Spatio-temporal distribution of Devonian post-accretionary granitoids in the Canadian Appalachians: implications for tectonic controls on intrusion-related mineralization

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Abstract: Intrusion-related mineralization in the Canadian Appalachian Orogen is widespread and associated with Devonian post-accretionary granitoids. Here we review the spatial and temporal distribution of post-accretionary magmatism across the orogen, and the coeval structural network that may have facilitated magma ascent and emplacement. We demonstrate that magmatism and associated intrusion-related mineralization were particularly widespread during the Late Devonian, occurring within all tectonic zones of the orogen. This, along with published petrological arguments, suggests a deep and orogen-scale source for both magma and metals. Lithospheric delamination following terminal continent–continent collision may be a plausible process to initiate magmatism at such a scale, and if so, may be an important geodynamic process for intrusion-related mineralization. The magmatic belts are spatially associated with shear zones and faults that formed or reactivated during the Late Devonian and likely facilitated magma ascent independent of their kinematics. Further work is required to relate fault kinematics and slip events to magma emplacement.

Résumé : Dans l'orogène des Appalaches au Canada, de la minéralisation apparentée à des intrusions est très répandue et est associée à des granitoïdes post-accrétionnaires du Dévonien. Nous examinons ici la distribution spatiale et temporelle du magmatisme post-accrétionnaire dans l'orogène, ainsi que le réseau structural existant à la même époque qui a pu faciliter la remontée et la mise en place du magma. Nous démontrons que l'activité magmatique et les processus associés de minéralisation apparentée à des intrusions étaient particulièrement étendus au Dévonien tardif, se manifestant dans toutes les zones tectoniques de l'orogène. Ceci, en accord avec les arguments pétrologiques déjà publiés, suggère l'existence d'une source profonde, à l'échelle de l'orogène, tant pour le magma que pour les métaux. Une délamination lithosphérique consécutive à la collision terminale continent-continent pourrait être un processus plausible de déclenchement du magmatisme à une telle échelle et, si tel est le cas, pourrait être un processus géodynamique important pour la minéralisation apparentée à des intrusions. Les ceintures magmatiques sont spatialement associées à des zones de cisaillement et à des failles qui se sont formées ou ont été réactivées au Dévonien tardif et qui ont probablement facilité la remontée du magma, indépendamment de leurs cinématiques. De plus amples travaux sont nécessaires pour relier la cinématique des failles et les épisodes de coulissage à la mise en place du magma.

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INTRODUCTION

Tin, tungsten, and molybdenum are expected to play a critical role in Canada's future. Global demand for these metals is projected to increase due to their importance in alloys used in the high-tech industry, and because of China's dominance of their global production, access may be affected by evolving geopolitics. There are several major Sn±W±Mo polymetallic intrusion-related deposits in the Canadian Appalachian Orogen, including the Mount Pleasant, Sisson, and Burnt Hill deposits in New Brunswick; the East Kemptville Sn deposit on mainland Nova Scotia; and the Ackley, Grey River, and Granite Lake deposits in Newfoundland. Many other smaller deposits in the region have similar ages and tectonic settings (Fig. 1). The causative intrusions to these deposits are regionally extensive suites of post-accretionary granitoid rocks of which the latest, most-evolved phases tend to be the most highly mineralized (e.g. Lentz and Mohammadi, 2014; Mohammadi et al., 2019). Although crystallization ages, duration of magmatism, potential magma sources, and geodynamic setting have been examined or proposed for several of these suites (e.g. Kerr, 1997; Wilson and Kamo, 2016), they have not yet been comprehensively discussed at the scale of the orogen. Similarly, the potential structural controls on their emplacement have not yet been considered at this scale. Under the Targeted Geoscience Initiative (TGI) program of the Geological Survey of Canada, we aim to address this missing perspective by contributing new geochronological data to refine the spatio-temporal history of post-accretionary magmatism in the Canadian Appalachian Orogen and determining the impact of coeval structures on magma emplacement by characterizing their deformation ages and kinematics. Our progress to date has been presented in several TGI reports of activities, as well as in additional publications (e.g. Kellett et al., 2014, 2016, 2017, 2018; Bickerton et al., 2018, 2019; Moning et al., 2018, 2019; Piette-Lauzière et al., 2018, 2019; van Rooyen et al., 2018; Grant et al., 2019). In this synthesis report, we review the results from previous work and these new investigations, including a compilation of >150 crystallization ages for Devonian plutonic and a few volcanic rocks (Appendix A). We also review published and new evidence for a network of reactivated faults that we hypothesize provided the structural pathways for magma ascent during the Devonian.

TECTONIC HISTORY OF THE CANADIAN APPALACHIANS

The Appalachian Orogen is an accretionary orogen that formed from the latest Precambrian to the mid-Paleozoic along the eastern margin (today's coordinates) of Laurentia and includes much of southeastern Quebec and all of Newfoundland, New Brunswick, P.E.I., and Nova Scotia (Fig. 1). Following the Neoproterozoic breakup of the supercontinent Rodinia, a passive margin developed in the newly formed Iapetus Ocean on Laurentia's eastern flank. Subduction initiated in the late Cambrian to Ordovician, and peri-Laurentian elements (the western Dunnage zone) subsequently accreted to the Laurentian margin in the Taconic Orogeny. The outer region of the Laurentian passive margin and adjacent continental slope was transported to the west, and the well-known ophiolites of western Newfoundland were emplaced. Subduction then moved outboard and peri-Gondwanan arcs, back-arc basins, and microcontinental blocks, collectively known as Ganderia, were progressively accreted to Laurentia during the Silurian, producing the widespread Salinic Orogeny. This was followed by latest Silurian accretion of Gondwanan-derived Avalonia to the now composite Laurentian margin, closing the Iapetus Ocean and forming the Acadian Orogeny. Finally, the Rheic Ocean, lying between Avalonia and Gondwana, started to close and in the process Megumia accreted to Laurentia, recorded by the Middle to Late Devonian Neoacadian Orogeny, ultimately forming the supercontinent Pangaea during Alleghenian terminal closure of the Rheic Ocean (for a full review, *see* van Staal (2007), Hatcher (2010)). Post-accretionary (i.e. occurring in previously accreted terranes) granitoid rocks intruded throughout all tectonic zones of the greater Canadian Appalachian Orogen during the Devonian, extending >500 km across the strike length of the orogen and >1000 km along its length, from close to the Appalachian front to Meguma (Fig. 1, 2). Below we review current knowledge on the type, distribution, and timing of those post-accretionary granitoids.

DURATION AND SPATIAL EXTENT OF DEVONIAN POST-ACCRETIONARY MAGMATISM

Quebec Appalachians

Devonian granitoid rocks occur in two regions of the Quebec Appalachian belt: on the Gaspé Peninsula and in southeasternmost Quebec, straddling the U.S.A. border (Fig. 2–4). The group of plutons on the Gaspé Peninsula, most of which lack published crystallization ages apart from the McGerrigle Mountains plutonic complex, tends to be elongated along the Appalachian structural trend. Those in the south are generally more equant in shape and form the northern extent of a more extensive belt of ca. 390 to 365 Ma granites, termed the New Hampshire plutonic suite (Aleinikoff et al., 2011; Ratcliffe et al., 2011). This pattern fits an interpretation of syn-tectonic emplacement for the northern suite and post-tectonic emplacement for the southern suite, as the Quebec Appalachians were broadly affected by the Neoacadian Orogeny (Tremblay and Pinet, 2016). Positive εNd and $\delta^{18}O$ values from the northern suite suggest a mantle to lower crust magma source (Whalen et al., 1994a).

