Ma. The dated dyke sample is a fine to medium grained with equal amounts of quartz, plagioclase, and microcline, and minor partly chloritized biotite with accessory oxides, sulphides, zircon, and apatite. Feldspars are extensively saussuritized/sericitized and epidote is common in veins and around feldspars. Zircon grains range in size from 50 to 200 µm and are generally euhedral and blocky with bipyramidal terminations. In CL most of the crystals show oscillatory zoning.

The full dataset (Fig 6e) shows that most of the zircon ages are clustered in one area but a few Proterozoic grains are also present. Twenty-six concordant grains yielded a concordia age of 491.0 ± 2.2 Ma (Fig. 6f). The MSWD and probability of concordance could be improved by using fewer grains. Near-concordant older grains at ca. 620 Ma, 1.47 Ga, and 1.88 Ga, and more discordant older grains at ca. 1.7 Ga are evidence for inheritance. The presence of these older grains may explain why the TIMS date reported by Barr et al. (1990) is somewhat older than the age obtain here because it used multigrain zircon fractions. However, it is also possible that the scatter in the data may indicate Pb loss, in which case the older TIMS age is the more reliable
crystallization age. The presence of extensively saussuritized and sericitized feldspar and abundant epidote and chlorite suggest that fluids may have played a role in Pb loss.

DISCUSSION

Plutonic history

The minimum age of the large and compositionally composite Boisdale Hills pluton was constrained previously only by $^{40}$Ar/$^{39}$Ar cooling ages for hornblende of ca. 530 Ma (Keppie et al. 1990). Earlier Rb-Sr and K-Ar results ranging from ca. 502 to 563 Ma (e.g., Cormier 1972, 1979; Wanless et al. 1968) have large errors and are not considered reliable (Barr et al. 1990, 1999). Based on petrological similarities, the pluton was thought to be similar in age to the Shunacadie pluton to the northwest which was dated by TIMS at 564 ± 3 Ma and 565 ± 5 (Barr et al. 1990, 1999). Tonalite sample BH035 dated in the present study has an age of 540.5 ±1.6 Ma (Fig. 3f), showing that at least part of the Boisdale Hills pluton is about 25 million years younger than the Shunacadie granodiorite and tonalite. However, a granodiorite sample from the northern part of the pluton yielded more equivocal age data. Thirteen of the analyzed grains are concordant and near-concordant grains and yield a concordia age of 562.1 ±2.2 Ma, the same as the age of the Shunacadie pluton within error. However, the five youngest grains in that distribution on their own have a concordia age of 541.5 ±3.0 Ma (Fig. 3e), similar to the age of the tonalite sample. Since it is likely that the two plutons intersect at depth, we favour the interpretation of a younger 540 Ma crystallization age for the Boisdale Hills pluton and a component of inheritance from the older 560 Ma Shunacadie pluton, which would indicate that there was significant interaction between the two plutons during the emplacement of the younger Boisdale Hills pluton. The younger age is consistent with $^{40}$Ar/$^{39}$Ar (hornblende) cooling ages of
ca. 530 Ma for 3 samples from the Boisdale Hills pluton (Keppie et al. 1990). Elsewhere in the Bras d’Or terrane the 570-540 Ma plutons have been interpreted as products of an Andean-type subduction zone margin that were emplaced as continental arc plutons (Farrow and Barr 1992).

The young (Cambrian) ages of the 515 – 510 Ma from dioritic and granodioritic samples SMB16-219 and SMB16-220 from Kellys Mountain are unexpected as dioritic and granodioritic rocks on Kellys Mountain were previously assumed to be Neoproterozoic, like similar dioritic and granodioritic rocks elsewhere in the Bras d’Or terrane. The ages are slightly older that the volcanic rocks and associated high-level Mount Cameron syenogranite in the Boisdale Hills to the south (509 ±1.4 Ma Mount Cameron syenogranite; 505 ±3 Ma Long Island rhyolite; White et al. 1994). Both of these units have been interpreted to be linked to separation of Ganderia from Gondwana (White et al. 1994), suggesting a similar rift-related origin for the Kellys Mountain rocks dated here and linking the two areas during this period of rifting.

