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U-Pb (zircon) ages and provenance of the White Rock Formation of the Rockville Notch Group, Meguma terrane, Nova Scotia, Canada: Evidence for the “Sardian gap” and West African origin

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Abstract

The White Rock Formation is the lowermost formation of the Rockville Notch Group, an assemblage of Silurian-Devonian rocks preserved in five areas along the northwestern margin of the Meguma terrane of Nova Scotia. The formation consists mainly of mafic and felsic metavolcanic rocks, interlayered with and overlain by marine metasedimentary rocks. Felsic metatuff has now been dated from four locations near both the bottom and top of the volcanic pile and yielded a narrow age range (with errors) of about 446 to 434 Ma. These dates confirm a 30 Ma hiatus after deposition of the Early Ordovician Hellgate Formation in the underlying Halifax Group. This hiatus is coeval with the “Sardian gap” in the Lower Palaeozoic of peri-Gondwanan Europe. The metavolcanic-metasedimentary assemblage is overlain by mainly metasiltstone with abundant quartzite and metaconglomerate lenses; some of the latter were previously interpreted to be Ordovician tillite, an interpretation no longer viable. New detrital zircon data from metasedimentary samples indicate that the major sediment sources for the White Rock Formation have ages of ca. 670-550 Ma and ca. 2050 Ma, similar to ages from the underlying Goldenville and Halifax groups. A smaller population of Mesoproterozoic zircon grains indicates that the Meguma terrane interacted with a terrane composed mainly of Mesoproterozoic crust during the Silurian and Devonian. The occurrence of the “Sardian gap” and the detrital zircon record constrain the palaeoposition of the Meguma terrane to have been close to Cadomia and West Africa in the Early Cambrian to Early Silurian.

Keywords: U-Pb dating, Appalachian orogen, Detrital zircon, Cadomia

Introduction

The Meguma terrane is the most outboard of the collage of continental fragments that was assembled during the mid-Paleozoic to form the northern Appalachian orogen (Fig. 1 inset). It is best known for a thick (>12 km) succession of turbiditic sediments of the Cambrian-Ordovician Goldenville and Halifax groups (e.g., Schenk 1970, 1995a; Waldron 1992; White 2010a) and for voluminous mid to late Devonian peraluminous granitoid rocks (e.g., Clarke et al. 1997, 2004). However, along its northwestern margin in the Wolfville, Torbrook, Bear River, Cape St. Marys, and Yarmouth areas (Fig. 1), the Meguma terrane also includes Silurian and Early Devonian volcanic and sedimentary rocks, known collectively as the Rockville Notch Group (White 2010b; White and Barr 2017).

Although stratigraphy varies in the Rockville Notch Group (Fig. 2), historically the five areas where it occurs have been linked mainly because of prominent quartzite beds that occur in the lowermost unit of the group known as the White Rock Formation (Faribault 1909, 1920; Crosby 1962; Smitheringale 1960, 1973; Taylor 1965, 1969). Volcanic rocks are also a prominent component of the White Rock Formation in the Torbrook, Cape St. Marys, and Yarmouth areas, but not in the other two areas. In the Bear River, Torbrook, and Wolfville areas, the White Rock Formation is overlain by upper Silurian and Devonian sedimentary and locally volcanic rocks (White 2010b; White and Barr 2017). Fossils provide good age constraints on the upper Silurian – lower Devonian formations of the Rockville Notch Group, but they are rare in the White Rock Formation, and hence its maximum age has been uncertain, as well as its relationship (conformable vs unconformable) to the underlying Halifax Group (e.g., Smitheringale 1960, 1973; Schenk 1972; Schenk and Lane 1981; Lane 1992; Keppie 2000; White et al. 2012). U-Pb (zircon) ages of 442 ± 4 Ma from a rhyolite flow at the base of the White Rock Formation in the Torbrook area (Keppie and

Krogh 2000) and 438 ± 3 –2 Ma from the upper part of the White Rock Formation in the Yarmouth area (MacDonald et al. 2002) indicated an early Silurian age for the formation (Fig. 2). MacDonald et al. (2002) suggested that the volcanic activity recorded in the formation may have been related to rifting of the Meguma terrane from Gondwana.

The White Rock Formation has been interpreted by some workers to be part of an overstep succession that includes rocks of similar age in Avalonia and extends across much of the northern Appalachian orogen (Chandler et al. 1997; Keppie and Krogh 2000; Murphy et al. 2004a). It has also been suggested that Avalonia and the Meguma terrane travelled together after Avalonia rifted away from Gondwana in the Early Ordovician and that the Goldenville, Halifax, and Rockville Notch groups were deposited on Avalonian crust (Keppie and Krogh 2000; Murphy et al. 2004a, b). In contrast, others support the idea that Meguma and Avalonia are unrelated and were not together until the mid-Devonian or later through subduction and/or strike-slip motion (e.g., Schenk 1970, 1971; Clarke et al. 1997; MacDonald et al. 2002; Moran et al. 2007).