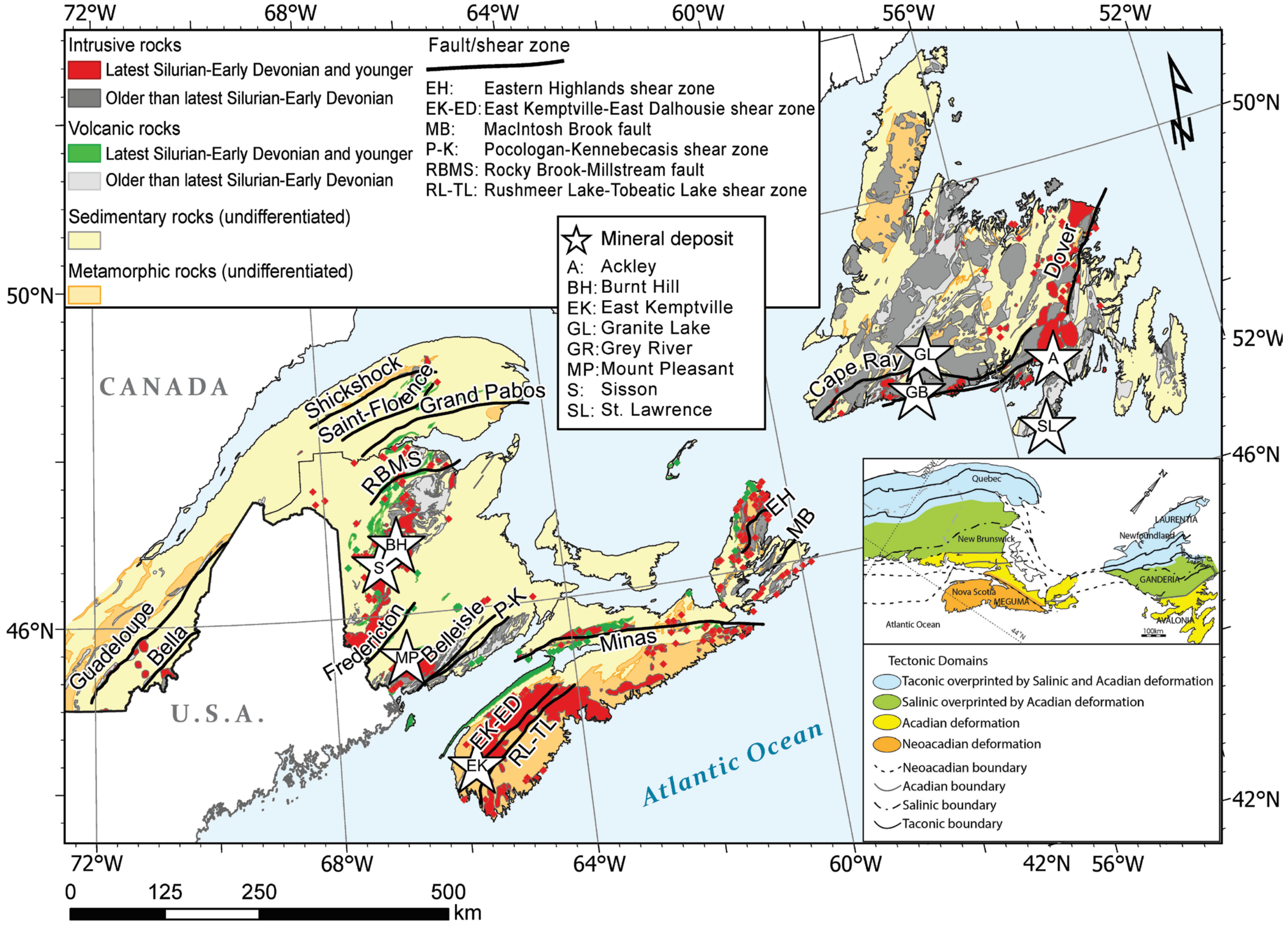

Figure 1. Geological map of the Canadian Appalachian Orogen, showing rock type and distribution of Silurian to early Carboniferous granites and structures (Keppie, 2006 (Nova Scotia); Department of Energy and Mines 2015 (New Brunswick); Thériault and Beauséjour, 2012 (Quebec); Colman-Sadd et al., 2000 (Newfoundland)). Tectonic domains and the extent of deformation of orogenic events for the Appalachian Orogen in Eastern Canada, modified from van Staal et al. (2009), are presented in the inset.

The available published ages for the Quebec Appalachians do not include Early Devonian granitoids. The McGerrigle Mountains plutonic complex is ca. 390 Ma (Whalen et al., 1991), whereas cooling ages for other plutons in the region indicate that they are older than ca.375 Ma (Whalen et al., 1994a). The southern suite ranges in age from ca. 385 to 368 Ma (*see* data and references in Appendices 1 and 2).

New Brunswick

Devonian post-accretionary granitoids and less extensive volcanic rocks occur primarily along two major belts in New Brunswick (Fig. 4). The Central plutonic belt of New Brunswick and coeval extrusive rocks were emplaced into the Miramichi Highlands (Fyffe et al., 1981; Bevier and Whalen, 1990; Whalen, 1993; Whalen et al., 1996). This belt also includes Ordovician and abundant Silurian intrusive rocks (Wilson and Kamo, 2016) that are concurrent with the main phase of the Acadian Orogeny. A few smaller, mineralized Devonian granitoid plutons and dykes also occur between the Central Plutonic Belt and the Gaspé Peninsula (Massawe and Lentz, 2019). The Southern plutonic belt is mostly composed of the late Silurian to Late Devonian Saint George Batholith and exposures are interpreted to represent the upper portions of this complex body (McLeod, 1987; 1990; Mohammadi et al., 2017). Within both belts, granitoid rocks span the entire Devonian period, though they are apparently more voluminous in the Early Devonian, and wane towards the end of the Late Devonian.

A recent study of several Devonian granitoid rocks across New Brunswick has defined three petrogenetic suites. Groups 1 and 2 overlap in distribution and age from Early to Late Devonian, and both are interpreted as I-type granites, but with arc and mantle to lower crustal sources, respectively. Group 3 rocks are Late Devonian or probable Late Devonian where undated, and are also interpreted as I-type, but are highly evolved, and have been interpreted as products of lithospheric delamination (Azadbakht et al., 2019).

