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Fluid Transfer and Granite Magmatism: The Appinite Connection

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Cover Image: On the left is a close-up photo of euhedral, skeletal hornblende with plagioclase cores in a plagioclase groundmass from the shoreline exposure in the Greendale Appinite Complex, Nova Scotia. Photo credit: Donnelly Archibald.

GAC MEDALLIST SERIES

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Appinite Complexes, Granitoid Batholiths and Crustal Growth: A Conceptual Model

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SUMMARY

Appinite bodies are a suite of plutonic rocks, ranging from ultramafic to felsic in composition, that are characterized by idiomorphic hornblende as the dominant mafic mineral in all lithologies and by spectacularly diverse textures, including planar and linear magmatic fabrics, mafic pegmatites and widespread evidence of mingling between coeval mafic and felsic compositions. These features suggest crystallization from anomalously water-rich magma which, according to limited isotopic studies, has both mantle and meteoric components.

Appinite bodies typically occur as small (~2 km diameter) complexes emplaced along the periphery of granitoid plutons and commonly adjacent to major deep crustal faults, which they preferentially exploit during their ascent. Several studies emphasize the relationship between intrusion of appinite, granitoid plutonism and termination of subduction. However, recent geochronological data suggest a more long-lived genetic relationship between appinite and granitoid magma generation and subduction.

Appinite may represent aliquots of hydrous basaltic magma derived from variably fractionated mafic underplates that were originally emplaced during protracted subduction adjacent to the Moho, triggering generation of voluminous granitoid magma by partial melting in the overlying MASH zone. Hydrous mafic magma from this underplate may have ascended, accumulated, and differentiated at mid-to-upper crustal levels (ca. 3–6 kbar, 15 km depth) and crystallized under water-saturated conditions. The granitoid magma was emplaced in pulses when transient stresses activated favourably oriented structures which became conduits for magma transport. The ascent of late mafic magma, however, is impeded by the rheological barriers created by the structurally overlying granitoid magma bodies. Magma that forms appinite complexes evaded those rheological barriers because it preferentially exploited the deep crustal faults that bounded the plutonic system. In this scenario, appinite complexes may be a direct connection to the mafic underplate and so its most mafic components may provide insights into processes that generate granitoid batholiths and, more generally, into crustal growth in arc systems.

RÉSUMÉ

Les corps d'appinite sont une suite de roches plutoniques, de composition ultramafique à felsique, qui se caractérisent par de la hornblende idiomorphe comme minéral mafique dominant dans toutes les lithologies et par des textures spectaculairement diverses, y compris des fabriques magmatiques planaires et linéaires, des pegmatites mafiques et de nombreuses preuves de « mingling », mélange hétérogène, des compositions mafiques et felsiques de même âge. Ces caractéristiques suggèrent une cristallisation à partir d'un magma anormalement riche en eau qui, selon un nombre limité d'études isotopiques, possède à la fois des composants mantelliques et météoriques.

Les corps d'appinite se présentent généralement sous la forme de petits complexes (~ 2 km de diamètre) mis en place à la périphérie des plutons granitoïdes et généralement adja-

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cents aux principales failles crustales profondes qu'ils exploitent préférentiellement lors de leur ascension. Plusieurs études soulignent la relation entre l'intrusion d'appinite, le plutonisme granitoïde et l'arrêt de la subduction. Cependant, des données géochronologiques récentes suggèrent une relation génétique de plus longue durée entre la génération d'appinite et de de magma granitoïde et la subduction.

L'appinite peut représenter des aliquotes de magma basaltique hydraté dérivées de sous-plaques mafiques à fractionnement variable qui ont été initialement mises en place lors d'une subduction prolongée adjacente au Moho, déclenchant la génération de magma granitoïde volumineux par fusion partielle dans la zone MASH sus-jacente. Le magma mafique hydraté de cette sous-plaque peut avoir remonté et s'être accumulé et différencié à des niveaux crustaux moyens à supérieurs (environ 3 à 6 kbar, 15 km de profondeur) et avoir cristallisé dans des conditions de saturation en eau. Le magma granitoïde s'est mis en place par impulsions lorsque des contraintes transitoires ont activé des structures favorablement orientées qui sont devenues des conduits pour le transport du magma. L'ascension du magma mafique tardif, cependant, est entravée par les barrières rhéologiques créées par les corps magmatiques granitoïdes structurellement sus-jacents. Le magma qui forme des complexes d'appinite a échappé à ces barrières rhéologiques car il a exploité préférentiellement les failles crustales profondes qui délimitaient le système plutonique. Dans ce scénario, les complexes d'appinite peuvent être une connexion directe à la sous-plaque mafique et ainsi ses composants les plus mafiques peuvent fournir des informations sur les processus qui génèrent des batholites granitoïdes et, plus généralement, sur la croissance crustale dans les systèmes d'arc.

Traduit par la Traductrice

INTRODUCTION

Mafic magma bodies are under-represented compared to intermediate–felsic magmas in continental arc systems, which are typically dominated by composite granitoid batholiths that are the end-product of a sequence of subduction-related processes that transfer energy and mass from the mantle to the crust (e.g. Pearce et al. 1984; Pitcher 1997; Ducea 2001). Coeval mafic rocks exposed at the same structural level as the granitoid batholiths typically occur as small plutons (1–2 km in diameter) and syn-plutonic dykes that are peri-batholithic, i.e. preferentially located along the batholith periphery (Bowes and Wright 1967; Pitcher and Berger 1972; Ratcliffe et al. 1982; Fowler and Henney 1996; Pitcher 1997; Clarke et al. 1997). However, most internal domains of batholiths preserve field evidence of interaction between coeval granitoid and mafic magmas, such as the presence of mafic enclaves (e.g. Vernon 1984; Barbarin and Didier 1992; Clarke et al. 2000; Chen et al. 2018), as well as petrographic and geochemical evidence for processes such as mingling and mixing, which can produce rocks of intermediate compositions (e.g. Chappell 1996; Tate et al. 1997; Baxter and Feely 2002; Miller et al. 2009; Muir et al. 2014). These overall relationships imply a genetic linkage between the felsic–intermediate magmas that dominate the batholiths and coeval mafic magmas.

Appinite complexes are hornblende-rich plutonic rocks, predominantly mafic in composition, that typically occur as small bodies around the periphery of large, composite granitoid batholiths (Murphy 2013). Field relationships (e.g. Pitcher and Berger 1972) and geochronological studies (e.g. Archibald et al. 2021) indicate emplacement of appinite bodies and granitoid batholiths are broadly coeval. Their hornblende-rich mineralogy, together with their spectacularly diverse array of textures, even on a hand-specimen scale, suggests crystallization from anomalously water-rich magma (e.g. Pitcher and Berger 1972; Bowes and McArthur 1976; Pitcher and Hutton 2003; Murphy 2013, 2020). Although data are very limited, recently published O- and H-isotope data from magnesio-hornblende in an appinite body (Greendale Complex, Nova Scotia, Canada) identified a mantle component to the water incorporated in the hornblende crystal structure of mafic–ultramafic appinite (Cawood et al. 2021), suggesting a connection to the mantle processes that may have stimulated the generation of coeval granitoid magma. However, the potential importance of appinite in understanding the origin of batholiths in continental arcs (and by implication, the generation of continental crust) is often overlooked, possibly because of its subordinate volume relative to the adjacent batholith.