Because of the importance of the White Rock Formation, both in understanding the geological history of the Meguma terrane and in regional tectonic interpretations, a U-Pb (zircon) dating study was undertaken to better constrain the age of volcanic components and the provenance of sedimentary components in the formation. The new data include two additional igneous crystallization ages from volcanic rocks in the Cape St. Marys and Yarmouth areas and four detrital zircon age spectra, two from quartzite units in the Yarmouth area, one from quartzite in the Cape St. Marys section and one from a conglomerate unit near Wolfville previously interpreted as a glacial diamictite (Schenk and Lane 1981). These data, combined with mapping and petrological studies (White 2010b; White and Barr 2017), clarify stratigraphic relations in the Meguma terrane and provide new constraints on the origin of the terrane and its relationship to Avalonia.

Geological Setting

Early Cambrian to early Ordovician turbiditic metasandstone and slate of the Goldenville and Halifax groups, with a minimum cumulative thickness of about 12 km, underlie more than half of the Meguma terrane (Fig. 1; White 2010a; White et al. 2012). In contrast, the overlying metasedimentary and metavolcanic rocks of the Rockville Notch Group are relatively thin and confined to the northwestern part of the terrane, northwest of the Chebogue Point shear zone (Fig. 1). All these rocks were deformed and variably metamorphosed (greenschist- to amphibolite-facies) during the Early to Middle Devonian Neoacadian orogeny (ca. 405-365 Ma; Hicks et al. 1999), and intruded by numerous, late syntectonic, mainly Middle to Late Devonian, peraluminous, granitic plutons, largest of which is the South Mountain Batholith (Clarke et al. 1997, 2004). This orogenic event and the tectonic setting of the voluminous granitic plutons are not yet well understood but both were related at least in part to the dextral transpressive motion of the Meguma terrane against adjacent Avalonia along the Cobequid-Chedabucto fault system. Subsequent Carboniferous motion on the fault system and renewed transpression throughout the Meguma terrane may have been related to docking of Gondwana (Africa) outboard of Meguma terrane (Moran et al. 2007; Waldron et al. 2015).

Detailed mapping during the past 15 years resulted in subdivision of the Goldenville and Halifax groups into regionally extensive formations and members (e.g., Horne and Pelley 2007; White 2010a, b; White 2013). Their ages have been relatively well constrained by detrital zircon dating and trace and microfossils to the early Cambrian through Early Ordovician (Waldron et al. 2009; Gingras et al. 2011; White et al. 2012). Some stratigraphic differences occur northwest and southeast of the Chebogue Point shear zone (White 2010a; Waldron et al. 2009). The lowest part of the Goldenville Group is of early Cambrian age, but the base is not exposed and its basement is

unknown (Fig. 2).

The Meguma terrane is generally accepted to be peri-Gondwanan, although the specific location along the margin of Gondwana where it originated remains a topic of speculation. Traditionally, the Goldenville and Halifax groups were interpreted to have been deposited on the continental rise and/or slope to outer shelf of a passive margin that was part of, or adjacent to, the North African craton during the Cambrian, perhaps in close association with Armorica (Schenk, 1971, 1981, 1991, 1997), but Amazonian connections have also been proposed (e.g., Keppie 1977; Waldron et al. 2009). Waldron et al. (2009) concluded that the combination of stratigraphic differences across the Chebogue Point shear zone, similarities to Avalonian detrital zircon populations, juvenile Nd isotopic compositions, and sparse faunal evidence suggesting Avalonian affinity (Pratt and Waldron 1991) indicates that the Meguma terrane formed in a rift between Gondwana (Amazonia) and Avalonia.

Stratigraphy and Sample Locations

Wolfville area

In the Wolfville area the White Rock Formation overlies the Lower Ordovician Hellgate Falls and Elderkin Brook formations of the Halifax Group, and underlies the upper Silurian to lower Devonian Kentville and New Canaan formations (Figs. 2, 3). The lower part of the White Rock Formation contains a series of quartzite beds/lenses interlayered with dark grey to red-brown metaconglomerate to breccia and black metasiltstone to slate. The conglomerate beds were interpreted to be diamictite or tillite by Schenk and Lane (1981), who included them in the upper part of the Halifax Group rather than in the White Rock Formation. Long (1992) re-interpreted the diamictite to have a non-glacial origin, although he still considered it to be part of the Halifax Group. However, the interlayered black slate typically contains phosphatic nodules not present in

similar-looking slate in the underlying Halifax Group and hence the metaconglomerate and black slate are now included in the White Rock Formation (White and Barr 2017). The contact with the overlying Kentville Formation is gradational, the quartzite beds thinning and then disappearing over a stratigraphic thickness of 50 m.

Sample MEG7 for detrital zircon study was collected from a conglomerate outcrop designated by Schenk and Lane (1981) as diamictite/tillite (Fig. 3). Henderson (2016) reported a detrital zircon age spectrum for a sample from the same location and Murphy et al. (2004a) reported data from an overlying quartzite (Fig. 3).

Torbrook area

In the Torbrook area the White Rock Formation overlies the Hellgate Falls and Elderkin Brook formations of the Halifax Group and is overlain by the Kentville and Torbrook formations (Fig. 2). In places, the base of the White Rock Formation is a rhyolitic tuff or flow that is overlain by amygdaloidal to pillowed basaltic flows. Along strike the volcanic rocks are absent and the basal unit is either a quartzite and metasiltstone package up to 5 m thick or ironstone (White 2010b; White and Barr 2017). The upper part of the White Rock Formation contains a 'double quartzite member' separated by black featureless metasiltstone to slate. In other places, green mafic lithic metatuff forms the top of the formation.