These ages are slightly older than the age of leucogranite intrusion into the Kellys Mountain paragneiss. Although the age of 498 ± 2 Ma reported by Barr et al. (1990) and the age of 491 ± 2.2 Ma obtained are different, it is clear from field observations that these samples must be the same age – the 498 Ma age might be somewhat older due to slight inheritance, or the age reported here may be slightly too young due to Pb loss. The same granite occurs at Cape Smoky where it has yielded an age of 493 ± 2 Ma (Dunning et al. 1990), and ca. 493 Ma may be the most accurate age for this extensive rock type, attributed to the same extensional environment that formed the somewhat older volcanic and plutonic rocks of the Bourinot belt. It is not unusual for a unit with a large special extent to have slight variations in crystallization age in different areas so an intrusive age of 493 – 498 Ma may be the best way to interpret these data.
The Cambrian ages reported here for the Kellys Mountain plutonic rocks also put the previously reported ca. 515 Ma metamorphic monazite age (Keppie et al. 1998) into better context. The 515 Ma monazite age likely represents contact metamorphism in the aureole of the intrusive rocks now dated at the same age within analytical uncertainty. The ca. 550 Ma muscovite cooling ages reported in the MacMillan Flowage and Barachois River formations were interpreted by Dallmeyer and Keppie (1993) to be a cooling age after regional metamorphism because muscovite grew in a regional foliation. These units are at higher grade than the other metasedimentary low-grade units in the Bras d’Or terrane where the regional foliation has not been dated and the only certain constraints on age of metamorphism come from the contact metamorphic aureoles. However, based on the pattern of contact metamorphism surrounding plutonic rocks this muscovite age may represent a cooling age due to intrusion of the abundant plutons dated ca. 570 – 540 Ma (Dunning et al. 1990) in the eastern part of the Cape Breton Highlands, overprinting the regional metamorphic signature.

The ca. 515-493 Ma extensional magmatism may have been responsible for the thermal regime recorded by $^{40}$Ar/$^{39}$Ar cooling ages throughout the Bras d’Or terrane (Keppie and Dallmeyer, 1989; Dallmeyer and Keppie 1993). The evidence for dioritic/granodioritic magmatism of ca. 515 – 510 Ma presented above provides additional support for the proposed widespread thermal regime with extensive melt generation as indicated by the intermediate composition of the plutonic rocks of this age. The ca. 493 Ma age for the granite is broadly compatible with the ca. 480 Ma age of monazite recrystallization due to contact metamorphism in the Glen Tosh formation proposed by Shawwa et al. (2017) and suggests that there may be unmapped areas of younger granite associated with the main Kellys Mountain leucogranite that were responsible for the younger metamorphic overprint.
Detrital zircon patterns in Ganderian metasedimentary rocks

Samples BH036 and BH017 are similar quartz-rich metamorphic rocks from the same map unit and yet they show very different detrital zircon signatures. Sample BH036 contains mainly Archean to Paleoproterozoic zircon grains, with a single Mesoproterozoic grain (Fig. 4a). In contrast, sample BH017 contains a few Paleoproterozoic and Archean grains, but mainly Mesoproterozoic grains (Fig. 4b). The most prominent peaks are at 1.2 Ga and 1.6 Ga. The weighted mean of the $^{207}\text{Pb}/^{206}\text{Pb}$ ages of the youngest three overlapping grains indicates a maximum depositional age of ca. 950 Ma. The two samples have in common a double peak at about 1.9 and 2.1 Ga (Fig. 7). Field relations do not indicate any significant difference in stratigraphic position between the two samples. Hence these two samples illustrate the difficulty in recognizing an unequivocal “fingerprint” for Ganderian detrital zircon sources as compared to Avalonia, a problem also noted in earlier studies (Fyffe et al. 2009; Barr et al. 2012). It should also be noted that it is difficult to make unequivocal interpretations of source terrains in Neoproterozoic rocks. As documented by Andersen et al. (2016a; 2016b) and Kristoffersen et al. (2016) in case studies from southern African rocks deposited before the breakup of Rodinia, multiple cycles of erosion and deposition often obscure the original signatures of sources and make correlations extremely challenging. This serves to emphasize the need to use multiple lines of evidence including faunal and paleomagnetic data (e.g. Domeier 2015) to make robust interpretations of source terranes and likely paleogeographic positions of terranes.