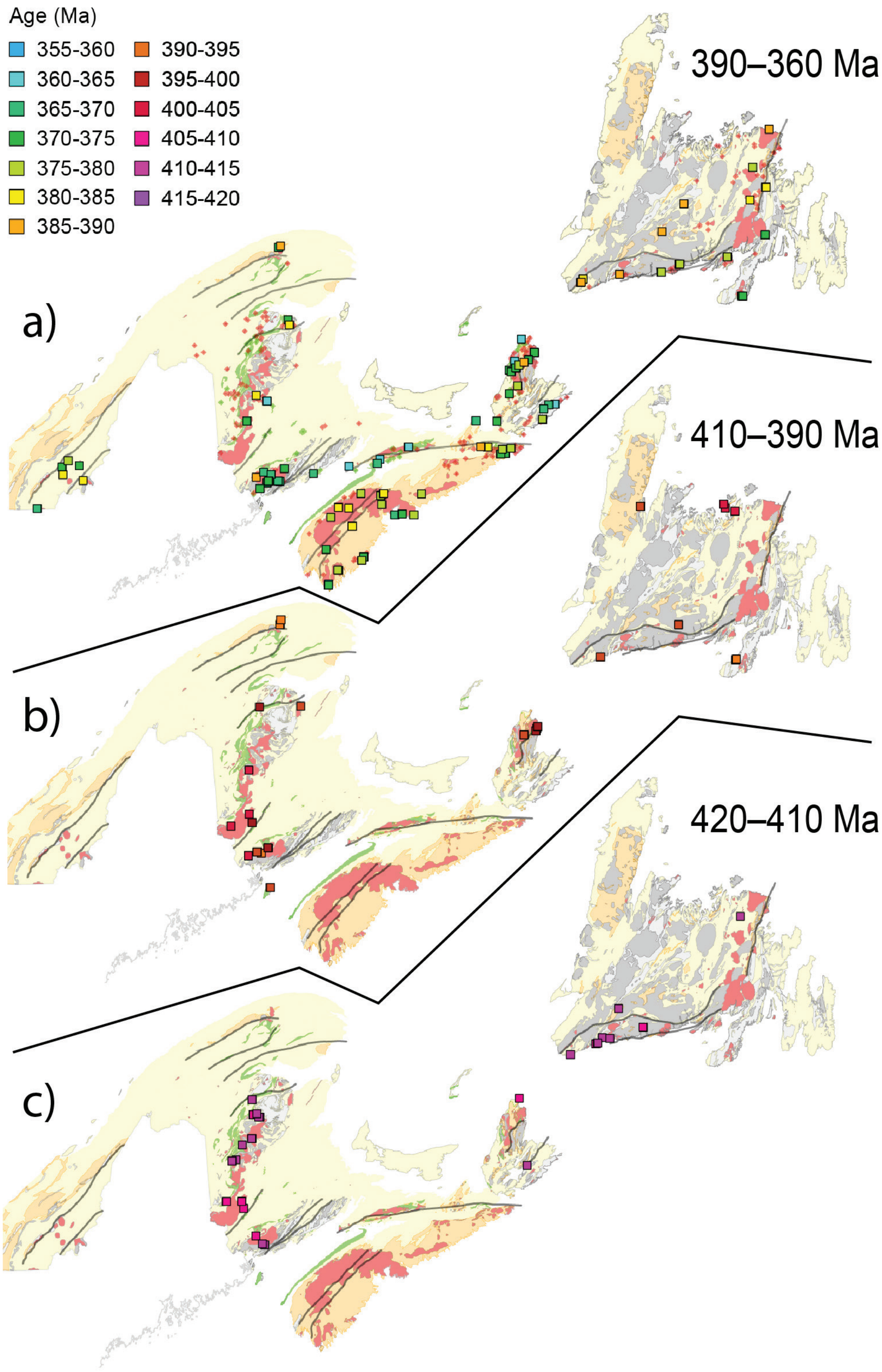

Figure 2. Maps of the Appalachian Orogen showing distribution of U-Pb ages during three-time intervals that span the Devonian period: **a)** 390–360 Ma, **b)** 410–390 Ma, **c)** and 420–410 Ma. *See* Figure 1 for legend. Crystallization ages used are listed in Appendix A.

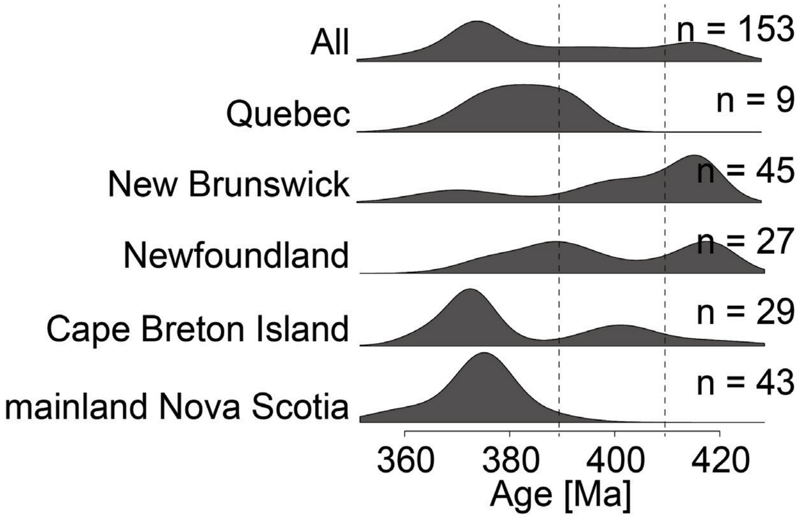

Figure 3. Kernel density estimate plots summarizing Devonian magmatic crystallization ages for the Canadian Appalachians, by region, plotted using IsoplotR (Vermeesch, 2018) such that the y-axis corresponds to density. Dashed lines show age divisions plotted in Fig. 2a–c.