No samples for U-Pb dating were collected from the Torbrook area during the current study, but Keppie and Krogh (2000) reported an igneous crystallization age of 442 ± 4 Ma from a rhyolite flow at the base of the White Rock Formation (Fig. 2), and the ages of the overlying Kentville and Torbrook Formations are well constrained by fossils (Degardin et al. 1991; Bouyx et al. 1997). Murphy et al. (2004a) reported a detrital zircon age spectrum for a sandstone sample from near the top of the Torbrook Formation (Fig. 2), from which the youngest zircon yielded an age of 388 ± 8

Ma. If reliable, this date suggests a maximum depositional age of ca. 390 Ma, or latest Early Devonian, which is as little as 10 million years prior to intrusion by the South Mountain Batholith and permits only a narrow window for deformation and metamorphism associated with the Neoacadian orogeny.

Bear River area

In the Bear River area, units equivalent to the Hellgate Falls and Elderkin Brook formations of the Halifax Group are absent, and the White Rock Formation overlies the Tremadocian Bear River Formation (Fig. 2). The Kentville Formation has not been recognized as separate from the White Rock Formation on the basis of rock type, and hence the White Rock Formation is overlain directly by the Torbrook Formation. However, the presence of Late Silurian fossils (Blaise et al. 1991; Bouyx et al. 1997) indicates that the upper part of the White Rock Formation in that area is age-equivalent to the Kentville Formation (Fig. 2).

No volcanic rocks are present in the Bear River area and the White Rock Formation consists mainly of grey to dark grey slate and metasiltstone, with minor light grey to white metasandstone (White et al. 1999; White and Barr 2017). The slate tends to be darker grey, less laminated, and siltier than that of the underlying Bear River Formation. The metasiltstone beds are 5 to 20 cm thick and are massive to laminated. Rare grey marble beds, less than 15 cm thick, occur at the base of the formation, and calc-silicate lenses are present in places. The top of the formation contains lenses less than 3 cm thick of intraformational conglomerate.

Cape St. Marys area

In the Cape St. Marys area, the Rockville Notch Group is represented only by the White Rock Formation, which outcrops on the western limb of an inferred syncline (Fig. 4). It is highly

sheared, together with adjacent rocks of the Halifax Group, in the Cape St. Marys shear zone (Culshaw and Leisa 1997; Culshaw and Dickson 2015). At the exposed western contact, sheared and deformed slate and metasilstone of the Tremadocian Bear River Formation (White 2010a) are overlain by highly strained felsic metatuffaceous rocks. Lithic metatuff at the base apparently corresponds to the tillite of Schenk and Lane (1981), which they described as a pebbly mudstone, 1 m in thickness. However, examination of samples in thin section in the present study shows that the rocks are felsic lithic-crystal lapilli metatuff (Fig. 5a, b). The metatuff is in sharp contact with sheared and altered mafic metavolcanic rocks, in places amygdaloidal. The mafic rocks are overlain by felsic metatuff and quartzite, overlain by another section of mafic metavolcanic rocks, more than 20 m thick, which includes several flows with amygdaloidal tops. Locally well preserved peperitic features contain basalt intermingled with metasandstone, and the section also includes a 1 m-thick layer of cross-bedded metasandstone. The volcanic rocks are overlain by metasandstone, in part tuffaceous, in a section about 40 m thick. The metasandstone grades upward into slate with abundant metasandstone beds and lenses. The slate was interpreted by Long (2016) to belong to the Kentville Formation but similarity to rocks in the White Rock Formation in the Overton section in the Yarmouth area indicates that the slate belongs to the White Rock Formation (White and Barr 2017).

For U-Pb (zircon) dating, sample B01-W13-001 was collected from the metatuffaceous unit (tillite of Schenk and Lane 1981) at the contact with the Halifax Group, and sample B01-W13-002 from the overlying quartzite unit. Henderson (2016) also reported detrital zircon data from a younger quartzite unit (Fig. 4). An age of 426.4 ± 2 Ma from the Mavillette gabbro sill (Warsame et al. 2017) provides a minimum age for the White Rock Formation in the Cape St. Marys area (Figs. 2, 4).

Yarmouth area

As in the Cape St. Marys area, only the White Rock Formation of the Rockville Notch Group is present in the Yarmouth area (Figs. 2, 6). The metamorphic grade (lower amphibolite facies; MacDonald et al. 2002) is higher than in the other four areas. The southeastern margin is a fault that juxtaposes staurolite-grade, typically schistose, rocks of the White Rock Formation against chlorite- and biotite-grade rocks assigned to the Acacia Brook Formation of the Halifax Group (White and Barr 2017). This brittle fault is located within the broader Chebogue Point shear zone of Culshaw and Liesa (1997) that affects both the White Rock Formation and the adjacent Halifax and Goldenville groups.

On the northwest, the position of the contact between the White Rock Formation and Halifax Group is poorly defined because of lack of exposure both inland and on the coast. In the absence of outcrop, the contact position is inferred by a strong aeromagnetic signature that appears to be associated with the Halifax Group, deformed in that area by the Cranberry Point shear zone (Culshaw and Leisa 1997; White et al. 2001).