The lack of zircons younger than Mesoproterozoic in these two samples could be interpreted as evidence for a ca. 950 Ma maximum depositional age. However, such a lack of post-Mesoproterozoic zircon grains appears to be a characteristic feature of quartzite units in
Ganderia, such as those in the Ashburn Formation in the Brookville terrane of southern New Brunswick and in the Creignish Hills of the Bras d’Or terrane (Keppie et al. 1998; Barr et al. 2003, 2014). In contrast less quartz-rich samples in the same rock packages such as paragneiss samples KM10-04 and DB002 from the Kellys Mountain metamorphic suite, as well as the Blues Brook Formation in the Creignish Hills and the Martinon Formation in the Brookville terrane of southern New Brunswick, contain large populations of Neoproterozoic grains (Fig. 8). These Neoproterozoic populations differ in some details but are remarkably similar overall and were likely derived from Pan-African sources going back to about 800 Ma. The samples in this study (and the comparison ones shown on Figure 8) record primarily the youngest phase of the Pan-African orogeny after ca. 610 Ma during which the Congo and Kalahari cratons collided with the West African craton (Hanson et al. 1994). Younger Ganderian units (e.g. Fyffe et al. 2009; Park et al. 2010) are dominated by similar Neoproterozoic detrital zircon age signatures but even sparser older grains.

The two samples from the Kellys Mountain paragneiss both have prominent populations of Neoproterozoic zircons. Sample KM10-04 also has a wide range of Meso- to Paleoproterozoic grains, which are extremely sparse in the DB002 sample. Both of the interpreted late Neoproterozoic maximum depositional ages for the Kellys Mountain paragneiss are similar to those reported by White et al. (2016) from the Blues Brook Formation in the Creignish Hills where the maximum depositional age was proposed to be 600 Ma. Hence these results support the proposed correlation of low-grade metamorphic units with higher-grade rocks and extends that correlation from the Kellys Mountain/Glen Tosh area to the other low-grade units in the Bras d’Or terrane. The number of grains available for analysis in sample DB002 was small (42 concordant grains used in interpretations) compared to the other samples so it is
possible that populations of zircons could have been missed (Fedo et al. 2003; Vermeesch 2004; Andersen 2005). However, the major population is the youngest one, and it overlaps with the youngest population in the other Kellys Mountain paragneiss sample (KM10-04) which provides confidence that the interpretation of the maximum deposition ages of these samples is robust. The lack of older zircon grains in sample DB002 might present some difficulty for correlation with other Bras d’Or and Brookville terrane samples if it were used in isolation, but sample KM10-04 is from the same unit and has a large number of grains spanning the Neo- to Paleoproterozoic. Hence, we are confident that the Kellys Mountain paragneiss as a whole contains those populations and that our study has successfully documented the older zircons in the unit. Lithofacies and heterogeneity within units can exert considerable control in detrital zircon studies as documented by DeGraaff-Surpless et al. (2003) so it is not unexpected that a heterogeneous metasedimentary unit like the Kellys Mountain gneiss has variable zircon contents in different parts. Combination of multiple samples from the unit ensures that the interpretations made are robust even though one of the samples is relatively poor in zircon.

In contrast, quartz arenite sample SMB06-110 from the Middle Cambrian Eskasoni Formation lacks 600-700 Ma grains and is dominated by 515-600 Ma grains (Figs 7 and 8). The youngest population in this sample consists of 11 overlapping grains with a concordia age of 518.0 ± 2.9 Ma, a maximum deposition age for the Eskasoni Formation. These data confirm its middle Cambrian age, in contrast with Cambrian sections in the adjacent Mira terrane which lack volcanic components and extend back to the base of the Cambrian and into the Neoproterozoic (Willner et al. 2013). This sample has fewer zircon analyses than most of the others in this study (99 in total, 82 concordant enough for use in interpretations) but it is possible within 95% confidence to consider that no major populations were missed in this analysis (Fedo et al. 2003; Vermeesch 2004; Andersen 2005). The sparse nature of the Precambrian populations does indicate that
they are not a major component of the ages represented in this unit, but the fact that all the major
populations found in the older units from the Frenchvale Metamorphic Suite and the Kellys Mountain
paragneiss are also present in the Bourinot Group sample indicates that all the major populations were
documented and that our interpretations of both the maximum depositional age and the contributing
sources are robust.