The tectonic setting of appinite emplacement has been largely inferred from regional studies which have emphasized the close spatial and temporal association between intrusion of appinite complexes and termination of subduction following accretional or collisional orogenesis (Atherton and Ghani 2002; Neilson et al. 2009; Granja Dorilêo Leite et al. 2021; Yuan et al. 2022). Such studies imply that appinite may be an important indicator of the tectonic processes responsible for the generation of granitoid batholiths, and by implication, the crustal growth which primarily occurs in continental arc environments (Cawood et al. 2013; Hawkesworth et al. 2013).

The purpose of this article is to highlight the potential genetic connection between appinite suite rocks and mantle-derived mafic magmas that underplate the crust and trigger the formation of granitoid magma. We also review recent geochronological evidence that the relationship between appinitic and granitoid magmas may have initiated during the subduction cycle and so may be of longer duration than hitherto realized, thereby constraining the tectonic setting of both magma generation in the lower crust and its subsequent emplacement in mid-to-shallow crustal levels.

GEOLOGICAL CONTEXT

Arc granitoid rocks commonly occur as trans-crustal composite batholiths that reflect transport of magma from the mantle and lower crust in incremental batches over timescales ranging from thousands to tens of millions of years (Petford et al. 1993, 2000; Paterson and Vernon 1995; Pitcher 1997; Glazner et al. 2004; Miller et al. 2007; Clemens and Stevens 2012; Schoene et al. 2012; Miles and Woodcock 2016; Schaltegger et al. 2019; Smith et al. 2019; Collins et al. 2020, 2021; Archibald

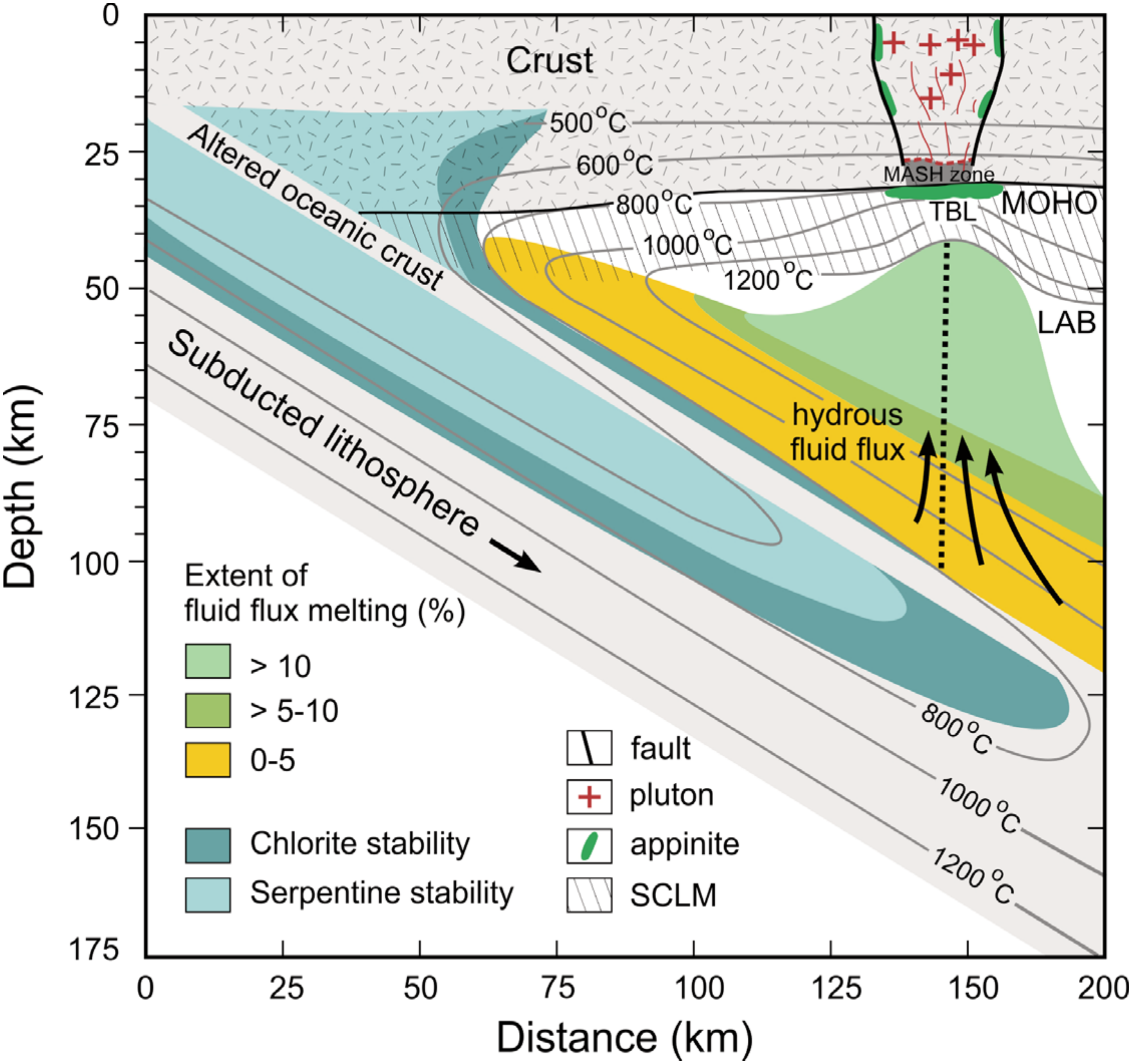

Figure 1. Concentration of arc magma bodies above a zone of fluid flux melting of mantle lithosphere and mafic underplating beneath the Moho (based on Hyndman et al. 2005; Weaver et al. 2011; Grove et al. 2012; Collins et al. 2020). Hydrous fluxing from the subducting slab metasomatizes the lithospheric mantle and results in the generation of water-rich mafic magmas which underplate the Moho. As they cool and fractionate, they exsolve water which initiates melting in the overlying (MASH zone) crust (diagram modified after Grove et al. 2012; Collins et al. 2020). Appinite intrusions preferentially occur along or adjacent to major deep crustal faults that bound the plutonic system. The evolution of the region above the MASH zone is expanded in Figure 4. MASH, Melting, Assimilation, Silicification, Hybridization; LAB, Lithosphere–Asthenosphere Boundary; SCLM, Subcontinental Lithospheric Mantle; TBL, Thermal Boundary Layer.

et al. 2021; Bickerton et al. 2022). A wealth of experimental, theoretical and geochemical studies indicates these processes occur during ongoing subduction by (i) melting of a lithospheric mantle wedge metasomatized by hydrous fluids and by silicic melts rising from the subducting slab and (ii) melting reactions in the subducted slab and its carapace of sedimentary rocks at depths between 100 and 150 km (e.g. Spandler and Pirard 2013; Zhu et al. 2021).