Although deformation and amphibolite-facies metamorphism have obscured primary sedimentary and volcanic features in many outcrops of the White Rock Formation in the Yarmouth area, relict igneous features such as phenocrysts, amygdales, lithic and crystal clasts, and bombs, metavolcanic units are interpreted to include both flows and varied tuffaceous rocks. Pillow structures are preserved locally and, overall, the sequence appears to have been deposited in a shallow marine setting, with minor subaerial eruptions suggested by coarsely vesicular mafic flows and rare ignimbritic felsic units that contain vestiges of flow-banding and flattened pumice fragments (MacDonald et al. 2002). Some basaltic flows preserve amygdaloidal tops, and sedimentary and reworked tuffaceous units locally preserve cross-bedding and graded bedding that

enable the determination of younging direction. Although previously interpreted to be in a synclinal structure (Taylor 1967; Lane 1979; Hwang 1985; Culshaw and Liesa 1997; MacDonald 2000), younging directions are consistently to the southeast (White et al. 2001; MacDonald et al. 2002; White and Barr 2017). Overall, the rock types are like those preserved in the Cape St. Marys section, but much thicker (minimum 6 km). A brachiopod from the Overton member has a maximum age of Late Ordovician (A. Boucot, personal communication, 1971 in Lane (1975)). However, an assemblage of brachiopods and gastropods in the same area is likely Early Silurian (A. Boucot, written communication, 2002, in White and Barr 2017), a more reliable age constraint.

Four samples were collected in this study for U-Pb dating but only three were successful. Quartzite sample O16-W15-011 from near the top of the Chegoggin Point section yielded a detrital zircon population, and sample O16-W15-012 from an overlying felsic tuff (Fig. 4e, f) yielded an igneous crystallization age. An intermediate tuffaceous unit from the section at Overton did not yield any zircon and hence could not be dated but sample MEG3 from an underlying quartzite layer in the same section yielded detrital zircon. In previous studies, felsic crystal tuff in the Sunday Point area yielded an igneous crystallization age of $438 \pm 3/-2$ Ma (MacDonald et al. 2002), and the Brenton pluton in the Government Brook member within the Chebogue Point shear zone yielded an igneous crystallization age of $439 \pm 4/-3$ Ma (Keppie and Krogh 2000).

New Geochronology

Methods

Zircon concentrates were separated from 2-4 kg sample material at the Senckenberg Naturhistorische Sammlungen Dresden (Museum für Mineralogie und Geologie) using standard methods. Final selection of the zircon grains for U-Pb dating was achieved by hand-picking under a binocular microscope. Zircon grains of all grain sizes and morphological types were selected,

mounted in resin blocks and polished to half their thickness.

Zircons were analyzed for U, Th, and Pb isotopes by LA-SF ICP-MS techniques at the Museum für Mineralogie und Geologie (GeoPlasma Lab, Senckenberg Naturhistorische Sammlungen Dresden), using a Thermo-Scientific Element 2 XR sector field ICP-MS coupled to a New Wave UP-193 Excimer Laser System. A teardrop-shaped, low volume laser cell constructed by Ben Jähne (Dresden) and Axel Gerdes (Frankfurt/M.) was used to enable sequential sampling of heterogeneous grains (e.g., growth zones) during time resolved data acquisition. Each analysis consisted of approximately 15 s background acquisition followed by 30 s data acquisition, using a laser spot-size of 25 and 35 μm , respectively. A common-Pb correction based on the interference- and background-corrected ^{204}Pb signal and a model Pb composition (Stacey and Kramers, 1975) was carried out if necessary. Raw data were corrected for background signal, common Pb, laser induced elemental fractionation, instrumental mass discrimination, and time-dependant elemental fractionation of Pb/Th and Pb/U using an Excel® spreadsheet program developed by Axel Gerdes (Institute of Geosciences, Johann Wolfgang Goethe-University Frankfurt, Frankfurt am Main, Germany). Reported uncertainties were propagated by quadratic addition of the external reproducibility obtained from the standard zircon GJ-1 ($\sim 0.6\%$ and $0.5\text{--}1\%$ for the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$, respectively) during individual analytical sessions and the within-run precision of each analysis. Concordia diagrams (2σ error ellipses) and concordia ages (95% confidence level) were produced using Isoplot/Ex 2.49 (Ludwig 2001) and frequency and relative probability plots using AgeDisplay (Sircombe 2004). The $^{207}\text{Pb}/^{206}\text{Pb}$ age was taken for interpretation for all zircons >1.0 Ga. For further details on analytical protocol and data processing see Gerdes and Zeh (2006) and Frei and Gerdes (2009). Zircon grains showing a degree of concordance in the range of 90–110% are classified as concordant. Th/U ratios are obtained from the LA-ICP-MS measurements of investigated zircon grains. U and Pb content and Th/U ratio were calculated relative to the GJ-1

zircon standard and are accurate to approximately 10%. Measured Th/U ratio of the GJ1 standard was in a range of 0.05 to 0.06. Analytical results of U-Th-Pb isotopes and calculated U-Pb ages are given in Tables A1-A6 in the data repository.