The correlation of the Bras d’Or terrane with the Brookville terrane in southern New
Brunswick (Barr and Raeside 1989; White and Barr 1996; Barr et al. 1998) provides additional
data and constraints on the depositional history of the metasedimentary units. In the high-grade
pelitic rocks the two correlative units are the Brookville Gneiss and the Kellys Mountain
paragneiss. The Brookville Gneiss is a locally migmatitic paragneiss with associated
granodioritic to tonalitic orthogneiss, and minor calc-silicate, marble, quartzite and amphibolite
(Barr et al. 2014b) formed in a low pressure (2.5 ± 1 kbar), high temperature metamorphic
setting (White 1996). It is similar in metamorphic history to the Kellys Mountain paragneiss
even though the marble-quartzite-calc-silicate units are absent in the Kellys Mountain area.

Bevier et al. (1990) reported single grain TIMS U-Pb zircon ages from the Brookville Gneiss
ranging between ca. 640 and 2.6 Ga, very similar to the range of zircon ages reported in this
study for the Kellys Mountain samples, particularly KM10-04. Subsequent work by Barr et al.
(2014b) did not detect Neoproterozoic zircon ages in the Brookville Gneiss. The age of
metamorphism in the Brookville Gneiss of ca. 564 Ma reported by Bevier et al. (1990) was based
on the U-Pb zircon age of an orthogneiss in the unit, a match for the < 560 - 565 Ma
metamorphism in the Creignish Hills indicated by the igneous crystallization of age of the
Chuggin Road orthogneiss (White et al. 2016), strengthening the correlation of the high-grade
rocks within and across the two terranes.
Detrital signatures from the Blues Brook Formation in the Creignish Hills, Martinon Formation in the Brookville terrane, and the two Kellys Mountain paragneiss samples all have major populations of Neoproterozoic grains between ca. 600 Ma and 650 Ma, and much less abundant grains between 1 Ga and 2.2 Ga (Barr et al. 2014; White et al. 2016). It is likely that the basins in which these rocks were deposited experienced periods of deposition of mature arenitic sands representing mainly old source areas interspersed with periods of deposition of immature sediments containing younger zircon grains. Based on common zircon morphologies in the Kellys Mountain paragneiss where the sample with the least rounded, most euhedral zircons is also the one with the largest proportion of Neoproterozoic grains, it is likely that periods of extensive volcanism provided a young source of zircons that was eroded and deposited in basins which had previously sampled only older source areas.

Sources for detrital zircons in Ganderian terranes

The detrital zircon data presented here are focussed on Ganderian rocks older than the Paleozoic collisional events that built the Appalachian orogen (e.g., van Staal and Barr 2012). This is in contrast with the majority of studies in Appalachian areas that include post-collisional strata (for examples see Park et al. 2010). The detrital zircon studies that include post-collisional Appalachian rocks younger than ca. 500 Ma can be misleading when used to infer provenance of older pre-Appalachian rocks because the proximity of Laurentian rocks after the beginning of Pangaean amalgamation obscures the pre-Appalachian zircon populations and provides detrital material from large range of source areas. For example, there is no way as yet to distinguish detrital zircon grains from the African or Baltican segments of the Grenville orogen from those...
derived from Laurentian Grenville sources; samples from post-collisional strata may contain a mix of zircons of the same age from different sources.

Orogenic belts (Fig. 9) around the Amazonian craton that are appropriate sources for the detrital zircons seen in the samples from the Bras d’Or terrane as well as the New Brunswick Ganderian terranes are the Sunsás–Aguapeí (0.9–1.2 Ga), Rondônia–San Ignacio (1.2–1.4 Ga), Rio Negro–Jurena (1.5–1.75 Ga), the Ventuari-Tapajoc (1.98–1.81 Ga), and the Maroni-Itacalunas (2.25–2.05 Ga), or collectively the Trans Amazonian orogens between 1.9 and 2.25 Ga (Bettencourt et al. 1999; Dall’Agnol et al. 1999; Tassinari and Macambira 1999; Cordani et al., 2009). Similar to the New Brunswick Ganderian samples (Ashburn, Martinon, and Brookville) presented by Barr et al. (2014b) the Bras d’Or terrane samples broadly match the zircon distributions from the proto-Andean margin as presented by Chew et al. (2008), but with a smaller proportion of ca. 1 Ga zircons suggesting that only the earlier phase of the Sundas-Aguapeí is preserved in the Ganderian samples. This agreement of data from the Ganderian terranes of New Brunswick and Nova Scotia strengthens the correlations previously proposed (Barr et al. 2014a, b; White et al. 2016).