Although the details are controversial, melting of the metasomatized mantle wedge produces hydrous to super-hydrous (> 8 wt.% H_2O) mafic magmas that rise and congregate in the vicinity of the mantle–crust boundary (Fig. 1) where they underplate, assimilate and mix with overlying continental crust (e.g. Hildreth and Moorbath 1988; Castro 2020; Collins et al. 2020, 2021). A combination of magma, heat and fluids emanating from this mafic underplate generates a crustal regime above the underplate dominated by melting, assimilation, storage and homogenization, known as a MASH zone (Hildreth and Moorbath 1988; Annen et al. 2006). Geophysical data beneath modern arcs indicate that (i) such MASH zones typically occur at depths of ~25–30 km beneath magmatic arcs (Whitney 1988; Daczko et al. 2002; Miller et al. 2009), (ii) may be hydrous to super-hydrous (> 8 wt.% H_2O) (e.g. Bedrosian et al. 2018; Gavrilenko et al. 2019; Müntener et al. 2021) and (iii) are commonly overlain, at mid-crustal levels (ca. 6 kbar), by H_2O-rich (up to 10 wt.%) magma which stalls at these depths due to a combination of decompression-induced crystallization and fractionation, which increases magma viscosity (Laumonier et al. 2017). Exsolution of fluids as a result of water-saturation raises the solidus temperature and so induces rapid crystallization.

MASH zones are viewed as sites where granitoid magmas originate and gestate, prior to their emplacement as composite batholiths in middle-to-upper crust (Annen et al. 2006; Jackson et al. 2018). Precise U–Pb geochronological studies indicate that gestation may be up to 20 m.y. in duration (e.g. Memeti et al. 2010; Schoene et al. 2012; Miles and Woodcock 2016; Schaltegger et al. 2019; Archibald et al. 2021; Bickerton et al. 2022). The transition from gestation to emplacement is likely triggered by a range of variables, including changes in tectonic setting (e.g. Ringwood et al. 2021) that either initiate or reactivate favourably oriented crustal structures which then become conduits for magma transport (e.g. Vigneresse 1995; Cruden 1998; Petford et al. 2000; Archibald et al. 2021).

Models to explain the generation of the felsic magmas that dominate granitoid batholiths generally fall into three end-member categories, though they are not mutually exclusive: (i) fractionation of a mafic parent (e.g. Fowler et al. 2001, 2008; Lee and Bachmann 2014; Jagoutz and Klein 2018; Müntener and Ulmer 2018; Ulmer et al. 2018; Granja Dorilêo Leite et al. 2021), (ii) relatively low temperature (< 850°C) water-fluxed partial melting of lower crust induced by heat and fluids rising from the mafic underplate (Castro 2020; Collins et al. 2020, 2021), and (iii) fluid-absent partial melting of lower crustal rocks at higher temperatures (≥ 850°C; Thompson 1982; Clemens 1998; Brown 2007).

Fractionation and water-fluxed models both require mafic magma to be more voluminous at depth than is represented at the crustal level of batholith emplacement. Exposed trans-crustal arc sections (e.g. Sierra Nevada and Woolley Creek batholiths, California, Ague 1997, Saleeby et al. 2003, Barnes et al. 2016; Fiordland, New Zealand, Dazcko et al. 2002; Sierra Valle Fertil complex, Argentina, Walker et al. 2015) are characterized by lower crustal mafic rocks and ultramafic cumulates, which likely represent vestiges of the mafic underplate. In the fluid-absent model, water is provided only from the breakdown of hydrous minerals and the process is also known as dehydration melting (e.g. Thompson 1982) or hydrate-breakdown melting (Brown 2007). As recent geochronological studies have shown that many granitoid batholiths are assembled episodically over tens of millions of years (Miles and Woodcock 2018; Clemens et al. 2020; Archibald et al. 2021; Bickerton et al. 2022), these models should be considered end-members in a scenario in which water activity in the source rocks can vary over time within an evolving tectonic setting (Collins et al. 2021).

Characteristics of the Appinite Suite

Appinite suite rocks (see Murphy 2013, 2020 for details) were first defined in the Scottish Highlands (Bailey and Maufe 1916) as the plutonic equivalent of lamprophyre, with which they are commonly spatially and temporally associated. Although predominantly mafic, the appinite suite ranges from ultramafic to felsic in composition. The suite's unifying characteristics include (i) idiomorphic hornblende as the dominant mafic mineral in ultramafic to felsic rocks, and (ii) a spectacularly diverse array of textures, even on a hand-specimen scale, varying from coarse mafic pegmatite to fine grained "salt-and-pepper" hornblende gabbro and diorite (Fig. 2).

Ultramafic rocks have affinities with lamprophyre intrusions, and on IUGS classifications range from hornblendite to olivine–pyroxene hornblendite to hornblende peridotite. Volumetrically dominant mafic to intermediate rocks have a simple mineralogy (hornblende, plagioclase) and are classified as hornblende gabbro and hornblende diorite, respectively. Despite their mineralogical simplicity, geochemical analyses indicate that mafic to intermediate rocks range from high-K shoshonitic to low-K calcalkaline compositions. Intriguingly, high-K shoshonitic rocks are associated with high-K, Ba–Sr rich granite with adakitic affinities whereas granite associated with low-K calc-alkaline mafic compositions are also low-K calc-alkaline, implying a genetic relationship between coeval mafic and felsic compositions (Murphy 2020; Archibald and Murphy 2021; Archibald et al. 2022).

Taken together, these mineralogical and textural features suggest appinite bodies crystallize from anomalously water-rich mafic magma (e.g. Bowes and Wright 1967; Pitcher and Berger 1972; Pitcher and Hutton 2003) in which the stability field of hornblende is expanded relative to olivine, pyroxene and plagioclase (Moore and Carmichael 1998; Grove et al. 2003; Krawczynski et al. 2012; Loucks 2014; Fig. 3). The low viscosity of water-rich mafic magma promotes the local growth of pegmatitic textures dominated by hornblende with subordinate biotite (Fig. 2; Murphy 2013).

In addition to their peri-batholithic location, appinite bodies also preferentially occur adjacent to major fault zones, which act as conduits that facilitate their ascent to higher structural levels (Hutton 1988; Murphy and Hynes 1990; Rogers and Dunning 1991). Appinitic rocks also occur within subhorizontal mafic sheeted complexes interlayered with migmatite at the base of some plutons, which can be interpreted as active extensional detachments (Richards and Collins 2004). In some complexes, appinite bodies also exhibit locally developed planar and linear fabrics (e.g. Murphy and Hynes 1990). The subvertical planar fabrics reflect multiple cycles of magma injection and crystallization along the extensional plane of the