Results – tuffaceous samples

The two tuffaceous samples contain needle-shaped zircon crystals, which are euhedral, clear, and colourless, and about 80 to 120 μm long. Some contain a core, and such grains trend to have more compact shape. Th/U ratios below 1.0 suggest a felsic magma source.

Cape St. Marys felsic metatuff sample B01-W13-001 consists of scattered broken crystals < 1 mm in size of quartz, K-feldspar, and plagioclase in a fine-grained quartzofeldspathic groundmass (Fig. 5a, b). A few elongate felsic lithic clasts are also present. The lithic clasts and groundmass contain abundant sericite and carbonate. The sample yielded 20 zircon grains with analyses less than 10% discordant (Table A1). Most (14) of the ages are around 442 Ma (Fig. 7a); 6 older ages (506, 645, 694, 1121, 1687, and 2072 Ma) are from cores and are interpreted to represent inherited grains from older recycled rocks. The concordia age of 442.9 ± 2.1 Ma is considered to represent the eruptive age of the tuff.

Sample O16-W15-012 is felsic crystal-lithic metatuff layer about 2 m thick in the Chegoggin Point section in the Yarmouth area. It is well foliated and contains relict crystals of quartz and feldspar in a fine-grained recrystallized groundmass of mainly quartz, feldspar, and biotite (Fig. 5c, d). The sample yielded 36 zircon grains with analyses less than 10% discordant (Table A2). Of those, 32 yielded a concordia age of 435.8 ± 2.1 Ma that is considered to best represent the eruptive age of the tuff (Fig. 7b). The large MSWD of 2.1 is caused by the relatively large spread of the mean of the single measurements. The four older concordant zircon cores have ages of 457-484 Ma (Table A2). These ages are interpreted to reflect the recycling of rift-related Ordovician igneous rocks as is

typical for most terranes derived from the peri-Gondwanan margin.

Results – detrital samples

Zircon grains in the detrital samples are well- to sub-rounded, although some grains are euhedral in shape. Roundness points to moderate transport distances. Grain diameters range from 75 to 240 μm , but most are smaller than 120 μm . Most grains show magmatic zoning and are clear and colourless to yellowish and transparent. Needle-like zircon grains are common. Complex zircon grains showing clear rims and cores are scarce. Th/U ratios of most zircon grains are below 1.0 and suggest dominance of felsic igneous source rocks.

Metaconglomerate sample MEG7 from the Wolfville area (Figs. 2, 3) consists of varied metasedimentary clasts in a fine-grained sericitic matrix. Most of the clasts are metawacke (Fig. 5e, f). The sample yielded abundant zircon grains; only 4 of those analyzed yielded earliest Paleozoic ages less than 10% discordant. The youngest grain (100% concordant) is at 516 ± 7 Ma. The youngest population of grains less than 10% discordant ($n=4$) has an age of 521.8 ± 5.1 Ma. The remaining analyzed grains are Neoproterozoic with a probability peak at 568 Ma (Table A3; Fig. 8a). A few grains are Mesoproterozoic, but most of the older grains are Paleoproterozoic with ages of about 2000-2100 Ma (Fig. 8b). The age pattern is similar to that reported by Henderson (2016) for a sample from the same location in which the youngest concordant population ($n=3$) is 539 ± 7 Ma. It is also similar to the age spectrum from the sample analyzed by Murphy et al. (2004a) from a nearby quartzite bed in which the youngest grain less than 10% discordant has an age of 542 ± 7 Ma.

Cape St. Marys quartzite sample B01-W13-002 consists almost entirely of a mosaic of quartz grains of uniform size (~ 0.2 mm). The grains are slightly elongated to define a weak foliation. Minor carbonate, sericite, and opaque grains are also present. The sample yielded a single

Paleozoic zircon grain at 479 ± 10 Ma and abundant Neoproterozoic ages between 540 and 900 Ma with prominent peaks at 567, 623, and 670 Ma (Fig. 8c). The youngest population of grains less than 10% discordant ($n=6$) has a weighted average (concordia) age of 566.7 ± 4.7 Ma. Older grains of both Mesoproterozoic and Paleoproterozoic ages are relatively abundant, with peaks at about 1200 Ma and 2000-2200 Ma (Fig. 85d). The age spectrum is similar to that reported by Henderson (2016) for a younger quartzite bed in the same section but in her sample the youngest concordant population ($n=4$) has an age of 514 ± 6 Ma. The sample also contains a single grain, less than 10% discordant, with an age of 430.2 ± 4.8 Ma, consistent with the age of 442.9 ± 2.1 Ma obtained here for the metatuff at the base of the section (Fig. 7a).