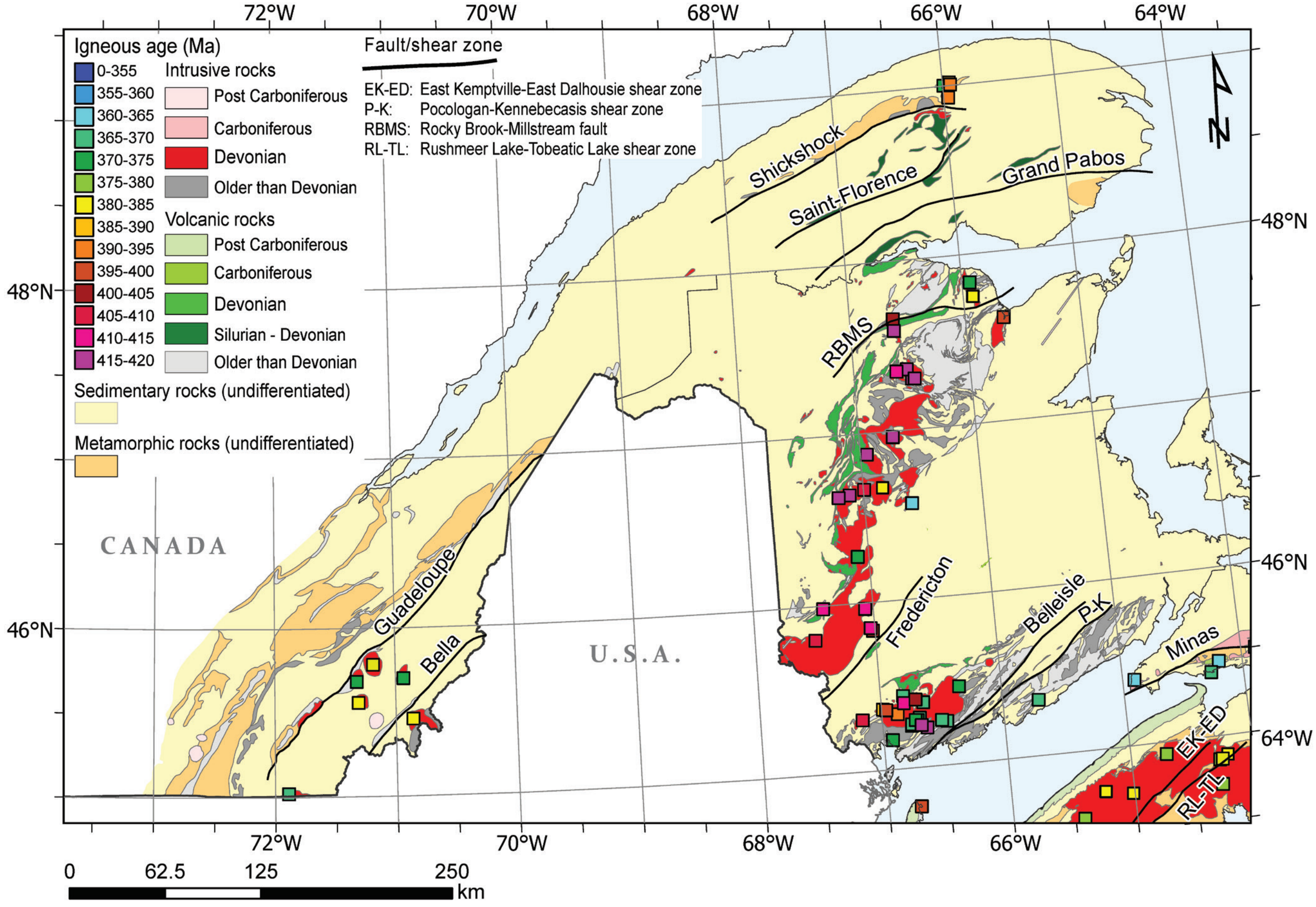

Figure 4. Geological map of Quebec Appalachians and New Brunswick showing rock type and Devonian magmatic crystallization ages (Department of Energy and Mines, 2015 (New Brunswick)); Thériault and Beauséjour, 2012 (Quebec)). Crystallization ages used are listed in Appendix A.

Newfoundland

Devonian granites in Newfoundland occur in a long sinuous belt that broadly follows the orogenic trend, although the granites themselves are generally undeformed (Fig. 5). Magmatism appears to have waned somewhat during the later Early Devonian, and the youngest of the Middle and Late Devonian granites tend to be the most highly evolved and host most of the intrusion-related mineralization (Kerr et al., 2009). Examples include the ca. 377 Ma Ackley Granite Suite, which hosts the Ackley W deposit (Tuach et al., 1987; Kontak, 1995; Kellett et al., 2014), and the ca. 387 Ma Grey River granite, which has been linked to the Grey River W and Moly Brook Mo deposits (Kerr and McNicoll, 2012). These older and younger suites have been denoted as Group A and Group B, respectively, in Kellett et al. (2014). Group A granites are locally deformed and interpreted to be syntectonic with the Acadian Orogeny (Kellett et al., 2014, 2016). Group B granites have a mixed mantle-crust source (Kerr, 1997), which has been interpreted to be the result of lithospheric delamination (Kerr, 1997; Schofield and D'Lemos, 2000), although slab breakoff of the Avalonia slab beneath Ganderia has also been considered (Kellett et al., 2014).

Cape Breton Island

As in New Brunswick and Newfoundland, granitoid magmatism on Cape Breton Island spans the Devonian, from ca. 415 to 365 Ma, and falls broadly into late Silurian to Devonian and Late Devonian suites, with an apparent waning of magmatism during the Middle Devonian (Fig. 2, 3, 6). Both age suites are represented in the Aspy terrane (Ganderia), and form a significant portion of the bedrock in the northern part of the terrane. Only the younger Late Devonian suite is represented in the Mira terrane (Avalonia), and there is a distinct absence of post-accretionary magmatism in the intervening Bras D'Or terrane (Ganderia basement; Barr et al., 2018). This heterogeneous distribution suggests both structural and tectonic controls on Devonian granitoid magma emplacement.

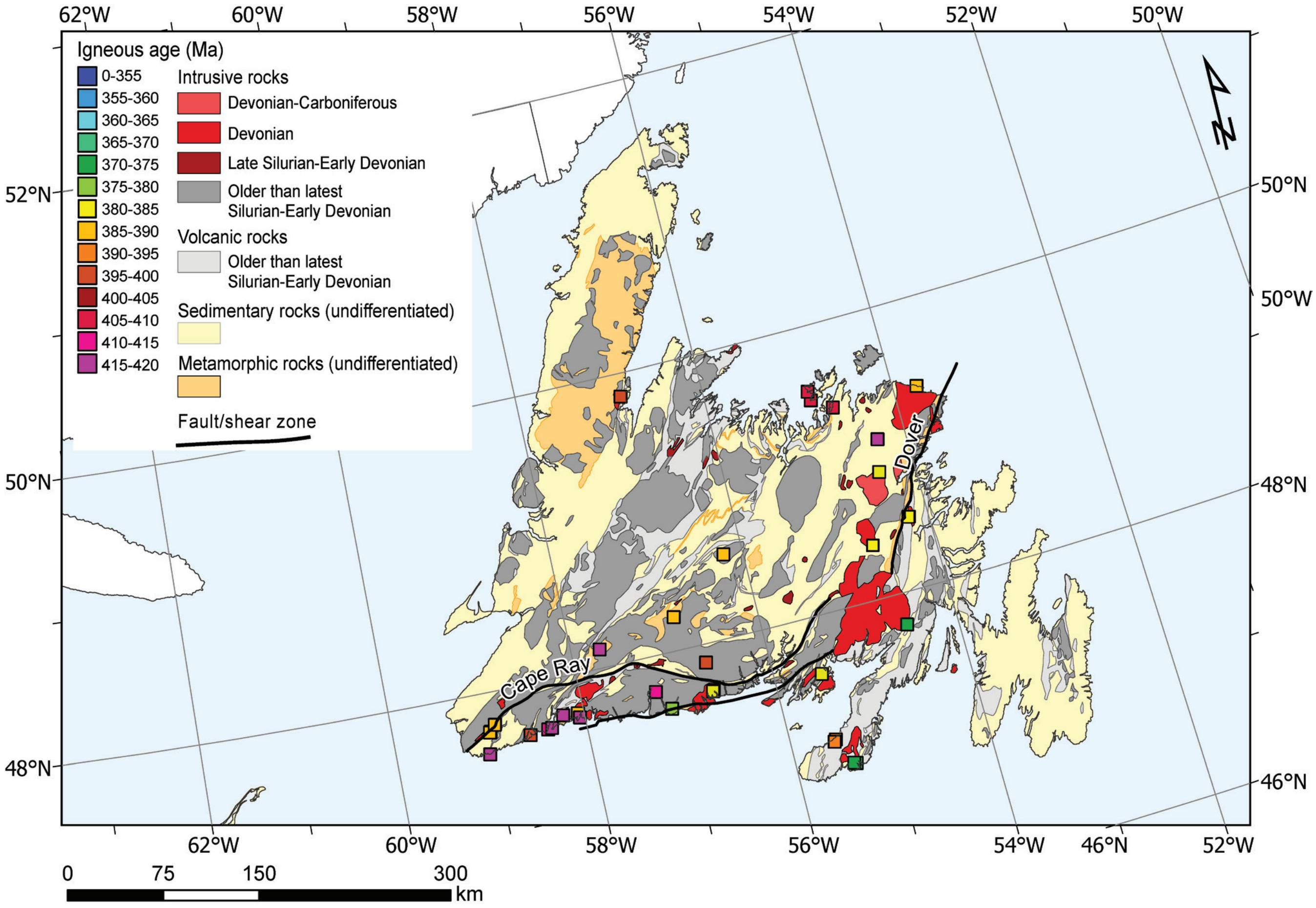

Figure 5. Geological map of Newfoundland showing rock type and Devonian magmatic crystallization ages (Colman-Sadd et al., 2000). Crystallization ages used are listed in Appendix A.