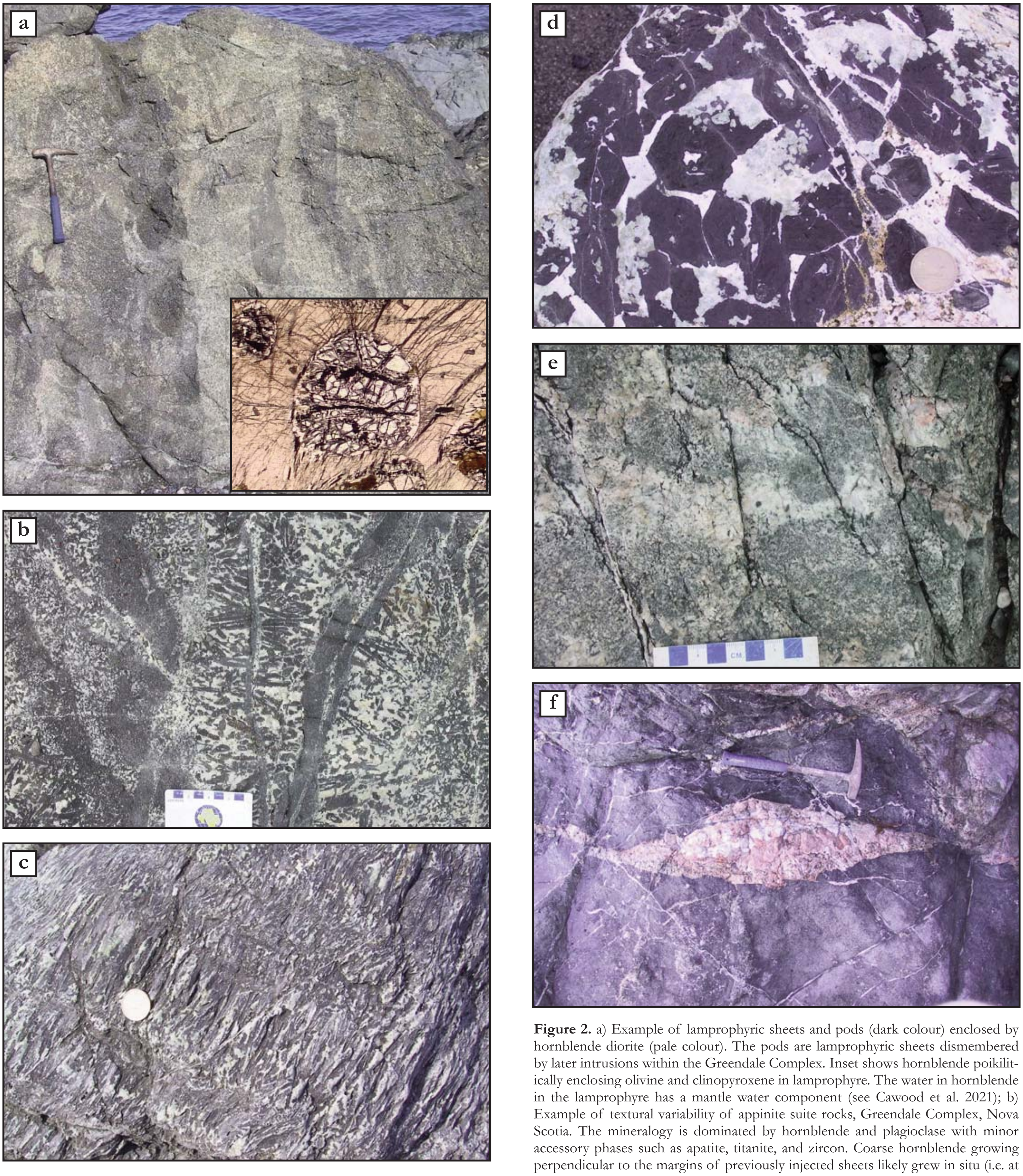

Figure 2. a) Example of lamprophyric sheets and pods (dark colour) enclosed by hornblende diorite (pale colour). The pods are lamprophyric sheets dismembered by later intrusions within the Greendale Complex. Inset shows hornblende poikilitically enclosing olivine and clinopyroxene in lamprophyre. The water in hornblende in the lamprophyre has a mantle water component (see Cawood et al. 2021); b) Example of textural variability of appinite suite rocks, Greendale Complex, Nova Scotia. The mineralogy is dominated by hornblende and plagioclase with minor accessory phases such as apatite, titanite, and zircon. Coarse hornblende growing perpendicular to the margins of previously injected sheets likely grew in situ (i.e. at the depth of emplacement of the Greendale Complex). The Al content of the finer grained hornblende indicates it grew at depth and was entrained in the magma as it ascended; c) Example of layering with "stacked log" hornblende growing perpendicular to the layer margins, indicating dilation during emplacement (see Murphy and Hynes 1990); d) Mafic pegmatite, dominated by idiomorphic and zoned hornblende, plagioclase, in a groundmass of hornblende, plagioclase ± quartz ± K-feldspar; e) example of mingling between coeval mafic and felsic phases; f) Example of structural control on the intrusion of felsic magma within a local "pull-apart" structure. Note the pegmatitic texture.