Quartzite sample O16-W15-011 from the Chegoggin Point section of the White Rock Formation in the western part of the Yarmouth area (Fig. 6) is from the upper part of a thick section of varied quartzite beds. The quartzite is overlain by amphibolitic mafic flows and tuff and is stratigraphically below dated felsic tuff sample O16-W15-012 (Fig. 2). The dated quartzite is clean, with just a few flakes of muscovite throughout. It consists almost entirely of a mosaic of quartz grains of uniform size (~ 0.2 mm). Rounded zircon grains are relatively abundant. The youngest grain (10% discordant) has a $^{206}\text{Pb}/^{238}\text{U}$ age of 466 ± 17 Ma. The youngest population of grains less than 10% discordant ($n=4$) has an age of 531.8 ± 6.4 Ma (Fig. 8e). The most abundant zircon grains in the sample have age peaks of 564 Ma, 617 Ma and 644 Ma. Only a small number of Mesoproterozoic and Paleoproterozoic grains are present, with a small peak at about 2100 Ma (Fig. 8f).

Quartzite sample MEG3 is from the Overton section near Yarmouth (Fig. 6), in the same part of the section where fossils suggest an early Silurian age (White and Barr 2017). The quartzite sample consists almost entirely of a mosaic of quartz grains and is petrographically similar to sample O16-W15-011. The youngest grain (2% discordant) has a $^{206}\text{Pb}/^{238}\text{U}$ age of 424 ± 9 Ma.

Although apparently younger than the early Silurian depositional age, the discordancy of the analysis and its error are consistent with an older age. Two other grains, both less than 10% discordant, yielded Paleozoic ages of 439 ± 6 Ma and 482 ± 17 Ma (Fig. 8g). The most abundant zircon grains in the sample have age peaks at 570 Ma, 621 Ma, and 651 Ma, almost identical to the peaks in Chegoggin Point quartzite sample O16-W15-011. As in that sample, only a small number of Mesoproterozoic and Paleoproterozoic grains are present (Fig. 8h).

Discussion

Stratigraphic implications

The two new U-Pb igneous crystallization ages from felsic volcanic units in the White Rock Formation support results from previous dating (Keppie and Krogh 2000; MacDonald et al. 2002) which indicated that the base of the White Rock Formation is Early Silurian, using the present position of the Ordovician-Silurian boundary at 443.8 ± 1.5 Ma (Cohen et al. 2017). The youngest unit in the Halifax Group is the Hellgate Falls Formation with an early Ordovician (Floian – 470–478 Ma) age (White et al. 2012). Hence the age gap with rhyolite at the base of the White Rock Formation in the Torbrook area dated by Keppie and Krogh (2000) at 442 ± 4 Ma is about 30 million years (Fig. 2). A similar age obtained in this study from felsic tuff at the base of the White Rock Formation in the Cape St. Marys section where it overlies the Bear River Formation indicates an even larger time gap of at least 37 million years in that area (Fig. 2). The minimum age of the White Rock Formation in the Cape St. Marys area is constrained by the date of 426.4 ± 2 Ma from a folded gabbroic sill (Warsame et al. 2017), showing that the entire section at Cape St. Marys is Early Silurian. In the Yarmouth area, the age of the base of the formation is less well constrained because of abundant faults and lack of outcrop but both dated volcanic units are early Silurian and similar within error. The age of $439 \pm 4/-3$ Ma reported by Keppie and Krogh (2000) for the Brenton

pluton is also similar; although the pluton is located in a shear zone, it is likely to be comagmatic with the volcanic rocks based on chemical similarities (MacDonald et al. 2002). The detrital zircon signatures for samples from the White Rock Formation show mainly Ediacaran to Cryogenian ages (Fig. 8a-h) and hence are not generally helpful in constraining depositional ages. However, sample MEG3 contains grains with $^{206}\text{Pb}/^{238}\text{U}$ ages of 424 ± 9 Ma and 439 ± 6 Ma with a degree of concordance of 98 % and 106%, respectively. The quartzite sample analyzed by Henderson (2016) also yielded a single grain with an age of 430.2 ± 4.8 Ma. Whether reliable or not, these ages are at least consistent with an early Silurian depositional age for the unit.

Hence the age constraints overall suggest that volcanic rocks occur only in the lower (Early Silurian) part of the White Rock Formation. If so, the absence of volcanic rocks in the Wolfville and Bear River areas suggests that the base of the sections in those areas may be younger than the volcanic activity recorded in the other three areas (Fig. 2).

Comparison to the Halifax and Goldenville groups

The combined detrital zircon signature in samples from the Rockville Notch Group, including data from the present study as well as Henderson (2016) and Murphy et al. (2004a), is similar to that from the underlying Goldenville and Halifax groups (Fig. 9a-d). Both data sets show an abundance of Neoproterozoic ages and a relatively subdued but prominent peak ca. 2065 Ma, broader in the case of the Rockville Notch Group, and a scattering of older ages back to the Archean. However, the Rockville Notch Group also contains a strong Mesoproterozoic population in the range of 1000 to 1600 Ma. Although apparent in all samples, this population is especially abundant in the quartzite sample from Cape St. Marys (Fig. 8c, d) and least prominent in the conglomerate from the Wolfville area (Fig. 8a, b). The appearance of Mesoproterozoic grains in the Silurian record suggests a contribution from an additional source area by that time, as discussed

below.