In addition to the presence of Amazonia-related ages in the zircon populations, our data show very little input from sources with ages between 750 Ma and 900 Ma (Figs. 7 and 8). Stephan et al. (2018) presented a larger-scale synthesis of detrital zircon data from the Gondwanan margin. They proposed that the pre-orogenic detrital zircon signature of peri-Gondwanan crust can be divided into major source areas that can statistically be distinguished from each other. As shown in the Stephan et al. (2018) compilation, the only Gondwanan source area that does not have major zircon sources in that range is Amazonia. This provides additional evidence that the Bras d’Or terrane is one of the fragments of Ganderia closely associated with
the Amazonian craton during its pre-Appalachian history. It also suggests that the main part of
the Pan-African/Brasilliano orogen represented in the Bras d’Or terrane are the phases that are
younger than 650 Ma, rather than the older amalgamation of the Kalahari and Congo cratons
(after ca. 820 Ma), or the accretion to greater India (ca. 680) (Hanson et al. 1994; Hoffman
1999). The detrital zircon ages in the Neoproterozoic (Figs. 8) most closely match the Brasiliano
orogen which involved the collision between Amazonia and the Sao Francisco craton during the
final assembly of Gondwana between 500 and 650 Ma (Brito Neves et al. 1999) and the
accretion of previously amalgamated cratons to West Africa at ca. 610 – 550 Ma (Hanson et al.
1994; Hoffman 1999). This evidence for sources of Neoproterozoic detrital zircon grains from
both the Bras d’Or terrane and the New Brunswick Ganderian terranes further strengthens the
proposed connection to Amazonia.

**Cambrian basin development**

Sample SMB06-110 from the basal quartz arenite unit of the Bourinot belt is dominated
by a large population of grains that span the late Neoproterozoic to Early Cambrian between ca.
600 and 510 Ma. The older zircons in this population have ages that predominantly overlap with
all the Bras d’Or granitoid ages (580 to 540 Ma). The younger zircons in the sample overlap with
the Cambrian igneous intrusions dated in and around the Kellys Mountain area, indicating that
all the units in that range were available for sampling during deposition of the Cambrian basal
sandstones in the Bourinot belt. The weighted mean of the youngest cluster of grains (Fig. 6a) is
517.9 ± 2.9 suggesting a maximum depositional age of 515 Ma which confirms previously
reported Cambrian ages for the basal units of the Bourinot belt (White et al. 1994; Palacios et al.
2012). The Mesoproterozoic and older populations are very sparse, but broadly mirror the
patterns and age groups seen in the quartzite samples from the Frenchvale Road metamorphic suite and the Kellys Mountain paragneiss.

However, it is significant that the Cambrian Eskasoni Formation does not contain the distinctive Neoproterozoic zircon populations that are characteristic of the Pan-African Brasillian orogen. Such populations are prominent in the two Kellys Mountain samples in this study and the comparison samples from previous work in the Martinon and Blues Brook formations (Barr et al. 2014; White et al. 2016). This distribution of ages supports the interpretation that the Bourinot belt was deposited in an active rift environment as suggested by the volcanic-sedimentary units that is contains (White et al. 1994). These rocks were deposited very shortly after intrusion of plutonic rocks that had been rapidly exhumed such as those in Kellys Mountain. The Bourinot Group received sediments derived from proximal Neoproterozoic to Cambrian sources, and not from the pre-Appalachian Gondwanan orogens.