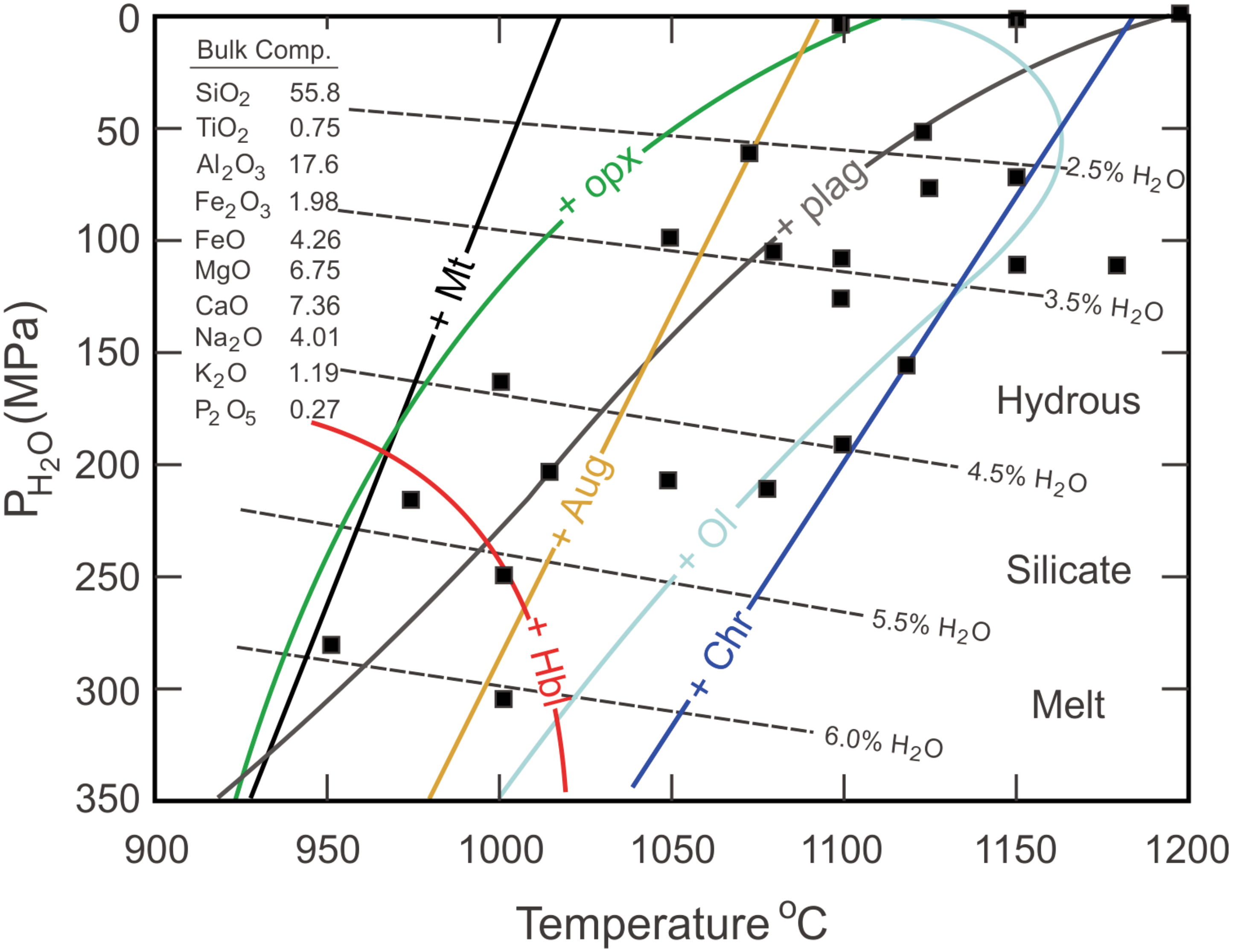

Figure 3. Summary diagram (after Loucks 2014) showing the effect of dissolved wt.% H_2O (grey contours) on the sequence of crystallization from an andesite melt in the upper crust (composition, upper left). Each black square represents experimental results of Moore and Carmichael (1998), in which the mineral products were identified and the dissolved H_2O was determined from quenched glass. The diagram highlights the dramatic change in the sequence of crystallization with increasing dissolved H_2O, especially affecting hornblende and plagioclase, the two dominant minerals in mafic appinite.

instantaneous strain ellipsoid associated with strike-slip motion on the bounding faults during their emplacement. The linear fabrics range from orientations perpendicular to planar fabrics, consistent with extension during magma emplacement, to orientations parallel to planar fabrics, where hornblende was entrained by magma flow.

Tectonic Setting

Several studies have emphasized the close spatial and temporal association between intrusion of appinite complexes and termination of subduction (Atherton and Ghani 2002; Neilson et al. 2009; Granja Dorilêo Leite et al. 2021; Yuan et al. 2022). These interpretations are largely based on regional syntheses in which a combination of field observations and geochronological studies indicate that emplacement of appinite complexes occurred either late- or after collision-related deformation. For example, according to Atherton and Ghani (2002), appinite emplacement occurred in the aftermath of the ca. 430–420 Ma closure of the Iapetus oceanic tract by collision between Ganderia–Avalonia and Laurentia. In this scenario, subduction of Laurentia continental crust following collision-initiated slab break-off with asthenospheric upwelling advecting heat and causing melting in the overlying mantle lithosphere which produced a mafic underplate. When the slab is detached and sinks into the mantle, rapid uplift occurs and high temperatures cause partial melting of the underplate to form granitic magma, which is emplaced in the upper crust. Similarly, appinite and coeval Ba–Sr granite of the West Kunlun orogen (northwestern margin of Tibetan Plateau; Ye et al. 2008) were emplaced during slab break-off after ca. 440 Ma closure of the Proto-Tethys Ocean (Wang et al. 2014). The advent of discrimination diagrams that identify "slab failure" granite plu-

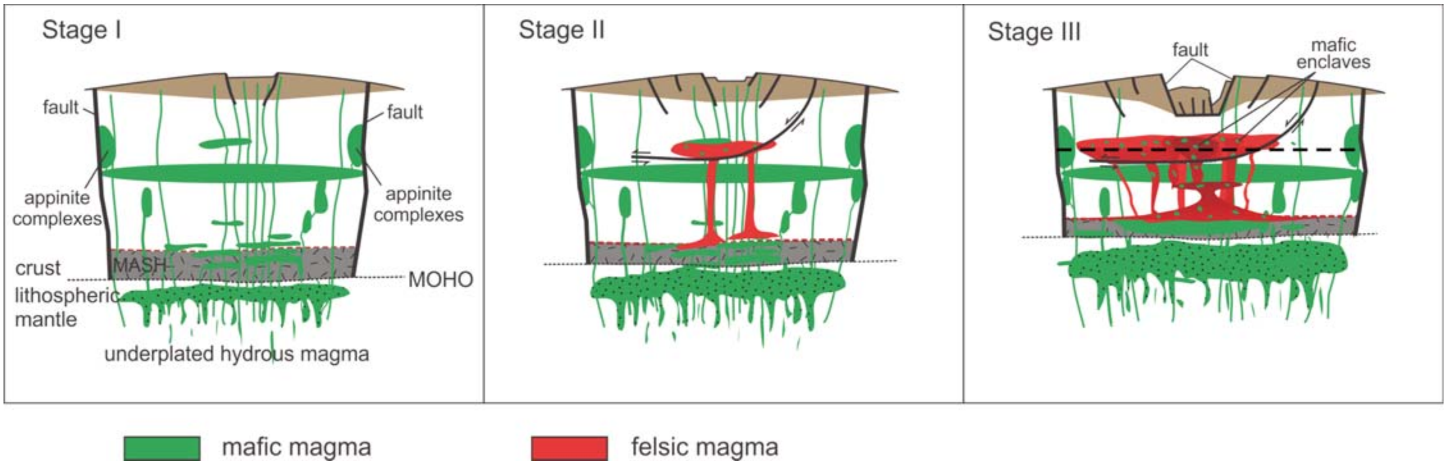

Figure 4. Conceptual model explaining the peri-batholithic position of appinite complexes relative to granitoid batholiths and the mafic underplate in a transtensional setting (note increasing horizontal distance between faults from stages I to III). Appinite complexes are preferentially located adjacent to deep crustal faults. Stage I. Early phase of hydrous mafic magmatism includes the formation of the mafic underplate, which becomes part of the crust. Magmas are derived from metasomatized spinel- or garnet-bearing lithospheric mantle, or asthenospheric mantle. Magma derived from melting of spinel lherzolite mantle predominantly has low-K calc-alkalic affinity. Magma derived from garnet lherzolite has shoshonitic affinity. Stage II. Felsic magma masses form by fractionation of a mafic parent, by anatexis (fluid flux melting) of the lower crust and/or by melting of the mafic underplate. Felsic magma rises to the mid- and upper crust where it can become (i) neutrally buoyant, (ii) impeded by resistant lithologies, (iii) water-saturated, or (iv) trapped in extensional decollement structures that provide accommodation space for repeated injections of magma (e.g. Richards and Collins 2004). Stage III. Felsic magma bodies spread out laterally forming a rheological barrier that impedes the subsequent rise of mafic magma. Early mafic intrusions are entrained as enclaves or are hybridized. Only the appinite bodies intruding along the periphery of the system are preserved intact. The long-dashed line in Stage III shows the typical exposure level of the batholiths and appinite complexes. The short-dashed line is the Moho. Scheme modified from Hildreth and Moorbath (1988), Richard and Collins (2004) and Murphy (2020).

tons (Hildebrand and Whalen 2017; Hildebrand et al. 2018) supports models in which significant volumes of granitoid and related appinitic plutonism are late- to post-tectonic and related to slab failure (e.g. Archibald and Murphy 2021).