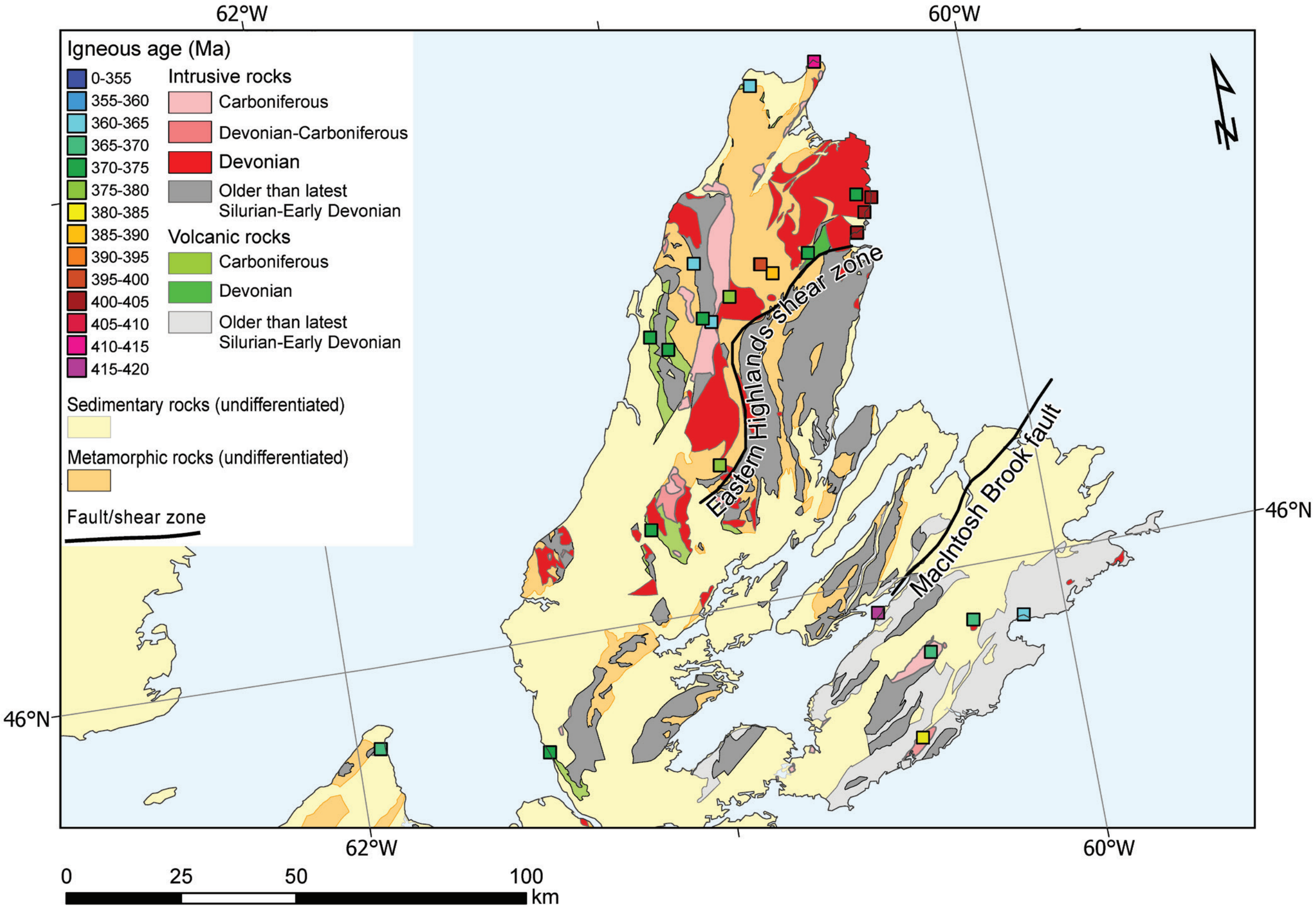

Figure 6. Geological map of Cape Breton Island showing rock type and Devonian magmatic crystallization ages (Keppie, 2006). Crystallization ages used are listed in Appendix A.

Mainland Nova Scotia

Devonian to Carboniferous intrusive rocks on mainland Nova Scotia are dominantly peraluminous felsic granites with lesser tonalite to granodiorite and subordinate (< 5%) bimodal plutonism (e.g. Clarke et al., 1997). The most voluminous of these intrusive rocks are granites, which make up the approximately 7300 km^2 South Mountain Batholith on the southern half of mainland Nova Scotia. The South Mountain Batholith is host to the past-producing East Kemptville Sn deposit (cf. Kontak et al., 2001) and is a meta- to peraluminous composite granite body that was emplaced syn- to post-tectonically (e.g. Clarke and Chatterjee, 1988; Benn et al., 1999; Culshaw and Bhatnagar, 2001; MacDonald, 2001).

The South Mountain Batholith comprises two suites of plutons distinguished by textural and mineralogical characteristics: an early suite dominated by granodiorite to monzogranite, and a later, more evolved suite of monzogranite to leucogranite (MacDonald, 2001). Recent age data from Bickerton et al. (2018, 2019) indicate that the South Mountain Batholith intrusive suite spans a wide range of crystallization ages from ca. 383 to 375 Ma in the less evolved plutons and ca. 379 to 370 Ma in the more evolved plutons (Fig. 2, 3). Peripheral to the South Mountain Batholith are slightly younger mafic intrusions and their hybridized intermediate to felsic equivalents, which range in crystallization age from ca. 368 to 357 Ma (Fig. 7; e.g. Tate and Clarke, 1995; MacLean et al., 2003; Shellnutt and Dostal, 2019).

DEVONIAN STRUCTURAL HISTORY OF THE CANADIAN APPALACHIANS

In this section we discuss some of the better-known faults that were active during the Devonian period. Although we attempt to describe most of the major, crustal-scale faults and shear zones, we cannot cover all of the structures in this complex area, so this should be considered a representative, rather than exhaustive, list.

Quebec Appalachians

Several faults were active in southern Quebec and the Gaspé Peninsula during the Devonian, at which time the entire region was pervasively deformed at low metamorphic