Deposition of the Bourinot belt rocks overlaps the youngest granitic plutonic activity in the Bras d'Or terrane and the lack of zircon grains from the Pan-African/Brasiliano orogen suggest that at the time of deposition of these rocks the overall tectonic environment had changed from compressional to extensional. The compressional phase produced the subduction-related plutons in the Boisdale Hills (ca. 580 to 540 Ma), and by the time the sedimentary and volcanic rocks of the Bourinot belt were being deposited the overall tectonic setting was an extensional environment as indicated by the bimodal magmatism in the Boisdale Hills and Kellys Mountain areas. This is consistent with the earlier paleomagnetic work (Johnson and van der Voo 1985) and faunal work (Cocks and Fortey 1985) that showed the beginning of northwards translation of the Ganderian terranes during the Cambrian after being situated on the Gondwanan margin.
Conclusions

New U-Pb dating of both detrital zircon grains in metasedimentary samples and zircon in plutonic samples from the Boisdale Hills and Kellys Mountain areas provide new insights into the sedimentary, igneous, and metamorphic history of the Ganderian Bras d’Or terrane. This study represents a significant advance in understanding the Bras d’Or terrane because it is focussed on the oldest known units in Ganderia, which predated the major collisional events in the Appalachian orogen. Detrital zircon data from rocks that predate the main collisional events of the orogen are vital in reconstructing its pre-amalgamation tectonic history because in syn- or post-orogenic units the detrital zircons derived from Laurentia typically obscure evidence for other source areas that were significant in the older metamorphosed areas of the terrane. The detrital zircon data from Neoproterozoic rocks of the Bras d’Or Gneiss and Frenchvale Road metamorphic suite indicate that Ganderia and Amazonia are related and that the Ganderian rocks contain detritus from all the major Amazonian orogenic events. The data also strengthen previously proposed correlations of the Bras d’Or terrane with other Ganderian terranes and that high- and low-grade metamorphic units across the Bras d’Or terrane and in the Brookville terrane in New Brunswick are likely correlative, and that units of different metamorphic grade represent different thermal conditions rather than different protoliths.

The new U-Pb ages for plutonic samples indicate that the Bras d’Or terrane is a composite arc terrane with several episodes of pre-and post-accretionary bimodal magmatism. The magmatism is more extensive and longer-lasting than previously documented and represents a long-lived arc-related peri-Gondwanan magmatic system. Detrital zircon data from Cambrian rocks in the Bourinot belt indicate that local basin development occurred in an active extensional environment and that the basin fill was locally derived from proximal latest Neoproterozoic and
Cambrian rocks with ages that match the intrusive phases documented here in the Kellys Mountain plutonic rocks and Boisdale Hills pluton. The Cambrian rocks do not show evidence for the distinct &gt; 600 Ma Neoproterozoic zircon populations that are characteristic of the Pan-African/Brasiliano orogen, indicating that by that time the Gondwanan terranes were no longer the most important detrital sources.

These data along with the new detrital zircon U-Pb data document the tectonic evolution of the Bras d’Or terrane from its origins in the peri-Gondwanan realm to the development of arc-related subduction zones and intrusive rocks, and subsequent development of local extensional basins within the terrane. The data support and strengthen previous correlations with the Brookville terrane of southern New Brunswick. The data also support the interpretation that Ganderia was in proximity to Amazonia prior to its separation in the late Cambrian as a ribbon continent during the opening of the Rheic Ocean.

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SUPPLEMENTARY FILES

Appendix A: LA-ICP-MS U-Pb isotopic analyses of detrital zircon samples analyzed at the University of New Brunswick.

Appendix B: LA-ICP-MS U-Pb isotopic analyses of igneous zircon samples analyzed at the University of New Brunswick.

Appendix C: LA-ICP-MS U-Pb isotopic analyses of zircon reference materials analyzed at the University of New Brunswick.

FIGURES

Figure 1: Simplified geological map of Cape Breton Island with inset showing simplified Appalachian terranes modified from White et al. (2016).

Figure 2: Simplified geological map of the Boisdale Hills area of the Bras d’Or terrane showing sample locations based on maps in White et al. (1994) and Barr and White (2017a, b). Stars indicate previous dating by Barr et al. (1990, 1999).

Figure 3: Simplified geological map of the Kellys Mountain area of the Bras d’Or terrane showing sample locations based on map data from Barr and White (2017a, b).

Figure 4: Probability distribution for detrital zircon samples from the Boisdale Hills and Kellys Mountain with insets showing weighted means of ages used in interpretations of maximum depositional ages.