However, recent studies that determined the precise crystallization age of the appinite, as well as the ages of antecrysts in the coeval batholiths, suggest the association between appinite and granitoid batholiths was more long-lived, and initiated during subduction that preceded slab-breakoff. For example, recent age data show that mafic and felsic magma generation associated with the Donegal Composite Batholith and adjacent appinite intrusions (NW Ireland) overlapped for at least 15 m.y. (ca. 431–416 Ma, Murphy et al. 2019; Archibald et al. 2021). Similarly, in Avalonia of northern Nova Scotia, late Neoproterozoic emplacement of appinite and granitoid plutons overlapped for about 30 m.y. (ca. 632–602 Ma; Keppie et al. 1990; Pe-Piper et al. 1996, 2010; Murphy et al. 1997a, b; Pe-Piper and Piper 2018; White et al. 2021, 2022).

These age relationships suggest that the parental magma for appinite, like that for granite, may gestate near the base of the crust or uppermost mantle for up to 20 m.y., and that emplacement at middle to upper crustal levels occurs in specific time intervals when transient stresses act on favourably oriented structures (Archibald et al. 2021). In this context, slab failure and associated asthenospheric upwelling may provide the final impetus of energy and mass transfer from the mantle to the crust but the apparent temporal association of magmatism with subduction termination may be because the latest appinite intrusions are the best preserved.

In summary, granitoid batholiths and coeval peri-batholithic mafic intrusions are the end-product of magma bodies produced throughout subduction. If so, interpretations that relate appinite magma genesis solely to subduction termination are an artefact of preservation potential within this dynamic and evolving magmatic system. Compositions representative of the mafic underplate that triggered granitoid magma formation may be preserved in specific regimes within appinite complexes whose emplacement spans the longevity of arc magmatism.

CONCEPTUAL MODEL FOR COEVAL APPINITE SUITE AND GRANITOID COMPLEXES

Recent high spatial resolution geochronological studies of both antecrystic and autocrystic zircon domains in granitoid batholiths have documented that (i) subduction beneath continental arcs generates granitoid magma continuously over millions of years, and (ii) batholiths are composite bodies constructed incrementally and in discrete time intervals when magma is transported from the lower crustal MASH zone and emplaced episodically in the middle or upper crust (see Glazner et al. 2004; Miles and Woodcock 2018; Archibald et al. 2021; Bickerton et al. 2022 and references therein). As emplacement is likely facilitated by transient stresses that reactivate brittle structures (Pitcher 1997; Cruden 1998), many composite batholiths are bounded by major, deeply penetrating crustal faults. These studies imply underplating of similar longevity for processes that trigger the formation of granitoid magma, i.e. the repeated intrusion into the lower crust by H_2O-rich mafic magmas (Fig. 4), an interpretation supported by field evidence and geochronological studies (e.g. Archibald et al. 2021). Recent petrological studies show that mafic arc magmas near the base of the crust in Kamchatka (1100–1050°C, 25–30 km depth) were “super-hydrous”, containing up to 14 wt.% H_2O (Goltz et al. 2020). Modeling shows that (i) this hydrous mafic underplate solidifies as hornblende gabbro with a pyroxenitic residue and (ii) as each successive underplate cools, the emanating heat and exsolved fluids trigger fluid-fluxed crustal melting that characterizes the overlying MASH zone (Collins et al. 2020).

Felsic magma, formed by a combination of fluid-fluxed melting and fractionation of the cooling mafic underplate, eventually rises to a crustal level where it either becomes neutrally buoyant, is impeded by resistant lithologies, is water-saturated, or becomes trapped in active subhorizontal decollements whose motion provides the accommodation space for repeated injections of magma (e.g. Richards and Collins 2004; Fig. 4). At this juncture, the felsic magma migrates laterally, thereby forming a rheological barrier that impedes the subsequent rise of mafic magma above the same structural level, except along the periphery where mafic magma can exploit the crustal faults that bound the system.

Early mafic magma masses from the underplate that intrude the crust are likely to accumulate and differentiate at mid-crustal levels (ca. 3–6 kbar, 10–18 km depth). At such depths, ascending hydrous magma becomes water-saturated, which induces crystallization, and the resulting increase in viscosity inhibits further ascent (Laumonier et al. 2017). More generally, mafic magma masses that intrude early in this evolutionary history would have been engulfed by the subsequent emplacement of voluminous felsic magma, especially if such emplacement preferentially occurred where motion on active faults provide accommodation space (e.g. local extensional, transtensional or pull-apart regimes, Fig. 4). Early infusions of magma from the mafic underplate therefore have low preservation potential, occurring only as mafic xenoliths or enclaves, or possibly as one end-member of intermediate (andesitic) magmas that reflect two-stage hybridization with felsic magma at various crustal levels (e.g. Muir et al. 2014; Li et al. 2021).

Later mafic infusions into granitic magma would also have low preservation potential. Their vestiges typically occur as enclaves (e.g. pillows) and distended syn-plutonic dykes that exhibit visible evidence of magma mingling and limited evidence of mixing, resulting in rocks with intermediate compositions (Collins et al. 2000; Chen et al. 2018). As the granite solidifies beyond the particle locking threshold (~72–75% solidification, Vigneresse et al. 1996), the latest mafic intrusions may be preserved as discrete syn- to late-plutonic dykes ranging from diabase to lamprophyre in composition.

In this overall scenario, appinite bodies may represent aliquots of hydrous basaltic magma derived from a variably fractionated mafic underplate that preferentially exploited either faults located along the periphery of the magmatic system, or late-stage fractures within the essentially solidified granitic crystal mush. Their peri-batholithic location implies that the appinite magma had more limited interaction with coeval granitoid magma and so appinite complexes, preferentially emplaced along faults which define the periphery of the system, may develop as the hydrous magma decompresses and fractionates upon ascent (e.g. McCarthy and Müntener 2016). This interpretation is supported by recent $\delta^{18}O$ and δD isotopic studies of hornblende in ultramafic appinite of the Neoproterozoic Greendale Complex, Nova Scotia (Cawood et al. 2021), which imply growth of a generation of hornblende from magma with a significant component of mantle-derived water ($\delta^{18}O$, 4.7–6.8‰; $\delta D < -90$‰). This generation of hornblende preferentially occurs in lamprophyric sheets and pods (sheets dismembered by later intrusions) within the complex where they poikilitically enclose olivine and clinopyroxene.

Although a study of the aureole of the Greendale Complex indicates emplacement at 3–5 kbar (Abad et al. 2011), hornblende with mantle water isotopic signatures has an Al content (e.g. high total Al, high Al^{iv}) consistent with crystallization between 5 and 8 kbar (Murphy et al. 2012; Pe-Piper and Piper 2018; Murphy 2020; Cawood et al. 2021). More generally, experiments suggest crystallization conditions of at least 1000°C at $P > 6$ kbar for the beginning of hornblende crystallization under water-saturated conditions (Krawczynski et al. 2012). Such depths imply water contents of ~10 wt.% or greater for such mid- to lower crustal appinitic magma (Krawczynski et al. 2012). Isotopic data imply that mantle water dissolved in the magma was captured by growing hornblende which was then entrained and transported by mafic magma to shallower crustal levels by exploiting the Hollow–Greendale fault system. On the other hand, hornblende in mafic to intermediate appinite, including grains that grew in situ across the vein walls and those that exhibit exquisite porphyritic textures, have $\delta^{18}O$ (0.9 to 4.6‰) and δD (−106 to −64‰) indicating mantle water became mixed with meteoric fluids as the magma ascended. This mixing could be explained by assimilation of rocks that had previously been altered by meteoric fluids but is also compatible with recent studies (e.g. Bindeman et al. 2008; Diamond et al. 2018) of active geothermal systems that imply meteoric water can penetrate along deeply penetrating crustal faults to depths of at least 9 km where these faults are involved in seismic events. The textures indicate rapid growth of hornblende and plagioclase, and suggest the magma was likely water-saturated, implying water contents between 7 and 10 wt.% H_2O (Müntener et al. 2021).