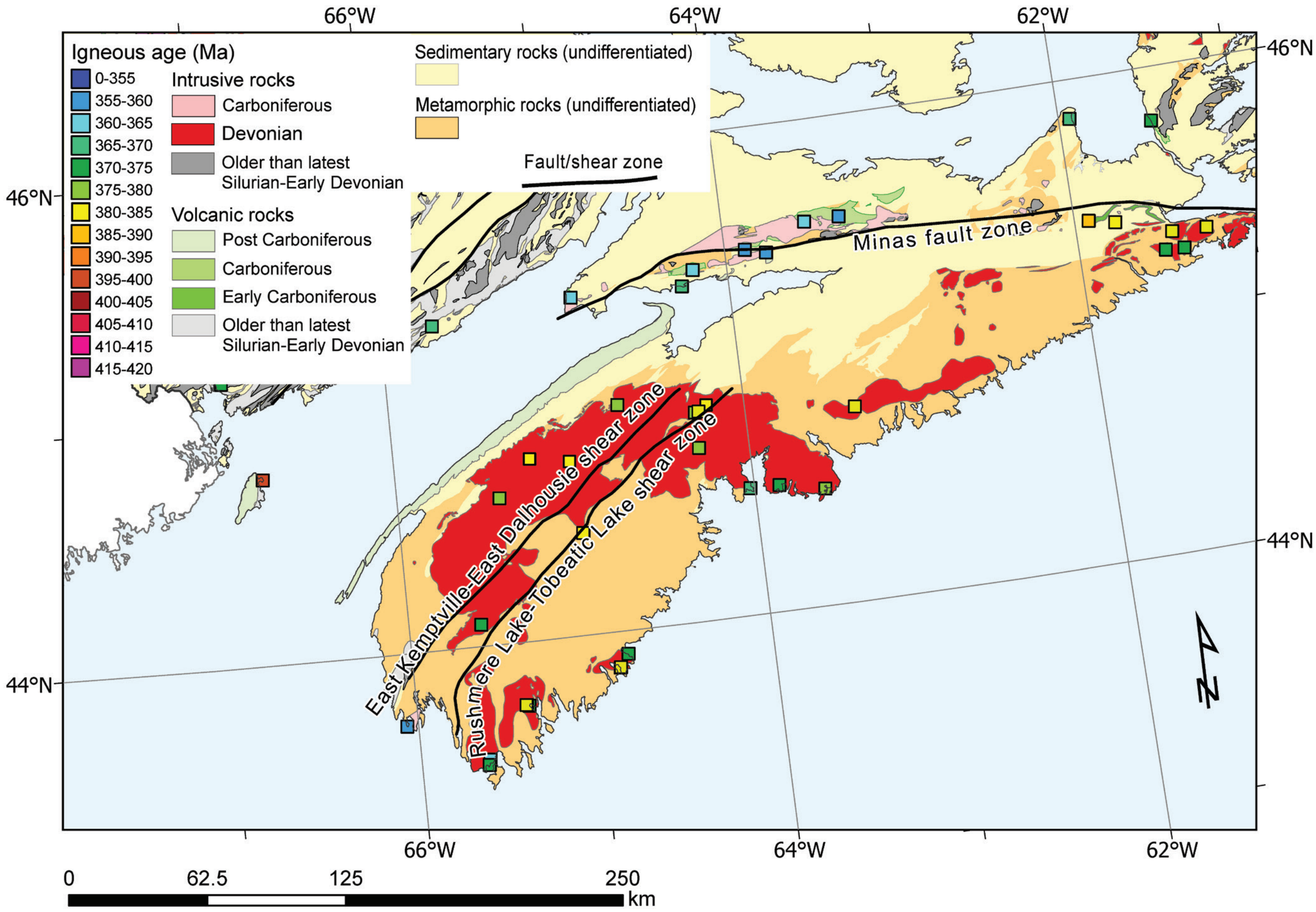

Figure 7. Geological map of mainland Nova Scotia showing rock type and Devonian magmatic crystallization ages (Keppie, 2006). Crystallization ages used are listed in Appendix A.

grade during the Neoacadian Orogeny (Tremblay and Pinet, 2016). Thrusts such as the Guadeloupe and Bella faults dominate in southern Quebec (Fig. 1, 4) Tremblay and Pinet, 1994; Tremblay et al., 2015), whereas dextral strike-slip faults including the Saint-Florence, Grand Pabos, and Shickshock faults occur in the Gaspé Peninsula region (Kirkwood and Malo, 1993; Malo et al., 1992, 1995). Detailed structural analyses demonstrate that shortening and thrusting predate strike-slip faulting (Kirkwood, 1995), although both structural sets were likely active from the Middle to Late Devonian (Tremblay and Pinet, 2016), and the kinematic differences may largely be a function of collision geometry during northwest-directed shortening (Malo et al., 1995).

New Brunswick

Structures that were active during the Devonian in New Brunswick are primarily strike-slip in type, although they may have originated as dip-slip structures (Fig. 1, 5; e.g. Park et al., 1994; Park and Whitehead, 2003). The Fredericton fault lies along the eastern boundary of the Central plutonic belt in New Brunswick, adjacent to the Pokiok Batholith, and cuts the Silurian Fredericton trough (Park and Whitehead, 2003). This fault lies along strike of the Waite strand of the Norumbega fault, which is a major ductile-brittle, dextral strike-slip fault system that extends south into Maine, U.S.A., and is thought to have first initiated at ca. 380 Ma (Wang and Ludman, 2002, 2004). The Rocky Brook–Millstream fault, lying on the northwest margin of the Central plutonic belt, has a dextral transpressional history that may also involve Devonian slip (Fyffe and Fricker, 1987; Tremblay and Dubé, 1991; van Staal and de Roo, 1995).

The Belleisle shear zone and the Pocologan-Kennebecasis shear zone are two structures internal to Ganderia that lie to the east of the Southern plutonic belt (Fig. 1). The Belleisle shear zone separates Neoproterozoic to early Cambrian granites, felsic tuffs, and pyroclastic rocks of the New River terrane to the northwest from Silurian bimodal orthogneiss of the Kingston complex to the southeast (Park et al., 1994; White and Barr, 1996, 2006). The Pocologan-Kennebecasis shear zone separates the Kingston complex from low-pressure, high-temperature gneiss, metasedimentary rocks, and Cambrian diorite to granodiorite and granite plutons of the Brookville terrane (Park et al., 1994; White and Barr, 1996, 2006). The Belleisle shear zone is characterized by strike-slip sinistral kinematics but was partially reactivated with a dextral sense of motion during deformation along the Pocologan-Kennebecasis shear zone (Doig et al., 1990). Doig et al. (1990) interpreted the orientation of rhyolite dykes in the Kingston complex to record asymmetric opening during sinistral deformation along the Belleisle shear zone; therefore, their crystallization age of 435.5 ± 1.5 Ma (U-Pb on zircon; Doig et al., 1990) is interpreted to represent the timing of the sinistral movement in the shear zone. The dextral shearing along the Pocologan-Kennebecasis shear zone, and associated partial reactivation of the Belleisle shear zone, is interpreted to be synchronous with local metamorphism of the Kingston complex because of the syn-kinematic development of a garnet-staurolite assemblage (White et al., 2006). Amphibole from deformed mafic dykes in the Kingston complex with ^{40}Ar/^{39}Ar ages of ca. 416 to 390 Ma are, therefore, interpreted to date metamorphism-related deformation along the Pocologan-Kennebecasis shear zone (Nance and Dallmeyer, 1993). That interpretation is consistent with metamorphic U-Pb monazite ages of ca. 417 and 388 Ma in specimens from the Pocologan metamorphic suite, which forms the high-strain zone of the Pocologan-Kennebecasis shear zone at the southeastern edge of the Kingston complex (Massonne et al., 2018). These ages are interpreted to record monazite growth during syn-kinematic exhumation of the metamorphic suite (Massonne et al., 2018). Similarly, extrusion and related exhumation of the Kingston complex is also interpreted to be related to motion along the Pocologan-Kennebecasis shear zone, reflecting significant transpression across the shear zone (Nance and Dallmeyer, 1993). This transpression-driven exhumation is consistent with the transition from ductile to brittle fabrics (Park et al., 1994) in the shear zone and may have lasted until 342 Ma, the ^{40}Ar/^{39}Ar age of muscovite from shear fabrics located close to the high-strain zones of the Pocologan-Kennebecasis shear zone (White and Barr, 2006).

Newfoundland

The Dover-Hermitage fault is the structural boundary separating the Ganderia and Avalonia terranes in Newfoundland. It formed as an approximately 20 km wide, ductile, sinistral strike-slip shear zone during ca. 423 to 395 Ma, was reactivated as a narrow, ductile-brittle, dextral strike-slip fault active at least during ca. 384 Ma, and was stitched by the Ackley Granite Suite by ca. 377 Ma (Holdsworth, 1994; Schofield and D'Lemos, 2000; Kellett et al., 2014, 2016). Although the extension of the Ganderia-Avalonia boundary southwest of the Hermitage Bay fault is generally interpreted to bend southward in offshore regions to pass into Cape Breton Island, the region along the south coast of Newfoundland has many geochronological and lithological similarities to either the Bras d'Or terrane or to Avalonia. This suggests that another terrane-bounding shear zone may intersect in this region, in which case Devonian granites there (e.g. Grey River granite) may also be situated along a reactivated structure (Dunning and O'Brien, 1989, Rogers et al., 2015).