(a) BH036Q Frenchvale Road Metamorphic Suite - Quartzite (South); Bras d'Or Gneiss
(b) BH017 Frenchvale Road Metamorphic Suite - Quartzite (North); Bras d'Or Gneiss
(c) KM10-04 Kellys Mountain paragneiss
(d) DB002 Kellys Mountain paragneiss
(e) SMB06-110 Bourinot Road quartz arenite

Figure 5: U-Pb concordia diagrams and probability distribution for igneous samples from the Boisdale Hills area.
Figure 6: U-Pb concordia diagrams for igneous units in the Kellys Mountain area.
(a) Sample SMB16-219 (Kellys Mountain diorite) full dataset
(b) Sample SMB16-219 (Kellys Mountain diorite) concordia age
(c) Sample SMB16-220 (Kellys Mountain biotite granodiorite) full dataset
(d) Sample SMB16-220 (Kellys Mountain biotite granodiorite) concordia age
(e) Sample DB006 (Kellys Mountain granite dyke) full dataset
(f) Sample DB006 (Kellys Mountain granite dyke) concordia age

Figure 7: Cumulative probability distribution comparison figure for detrital zircon samples from this study, with additional distributions from the Brookville paragneiss and the Martinon and Ashburn formations (Barr et al. 2014b) and Blues Brook Formation (White et al. 2016) for comparison. Major source areas in Trans-Amazonian Gondwanan terranes are highlighted (data
Figure 8: Cumulative probability distribution comparison figure for all detrital zircon samples with Neoproterozoic to Cambrian zircons with additional distributions from the Martinon Formation (Barr et al. 2014b) and the Blues Brook Formation (White et al. 2016). Single grains younger than the interpreted maximum depositional ages in the samples (see text) are white to indicate that they are not considered as maximum depositional ages. All samples except for the Eskasoni Formation have maximum depositional ages of ca. 600 Ma; the Eskasoni Formation lacks the distinctive populations > 600 Ma of the other samples.

Figure 9: Plate tectonic setting for Ganderia at ca. 615 Ma with major orogenic and crustal provinces in the Laurentian, Baltican, Amazonian, West African, and Sao Franciscan cratons. Plate positions and modern reference latitude/longitudes are based on McCausland et al. (2011), Pisarevsky et al. 2012), and Merdith et al. (2017) and the positions of Ganderia and based on Van Staal et al. (2012) and Barr et al. (2014). Data on orogens and major cratonic provinces are from Bettencourt et al. (1999), Brito Neves et al. (1999), Dall’Agnol et al. (1999), Davidson (1995), Nance et al. (2008), Tassinari and Macambira (1999), and Cordani et al. (2009).
Blair River Inlier

Mira Terrane (Avalonia)

Aspy Terrane

Bras d'Or Terrane

YOUNGER ROCKS

Carboniferous (mainly)
Sedimentary rocks

Devonian-Carboniferous
Volcanic & sedimentary rocks

BRAS D'OR TERRANE
Late Cambrian
Granitic plutons

Middle Cambrian-Ordovician
Sedimentary & volcanic rocks

Late Proterozoic
Granodiorite/granite
Dioritic rocks (mainly)
George River metamorphic suite
Bras d'Or metamorphic suite

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Aspy
Bras d’Or
Mira

Sedimentary rocks
ca. 620 Ma plutons
Volcanic and sedimentary rocks

MIRA TERRANE
Cambrian-Ordovician
Mount Cameron Syenogranite
Late Neoproterozoic or Older

BRAS D’OR TERRANE
Cambrian-Ordovician

Devonian-Carboniferous

Volcanic and sedimentary rocks
Mainly sedimentary rocks

Sydney

Fig.2

Fig.3

564.5 +/- 5.1 Ma
564 +/- 3.2 Ma
564 +3/-2 Ma
BH036
BH035
BH017
BH040
SMB06-110

Boisdale Hills Pluton
Shunacadie Pluton

George River Metamorphic Suite
Benacadie Brook Formation
Frenchvale Road metamorphic suite

Eskasoni
Shunacadie
East Bay

East Bay

Bras d’Or terrane
Mira terrane

CH

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**Carboniferous**
- Horton and Windsor groups