DISCUSSION

The origin of arc-related granitic batholiths and their genetic relationship with coeval mafic magma bodies is an enduring controversy in geology. Irrespective of whether coeval mafic magmatism is primarily a source of heat and/or fluids for crustal anatexis, or is a parental magma guiding crystal fractionation, a common factor is that these models each require more voluminous mafic magma underplated at depth than is reflected by the comparatively minor volume typically exposed at the crustal level of the batholiths. Indeed, seismic reflection data beneath the Scottish Caledonides, where appinite was originally defined, are interpreted to represent invasion of the lower crust by voluminous mafic magma (Hynes and Snyder 1995). Similarly, seismic data of the crust beneath the Taupo Volcanic Zone, New Zealand, a region of voluminous rhyolitic eruptions with one of the highest heat flow zones on Earth, are consistent with voluminous mafic intrusions and/or underplated mafic crust at depths between 16 and 30 km (Harrison and White 2006). As such underplated material is predominantly mafic in composition, it becomes part of the crust and so represents the transfer of mass from the mantle to the crust, implying the processes involved are important in understanding mechanisms of crustal growth.

Mafic and felsic magmas produced continuously during protracted, steady-state, subduction congregate and gestate near the Moho. Although magma production is semi-continuous, magma emplacement in the middle or upper crust is episodic, and occurs during favourable changes to the stress regime within the crust (e.g. Miles and Woodcock 2018) and/or build-up of fluid pressure (Karlstrom et al. 2010). Such episodes may reflect any number of discrete tectonic events (e.g. slab roll-back, terrane accretion, oceanic plateau subduction, slab failure) that either modify the subduction zone geometry or terminate subduction. According to geodynamic models (e.g. Currie et al. 2004), the back arc region of continental arcs is anomalously hot because of small-scale asthenospheric convection driven by the reduction in mantle viscosity, which reflects the influx of water derived from the dehydrating subducting slab (Hyndman 2015). In that scenario, mafic magma can be generated in both the lithospheric and asthenospheric mantle, especially the mantle wedge, and so may exhibit a wide range in radiogenic isotopic compositions.

The dominance of felsic relative to mafic rocks at mid-crustal levels may be because felsic magma forms a rheological barrier impeding the ascent of the mafic magmatic underplate, except along the deeply penetrating faults that bound the system where dyke complexes comprised of appinite and coeval lamprophyre bodies preferentially occur (Fig. 4). As such, although their composition may be modified during their ascent, appinite complexes (especially their most mafic components) may provide a window into the composition of the mafic underplate in arc systems (Cawood et al. 2021).

Despite their mineralogical simplicity, geochemical analyses of appinite complexes indicate that mafic to intermediate rocks vary from high-K shoshonitic to low-K calc-alkaline compositions. This contrasting geochemistry likely reflects differences in the volume and composition of subduction-derived fluids and melts that contaminated the lithospheric mantle source as well as the greater depth of shoshonitic magma formation compared to low-K calc-alkaline (garnet lherzolite and spinel lherzolite mantle sources, respectively) (e.g. Peate et al. 1997; Scarrow et al. 2008; Müller and Groves 2019).

Geochemical data are consistent with a genetic connection between mafic and felsic magmas. For example, in the Scottish and Irish Caledonides, high-K shoshonitic appinite bodies are associated with Ba–Sr rich syenite and granite with adakitic affinities to the north of the Great Glen Fault, whereas appinite and coeval granite plutons have low-K calc-alkaline compositions to the south of the Great Glen Fault (Archibald et al. 2022). Although they share similar depletions in HREE and HFS elements (e.g. Ta, Nb, Ti), suggesting mafic melt generation in the garnet peridotite stability field (> 70 km depth), the high Ba–Sr granite suites contrast with low-K calc alkalic granite suites in that they are strongly LREE enriched, and lack a significant Eu anomaly. However, the origins of each of these suites are controversial in their own right. According to fractionation models (Fowler and Henney 1996; Fowler et al. 2001, 2008), the high Ba–Sr syenite and granitoid compositions reflect 50% fractionation of olivine, calcic clinopyroxene, biotite, apatite and titanite from a mafic parent. The mafic magmas were themselves formed by melting of a mantle wedge metasomatized by Ba–Sr rich fluids and melts derived from subducted sedimentary rocks (Fowler et al. 2008). The high Ba and Sr contents, together with the lack of a Eu anomaly in both mafic and felsic rocks, is consistent with experimental studies indicating hydrous arc magmas are characterized by a delay in plagioclase crystallization relative to olivine, clinopyroxene and hornblende (Fig. 3; Blatter et al. 2013; Loucks 2014; Nandedkar et al. 2014; Yanagida et al. 2018). Indeed, water-saturated experiments on primitive high magnesian andesite suggest plagioclase crystallizes only at 3–4 kbar and 950°C (Krawczynski et al. 2012), which explains the high Ba–Sr contents with no Eu anomaly of many lamprophyric rocks. The high LREE/HREE signatures require melting occurred at > 1 GPa in the garnet stability field (see below).

The geochemical variability of appinite also may reflect the depth and extent of partial melting as well as composition of the lithospheric mantle source of the mafic underplate. Appinite bodies with shoshonitic tendencies are highly enriched in LREE relative to HREE, reflecting low-degree melting of a deep (> 2 GPa) garnet lherzolite lithospheric mantle source. In addition, subduction-induced metasomatism produces domains in the lithospheric mantle wedge that are enriched in volatile-bearing phases, such as amphibole and phlogopite, which renders those domains more susceptible to melting (e.g. Francis and Ludden 1990; Scarrow et al. 2008; Ghent et al. 2019). Mantle domains anomalously enriched in phlogopite may in turn reflect metasomatism by K-rich fluids and felsic melts produced by dehydration and/or melting of subducted K-rich protoliths (e.g. pelite; Mallik et al. 2015). Usually, enrichment at these depths occurs because the K- and other LILE-components are retained in phengite, which destabilizes at much greater depth than amphibole (e.g. Spandler and Pirard 2012). Melting of a metasomatized garnet lherzolite mantle at depths > 70 km would produce residual garnet and yield a K- and LREE-enriched magma and, hence, a mafic underplate with a shoshonitic composition. On the other hand, experiments by Codillo et al. (2018) showed that melting of a spinel lherzolite mantle contaminated by fluid, melt or buoyant diapirs derived from a serpentinite-dominated oceanic lithosphere or subducted mélange, can generate magma of both tholeiitic and low-K calc-alkaline affinities at depths less than 70 km.