Relationship with Avalonia

The widespread distribution of igneous and associated sedimentary rocks of Silurian age in the northern Appalachian orogen led to the suggestion that they are an overstep sequence, with the implication that the outboard terranes of the orogen were assembled along the Laurentian margin by that time (e.g., Chandler et al. 1987; Keppie and Krogh 2000; Lynch 2001). In particular, a link has been suggested between the Rockville Notch Group and the Arisaig Group of the Antigonish Highlands (Keppie and Krogh 2000; Murphy et al. 2004a). Murphy et al. (2004a) used the inferred stratigraphic continuity between the Halifax Group and White Rock Formation as evidence for a connection between the Meguma and Avalonia extending back to the Late Neoproterozoic. The data presented here further support the interpretation of White et al. (2012) that a significant time gap separates the Halifax and Rockville Notch groups and hence the assumption of stratigraphic continuity is no longer valid

Furthermore, the recognition that the Dunn Point and McGillivray Brook formations are Ordovician and hence not part of the Arisaig Group (Hamilton and Murphy 2004; Murphy et al. 2012) has lessened the significance of igneous comparisons between the ca. 460 Ma volcanic rocks of those formations and the ca. 440-435 Ma volcanic rocks of the White Rock Formation. A comparison of the detrital zircon signature of the Silurian-Devonian Arisaig Group with that of the Rockville Notch Group shows an abundance of Early Paleozoic (520-440 Ma) zircon grains which are little represented in the Rockville Notch Group (Fig. 9e, f). With such a sparse record of Early Neoproterozoic, Mesoproterozoic, and Paleoproterozoic zircon grains in all three data sets, it is difficult to make a case one way or the other about similarity or differences among the signatures (Fig. 9b, d, f).

If the within-plate alkalic volcanic rocks of the White Rock Formation are indicative of the

rifting of the Meguma terrane from Gondwana at ca. 440 Ma, as suggested by MacDonald et al. (2002), then the Avalon and Meguma terranes are unlikely to have been connected in the Silurian. Given the extent and impact of the ca. 400 - 390 Ma Neoacadian orogeny in the Meguma terrane and its relative absence in the Avalon terrane, it seems unlikely that the two terranes were fellow travellers even in the Devonian. It is more likely that widespread thermal activity in the Late Devonian-Carboniferous records the juxtaposition of Meguma and Avalonia (e.g., Willner et al. 2015), and that Carboniferous rocks are the first true overstep sequence between those terranes.

Provenance of the Meguma terrane

The ca. 30-40 million-year gap in sedimentation between the Halifax and Rockville Notch groups occurs in a similar stratigraphic range as the so-called “Sardian gap” (“Sardian unconformity”) known from peri-Gondwanan Europe, including Sardinia, Iberia, and Bohemia (Saxo-Thuringian zone) (Linnemann et al. 2010a, b). The latter areas are part of Cadomia, a peri-Gondwanan terrane formed by Cadomian orogenic processes in Late Ediacaran to early Cambrian time (Linnemann et al. 2010a, b). Contemporary occurrence of the “Sardian gap” in the lower Palaeozoic sedimentary successions of both Cadomia and the Meguma terrane points to a strong relationship between these areas in the Cambrian – Silurian. The “Sardian gap” was formed during rifting on the West African periphery of the Gondwanan margin and has been suggested to have resulted from the rifting away of a suspect terrane (Linnemann et al. 2010b). That suspect terrane could have been the Meguma terrane, or its postulated larger entity Megumia (Waldron et al. 2011).

Comparison of the detrital zircon record of the Saxo-Thuringian zone, part of Cadomia in Germany (Linnemann et al. 2014), with the detrital zircon record from the Rockville Notch Group, including the results of this study and other published work, shows an overlap of a population in the range of ca. 1800-2200 Ma (Fig. 10a, b). This age range reflects the Eburnean orogeny widely

distributed in the West African craton (e.g., Thiéblemont et al. 2004; Schofield et al. 2006). Furthermore, zircon populations overlap in the range of ca. 540-600 Ma (Cadomian), ca. 600-750 Ma (Pan-African), and ca. 750-900 Ma (dispersal of Rodinia). Such similarity in the detrital zircon population pattern is a strong argument for the provenance of the Meguma terrane from the Cadomian orogen, which formed the margin of West Africa in the Late Ediacaran to early Palaeozoic (Linnemann et al. 2014). It is very likely that Meguma rifted from the Cadomian—West African margin in the mid to late Ordovician and related rifting processes were responsible for the formation of the sedimentary gap detectable both in the Meguma terrane and in the Palaeozoic sedimentary pile overlying Cadomia. Hence, our data strongly support the West African provenance of the Meguma terrane as initially proposed by Schenk (1971, 1981).

The presence of a Mesoproterozoic population in the range of 1000 to 1600 Ma in most samples from the Rockville Notch Group that is absent in both the underlying Halifax and Goldenville groups and in Cadomia suggests that after rifting from Cadomia—West Africa, Meguma interacted with a crustal area which was able to deliver Mesoproterozoic zircon. A similar temporary plate tectonic interplay of Avalonian terranes with a Mesoproterozoic crustal unit was also stressed by Gärtner et al. (2016, 2017). Final amalgamation of Meguma with Avalonia occurred in Devonian through Early Carboniferous time.