**Late Cambrian**
- *Kellys Mountain pluton*
  - Kellys Mountain Granite
  - Dioritic and granodioritic rocks

**Neoproterozoic**
- Murray Mountain volcanic & plutonic rocks (undivided)
- Big Hill granite

**George River Metamorphic Suite**
- Metasedimentary rocks
- Glen Tosh formation
- Metasedimentary rocks
- Kellys Mountain Gneiss
- Bras d’Or Metamorphic Suite

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Sample number and location

- KM1
- Fault
- Road
- Foliation

- DB006  Kellys Mountain granite
- SMB16-219  Kellys Mountain diorite
- SMB16-220  Kellys Mountain granodiorite
- DB002  Kellys Mountain paragneiss
- KM10-04  Kellys Mountain paragneiss

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Boisdale Hills Pluton granodiorite BH035 All data (n=20)

Concordia Age = 540.5 ± 1.6 Ma (2σ)
MSWD = 2.5
Probability = 0.11

Boisdale Hills Pluton granodiorite BH040 All grains <600 Ma 98-101% concordant

Concordia Age = 541.5 ± 3.0 Ma (2σ)
MSWD = 4.7
Probability = 0.030

Boisdale Hills Pluton granodiorite BH040 (n=6) Younger group

Concordia Age = 562 ± 2.7 Ma (2σ)
MSWD = 10.2
Probability = 0.001

Boisdale Hills Pluton granodiorite BH040 (n=13) Older group

Light purple shows the grains included in the younger concordia group, dark purple shows the older grains.
Kellys Mountain granite dyke
DB006 All data (n=97)

207\(^{\text{Pb}}\)/235\(^{\text{U}}\)
data-point error ellipses are \(2\sigma\)

Kellys Mountain granodiorite
SMB16-220 All data (n=63)

206\(^{\text{Pb}}\)/238\(^{\text{U}}\)
data-point error ellipses are \(2\sigma\)

Kellys Mountain dionite
SMB16-219 All data (n=13)

Concordia Age = 510 ± 3.6 Ma (2\(\sigma\))
MSWD = 1.3
Probability = 0.26

Kellys Mountain granodiorite
SMB16-220 (n=12)

Concordia Age = 515 ± 5.7 Ma (2\(\sigma\))
MSWD = 0.051
Probability = 0.82

Kellys Mountain diorite
SMB16-219 (n=3)

Concordia Age = 510 ± 3.6 Ma (2\(\sigma\))
MSWD = 0.051
Probability = 0.82

Kellys Mountain granite dyke
DB006 All data (n=26)

Concordia Age = 491.0 ± 2.2 Ma (2\(\sigma\))
MSWD = 11.0
Probability = 0.001
The diagram shows the 

$^{206}\text{Pb}/^{238}\text{U}$ ages for samples from various formations and locations in Nova Scotia and New Brunswick. The data includes:

- SMB10-06 Quartz Arenite, Eskasoni Formation, Bourinot Belt (White et al. 2016)
- Blues Brook formation, Creignish Hills NS (White et al. 2016)
- Martinon Formation, Green Head Group NB (Barr et al. 2014)
- DB002 Paragneiss, Kellys Mountain
- KM10-04 Paragneiss, Kellys Mountain

The y-axis represents the age (Ga) and the x-axis represents the $^{206}\text{Pb}/^{238}\text{U}$ age.
Legend

- **Ganderia** (Brookville and Bras d’Or terranes)
- **Pan-African/Brasiliano**
- **Sunsás–Aguapeí**
- **Grenville**
- **Rondônia–San Ignacio**
- **Ketilidian–Svecofennian**
- **Rio Negra–Jurena**
- **Ventauri–Tapajoc**
- **Maroni–Itacalunas–Eburnean**
- **Central Amazonian–Liberian**
- **Kensal–Superior**

Time periods:
- 0.55–0.75 Ga
- 0.9–1.10 Ga
- 0.9–1.3 Ga
- 1.25–1.45 Ga
- 1.6–1.8 Ga
- 1.55–1.80 Ga
- 1.80–1.95 Ga
- 1.95–2.25 Ga
- > 2.3 Ga
- > 2.5 Ga

Ca. 615 Ma