The Cape Ray shear zone is located inboard of Ganderia in Newfoundland. It separates, from the northwest to the southeast, Proterozoic mafic to ultramafic orthogneiss of the Cape Ray igneous complex, Ordovician to Silurian volcano-sedimentary rocks of the Windsor Point Group (which form the high-strain zone of the Cape Ray shear zone), psammite mylonite of the Grand Bay Complex, and Ordovician felsic orthogneiss of the Port aux Basques gneiss (Wilton, 1983; Dubé and Lauzière, 1996; Dubé et al., 1996; Schofield et al., 1998). The Grand Bay Complex records two major ductile deformation events: 1) southeast-side-up sinistral oblique kinematics recorded in amphibolite-grade metamorphic rocks; and 2) reactivation during retrograde metamorphism, with the northeast-trending segment of the Cape Ray shear zone recording southeast-side-up kinematics and the east-northeast segment recording dextral strike-slip kinematics (Dubé and Lauzière, 1996). The maximum age of the first episode of deformation is interpreted to correspond to the crystallization age of the deformed Windowglass Hill Granite in the Windsor Point Group (424 ± 2 Ma; Dubé et al., 1996), whereas the age of the main shear event is approximated to the age of syn-deformation metamorphic monazite and titanite from the Port aux Basques gneiss (415 ± 2 Ma and 412 ± 2 Ma, respectively, U-Pb; Dunning et al., 1990, van Staal et al., 1994). Because the reactivation of the Cape Ray shear zone occurred during retrograde metamorphism, the ^{40}Ar/^{39}Ar hornblende and biotite ages of 407 ± 4 and 403 ± 4 Ma, respectively, from the Port aux Basques gneiss may be interpreted as broadly coeval with motion along the Cape Ray shear zone. The minimum age of the fault reactivation is defined by the undeformed, crosscutting Strawberry Hill granite (384 ± 2 Ma, U-Pb on zircon; Dubé et al., 1996).

Cape Breton Island

The northwestern tip of Cape Breton Island is underlain by Precambrian gneiss of the Blair River inlier, interpreted as part of the basement of the Humber zone of the Laurentian margin (Loncarevic et al., 1989). The inlier is separated from Ganderia on its south and southeast margin by the Red River and Wilkie Brook shear zones, respectively. The Wilkie Brook shear zone recorded sinistral strike-slip kinematics. It deformed rhyolite from the Money Point Group (427± 4 Ma, U-Pb zircon); is intruded by the syn-tectonic 414 ± 3 Ma Cape North granite (Keppie et al., 1992), and is stitched by the undeformed Margaree pluton (ca. 365.5 ± 3.3 Ma, U-Pb on zircon; Sombini dos Santos, 2018). This deformation can be correlated with the 423 to 395 Ma Acadian ductile deformation accommodated by the Dover-Hermitage fault (Kellett et al., 2016).

The Ordovician to Silurian volcano-sedimentary rocks and Devonian granitoids of the Aspy terrane and the Precambrian metasedimentary rocks and late Proterozoic dioritic to granitic plutons of the Bras d'Or terrane are both considered part of Ganderia (Barr and Raeside, 1989; Raeside and Barr, 1992; Lin, 1993; Barr et al., 1998). The boundary between these two terranes is the Eastern Highlands shear zone, where Ordovician to Silurian sedimentary rocks of the Bras d'Or terrane are interpreted to have been deposited unconformably on older rocks of the Aspy terrane. These sedimentary rocks have a detrital zircon record spanning the igneous crystallization ages found in the Aspy and Bras d'Or terranes, suggesting a basement-cover relationship (Lin, 1993; Chen et al., 1995). East-over-west dip-slip with minor sinistral strike-slip kinematics were initially recorded on the Eastern Highlands shear zone. The maximum age of this deformation event is constrained by the crystallization age of a rhyolite deformed within the shear zone (424 ± 4 Ma, U-Pb on zircon; Piette-Lauzière et al., 2019). The minimum age of this event has yet to be fully constrained; however, the crystallization age of an undeformed pegmatite dyke (ca. 391 ± 8 Ma; U-Pb on zircon) may provide a lower limit for its activity (Piette-Lauzière et al., 2019). The Eastern Highland and Wilkie Brook shear zones were, therefore, probably both active during the Acadian Orogeny, but only the Eastern Highlands shear zone was later reactivated. Lin (1993) reported oblique west-side-up and dextral reactivation with a maximum age constrained by the crystallization age of a deformed granite dyke dated at ca. 372 ± 4 Ma (U-Pb on zircon; Piette-Lauzière et al., 2019). No crosscutting relationships have been identified to determine the minimum age of reactivation of the Eastern Highlands shear zone and, based on the current data set, this reactivation is attributed to the Neoacadian Orogeny.

Farther southeast, the MacIntosh Brook fault separates the Bras d'Or terrane from the Mira terrane and is generally interpreted to represent the extension of the Dover-Hermitage fault in Nova Scotia (Barr et al., 1998); however, the MacIntosh Brook fault is poorly exposed so the time of motion is unknown.

Mainland Nova Scotia

The granites of the South Mountain Batholith on mainland Nova Scotia are thought to have been emplaced along northeast-trending structures, broadly parallel to the trend of the orogen, during regional northwest-directed transpression. The evidence for these structures comes largely from interpretation of regional gravity surveys and magnetic lineation maps, as well as the orientations of minor faults, primary igneous flow features, joints, dykes, and veins (Horne et al., 1992; Benn et al., 1999; MacDonald, 2001). The South Mountain Batholith and surrounding host rocks are transected by a series of the northeast-trending faults and shear zones in southern Nova Scotia (e.g. East Kemptville–East Dalhousie shear zone and Rushmeer Lake–Tobeatic Lake shear zone); this relationship and ^{40}Ar/^{39}Ar muscovite cooling ages indicate protracted displacement along these shear zones, from pre- to syn- to post-emplacement of the South Mountain Batholith (cf. Culshaw and Reynolds, 1997). Dextral transpression along the northeast-trending structures in southern Nova Scotia is indicated from field relationships such as a prominent C-S fabric observed within the East Kemptville shear zone (e.g. Kontak and Cormier, 1991). As a result of the emplacement setting and kinematics of the major faults in the area, several of the South Mountain Batholith plutons are elongated where they are transected by the shear zones, with their long dimensions parallel to the northeast trend of the orogen (e.g. East Dalhousie pluton and Davis Lake pluton; Horne et al., 1992).

The Minas fault zone is a major, dextral, transpressional, terrane-bounding structure that separates Avalonia from Meguma on mainland Nova Scotia (Keppie, 1982). The ca. 375 Ma Kelly Brook pluton is elongated and was deformed within the Minas fault zone (Archibald et al., 2018). Ductile deformation of the pluton was coeval with rapid exhumation of the southern wall of the shear zone, associated with regional exhumation of Meguma to the surface by ca. 359 Ma (Archibald et al., 2018).