Conclusions

After more than a century of uncertainty about stratigraphic relations and ages of the metasedimentary and metavolcanic rocks intruded by the South Mountain Batholith and related plutons in southern Nova Scotia, a well-constrained stratigraphic history has been constructed. The basis of the history was established by detailed mapping which led to the establishment of formations in the Goldenville and Halifax groups, in combination with age constraints provided by

microfossils and U-Pb dating of detrital zircon (White 2010a, 2013; Waldron et al. 2009; White et al. 2012 and references therein). The detailed mapping also resulted in clarification of stratigraphy in the overlying Rockville Notch Group, including the recognition that volcanic units in the White Rock Formation are of Early Silurian age (Keppie and Krogh 2000; MacDonald et al. 2002) and that quartzite units are numerous and not marker horizons in the White Rock Formation (White 2010b).

The additional two U-Pb (zircon) igneous crystallization ages reported here (442.9 ± 2.1 Ma for a felsic tuffaceous unit at the base of the White Rock Formation at Cape St. Marys and 435.8 ± 2.1 Ma for a similar unit higher in the section at Chegoggin Point) strongly support previously published ages indicating that the volcanic rocks were erupted over a relatively short time interval in the Early Silurian. That the entire formation is of Early Silurian age is further supported by the age of 426.4 ± 2 Ma reported by Warsame et al. (2017) for a folded gabbroic sill in the Cape St. Marys area, consistent with the ages of fossils reported in the overlying Kentville Formation and Kentville Formation-equivalent strata in the White Rock Formation (Blaise et al. 1991; Bouyx et al. 1997).

The presence of the “Sardian gap” (mid to late Ordovician) in the Meguma terrane and of detrital zircon populations in the Rockville Notch Group and underlying Halifax and Goldenville groups which show evidence of Cadomian (ca. 540-600 Ma), Pan-African (ca. 600-750 Ma), and Eburnean (1800-2200 Ma) orogenic events are strong arguments for the derivation of sediments in the Meguma terrane from the Cadomian orogen. The Cadomian orogen formed the margin of West Africa in the Late Ediacaran to early Palaeozoic, and hence, the data support the West African provenance of Meguma as initially proposed by Schenk (1971, 1981).

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Fig. 1. Simplified geological map of the Meguma terrane after White (2010a, b) showing the distribution of major rock units and the locations (black boxes) of the Wolfville, Torbrook, Bear River, Cape St. Marys, and Yarmouth areas described in the text. Inset map shows the location of the Meguma terrane in relationship to other components of the northern Appalachian orogen (after Hibbard et al. 2006). The black box outlines the approximate area shown on the main map.

Abbreviations: NB, New Brunswick; NL, Newfoundland; NS, Nova Scotia; QUE, Quebec.

Fig. 2. Simplified stratigraphic columns for the Rockville Notch Group in the Wolfville, Torbrook, Bear River, Cape St. Marys, and Yarmouth areas showing stratigraphic positions of U-Pb dating samples for this study (red stars, igneous samples; open stars, detrital samples) and previous studies. Blue numbers are igneous crystallization ages from Keppie and Krogh (2000), MacDonald et al. (2002), and Warsame et al. (2017). Lettered boxes indicate previous detrital zircon samples - M from Murphy et al. (2004a) and H from Henderson (2016). Other abbreviations: F, Floian; Ll, Llandovery; W, Wenlock; Lu, Ludlow; P, Pridoli; T, Tremadocian; E, Early; M, Middle; L, Late. In the text, early Cambrian is used informally to refer to Terreneuvian and Series 2 of the Cambrian timescale. The duration of the hiatus between the Halifax and Rockville Notch groups in the Torbrook and Cape St. Marys areas is inferred from age constraints described in the text.

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Fig. 5. Photomicrograph pairs of dated samples; plane-polarized light on the left and with crossed polars on the right. (a, b) Crystal-lithic metatuff sample B01-W13-001 from the base of the White Rock Formation at Cape St. Marys. (c, d) Crystal metatuff sample O16-W15-012 from Chegoggin Point. (e, f) Metaconglomerate (diamictite) sample MEG7 from the Wolfville area showing metawacke clasts in fine-grained recrystallized matrix. Long dimension of photographs is about 3 mm.

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Fig. 7. Concordia diagrams for meta-igneous samples from the White Rock Formation. (a) Felsic metatuff from the Cape St. Marys section. (b) Felsic metatuff from Chegoggin Point in the Yarmouth area. Abbreviation: MSWD, mean square weighted deviates.

Fig. 8. Probability plots for metasedimentary samples from the White Rock Formation; figures on the right show the full spectrum of ages from 0 to 3000 Ma; figures on the left show more detail of the ages between 300 and 1200 Ma. (a, b) metaconglomerate sample MEG7 from the Wolfville area; (c, d) quartzite sample B01-W13-002, from the Cape St. Marys section; (e, f) quartzite sample O16-W15-011 from Chegoggin Point in the Yarmouth area; (g, h) quartzite sample MEG3 from the Overton section in the Yarmouth area.

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Table A2. U-Pb data, Chegoggin tuff sample O16-W15-012.

Table A3. U-Pb data, Wolfville area conglomerate MEG7.

Table A4. U-Pb data, Cape St. Marys quartzite B01-W13-002.

Table A5. U-Pb data, Chegoggin Point quartzite O16-W15-011.

Table A6. U-Pb data, Overton quartzite MEG3.