DISCUSSION

Several first-order observations can be made from the above review of the spatio-temporal distribution of post-accretionary magmatism in the Canadian Appalachians and the relationships of magmatic suites to major structures active during the same general time period. Magmatism during the Early Devonian was largely confined to Ganderia, including intrusions in the Central and Southern plutonic belts of New Brunswick and those proximal to the Cape Ray shear zone in Newfoundland and Eastern Highlands shear zone on Cape Breton Island (Fig. 1–3). This distribution fits with a tectonic scenario in which Avalonia was advancing toward Laurentia as the lower plate and Meguma remained offshore, so that magmatism within Ganderia was generally subduction related (e.g. van Staal et al., 2009). In contrast, Middle to Late Devonian magmatism spans the orogen, intruding all of its tectonic zones (Humber, Ganderia, Avalonia, and Meguma). Furthermore, the Late Devonian episode of magmatism in particular was responsible for all the major Sn-W-Mo deposits, and for numerous smaller deposits. There is some intrusion-related mineralization associated with Early Devonian suites (e.g. *see* review for New Brunswick in Azadbakht et al. (2019)), but this is of comparatively minor extent. Notably, significant intrusion-related mineralization occurred within all tectonic domains. For example, the Lac Lyster W deposit in Quebec is associated with the ca. 368 Ma Averill pluton within the Humber zone (Perrot et al., 2018); the East Kemptville Sn deposit is hosted within the ca. 373 Ma Davis Lake pluton in Meguma (Bickerton et al., 2018); the Mount Pleasant caldera W-Mo deposit is thought to be the subvolcanic equivalent of the deeper ca. 368 Ma Sn-W-Mo–bearing Mount Douglas Granite, hosted in Ganderia (Thorne et al, 2013; Mohammadi, 2018, Mohammadi et al., 2020); and the Ackley Sn-W-Mo deposit formed in the ca. 372 Ma Ackley Granite Suite, hosted within Avalonia (Kellett et al., 2014). The broadening in spatial extent of magmatism suggests that the heat source and tectonic processes that generated Middle to Late Devonian magmatism occurred on the scale of the entire orogen. The widespread nature of mineralization further suggests that metal endowment is not tied to any particular tectonic domain. These two points suggest a mantle-derived heat source and potentially a mantle-derived metal source.

Lithospheric delamination is a geodynamic process that can add heat to the base of the crust over an extensive area and may be triggered by terminal continent-continent collision and associated crustal shortening (Kay and Kay, 1993). The manifestation of lithospheric delamination in the overlying crust includes rapid uplift and, in particular, abundant crustal- and mantle-derived magmatism. Many studies of distinct Devonian granitoid belts have invoked lithospheric delamination as a plausible process for producing this bloom of post-accretionary magmatism, including in Gaspé Peninsula (Whalen et al., 1994a; Tremblay and Pinet, 2005), New Brunswick (Whalen et al., 1994a, 1994b, 1996), and Newfoundland (Kerr, 1997; Schofield and D'Lemos, 2000), generally on the basis of petrological and geochemical/isotopic evidence for lower crust and/or mantle-derived melting (e.g. Azadbakht et al., 2019). However, only certain structurally bounded regions of the orogen experienced rapid uplift and exhumation immediately following Late Devonian magma emplacement, including northeastern Meguma (e.g. Archibald et al., 2018), western Ganderia in Newfoundland (e.g. Kellett et al., 2014), and the Aspy terrane in Cape Breton Island (e.g. Kellett et al., 2018). Elsewhere in the orogen, preserved Devonian sedimentary rocks, volcanic rocks, and relatively unmetamorphosed rocks attest to minimal exhumation. Recent geodynamic models of lithospheric delamination for composite orogens composed of terranes with diverse mantle lithosphere strengths and densities illustrate that delamination is likely to be non-uniform and idiosyncratic, in contrast to our previous understanding (Kelly et al., 2020).

Alternative tectonic scenarios proposed for particular regions of the orogen include subduction of a hotspot beneath Meguma (Keppie and Krogh, 1999) and, more commonly, (flat) slab breakoff of the Avalonia and/or Meguma slabs (van Staal et al., 2009; Kellett et al., 2014; Massawe and Lentz, 2019). Although slab breakoff of the Iapetus and Rheic slabs may have occurred, producing localized Devonian magmatism, we propose here that slab breakoff events may not sufficiently explain the orogen-wide extent of Late Devonian magmatism, particularly on both sides of the Avalonia-Meguma plate boundary.

Although intrusive magmatism is widespread during the Late Devonian, it is still largely confined to structural trends aligned with contemporaneous faults and shear zones, such as the Cape Ray and Dover shear zones of Newfoundland; the Eastern Highlands shear zone on Cape Breton Island; the Minas, East Kemptville–East Dalhousie, and Rushmeer Lake–Tobeatic Lake shear zones on mainland Nova Scotia; the Belleisle and Pocologan-Kennebecasis shear zones adjacent to the Southern plutonic belt and the Fredericton and Rocky Brook–Millstream faults adjacent to the Central plutonic belt in New Brunswick; and dextral and strike-slip fault sets in the Quebec Appalachians (Fig. 1, 2). From our compilation, it appears that nearly all fault kinematics (thrust, strike-slip, transpressive) were equally favourable as magma channels; however, new studies have highlighted that the kinematics of ductile shear zones can be more complex than initially interpreted from field observations (e.g. Xypolias et al., 2018; Kruckenberg et al., 2019) and that kinematic flow such as transpressive and triclinic might be more common in the Appalachian Orogen than is currently documented (e.g. Lin et al., 1998). Our understanding of the kinematics of shear zones, their timing of deformation, and magma emplacement may evolve as we develop new microstructural tools to better characterize their kinematics. Nevertheless, it seems plausible that active structures were required to weaken the crust; enhance the local porosity; and allow magma transfer, and as a result, heat through the crust (e.g. D'Lemos et al., 1997). It also seems that larger volume batholiths were emplaced both at the sutures between terranes (e.g. Black Brook granitic suite) and internally (e.g. South Mountain Batholith), which highlights the fact that shear zone surface expression is not necessarily proportional to its crustal extent. The deep crustal expression of these structures requires further study by combining and leveraging the existing geophysical databases.

CONCLUSIONS

Our regional compilation of granitoid and related magmatism crystallization ages across the Canadian Appalachian Orogen and assessment of their spatial links to coeval structures during the Devonian reveals that the dynamic processes responsible for granite generation had an orogen-wide extent, were broadly coeval with terminal continent-continent collision, and were locally immediately followed by rapid exhumation. Petrological studies in most regions point to lower crust and/or mantle magma sources with varying degrees of crustal assimilation. Associated intrusion-related Sn-W-Mo mineralization is not confined to particular compositional groups or tectonic terranes, suggesting a deep, more homogeneous metal source. We propose that the role of lithospheric delamination in the Canadian Appalachian Orogen be investigated further as a plausible mechanism for delivering metals from the mantle to the crust via granitoid melts.

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APPENDIX A

Devonian magmatic crystallization ages, Canadian Appalachians

All published magmatic crystallization ages used in this study are found in file POR-04_Appendix_A_Aug_28.xlsx. This Appendix has not been edited to Geological Survey of Canada specifications. The headings follow the format used in the Canadian Geochronology Knowledgebase (Canadian Geochronology Knowledgebase, 2017, Geological Survey of Canada, Earth Science Sector, Natural Resources Canada, https://atlas.gc.ca/geochron/en/). Age technique abbreviations are as follows: TIMS: thermal ionization mass spectrometry; SHRIMP: sensitive, high-resolution ion microprobe; LA-ICP-MS: laser-ablation inductively-coupled plasma mass spectrometry; EMP: electron microprobe. All references related to these ages are included in a separate worksheet.