CONCLUSION

Appinite complexes may represent aliquots of hydrous magmas derived from the mafic underplate that are preferentially emplaced into deep crustal faults along the periphery of coeval granitoid complexes. If so, detailed geochemical and isotopic studies of appinite complexes, especially their most mafic components, may provide insights into the mantle and subduction dynamics, water content, and conditions of mafic melt generation responsible for continental growth and the generation of composite granitoid batholiths.

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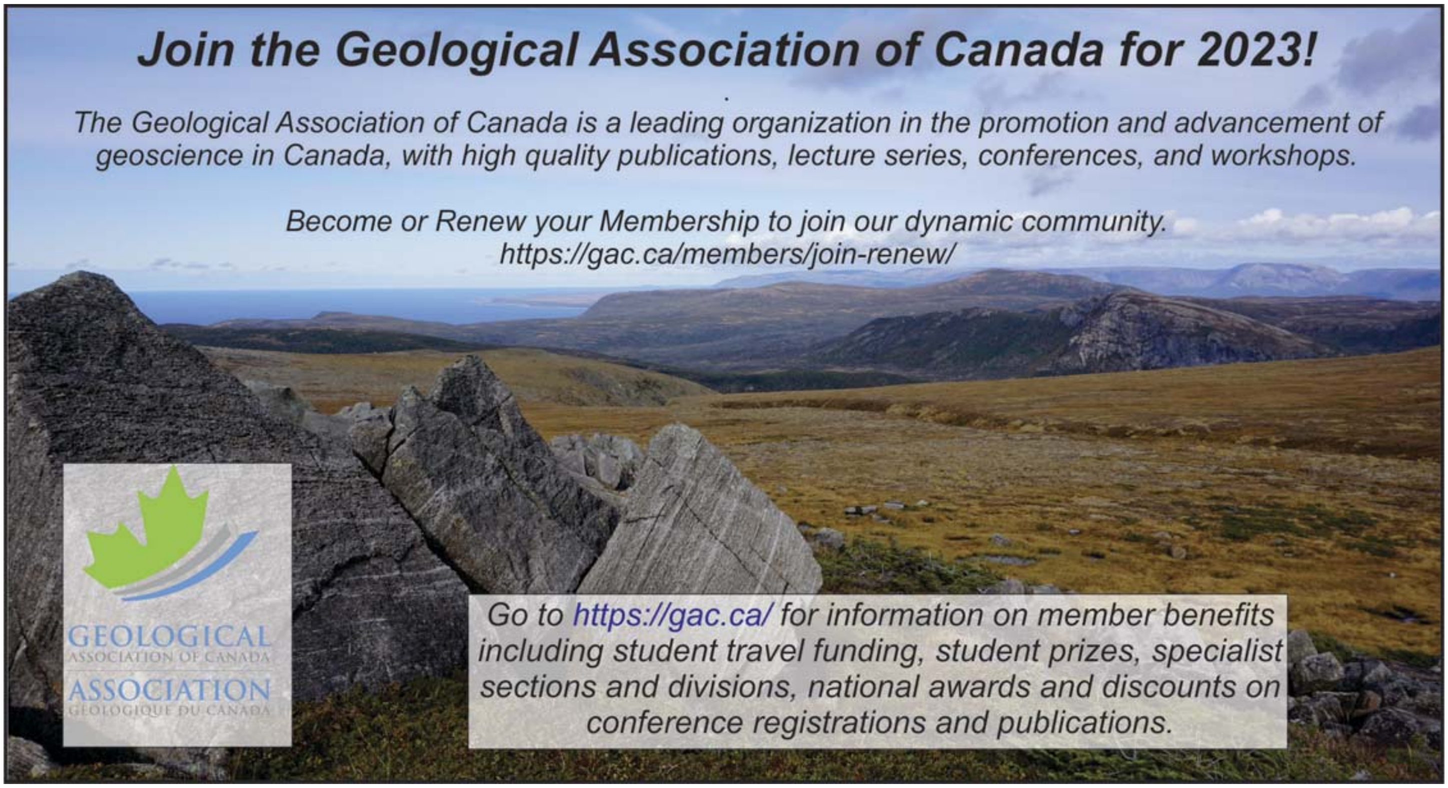

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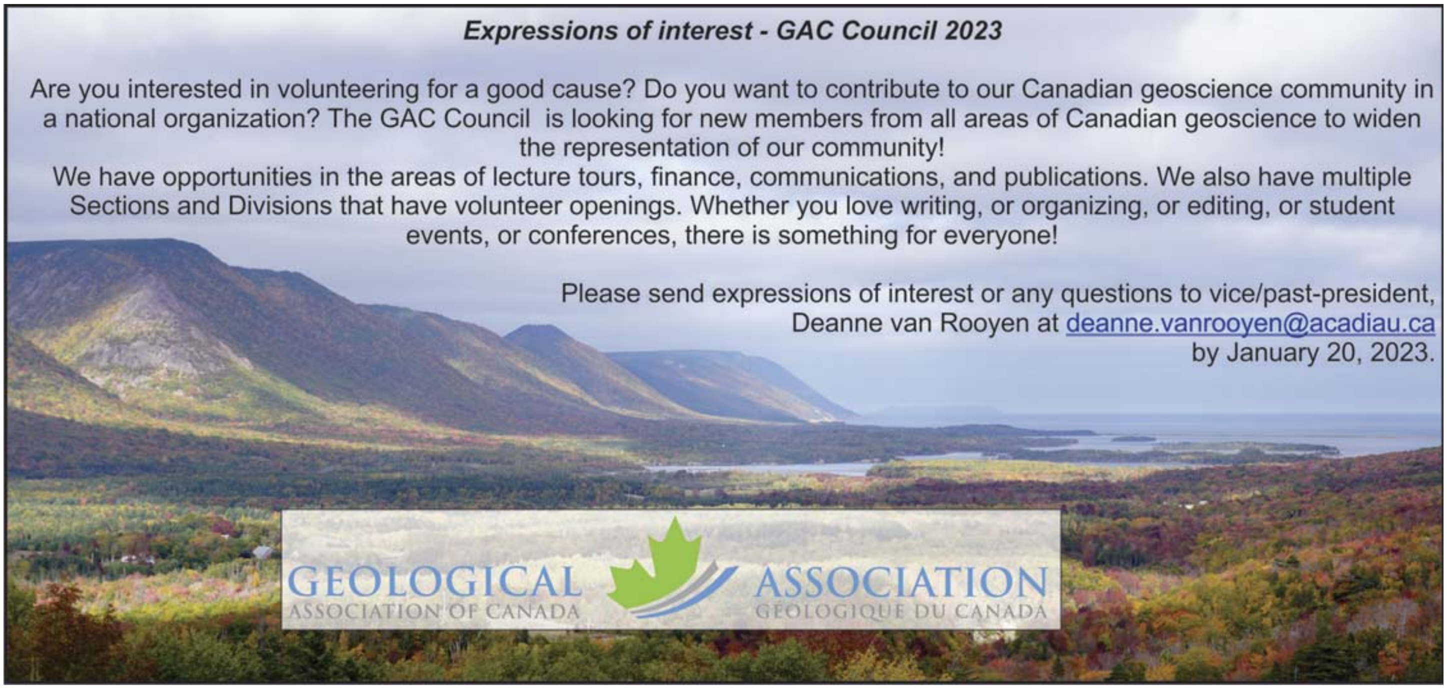

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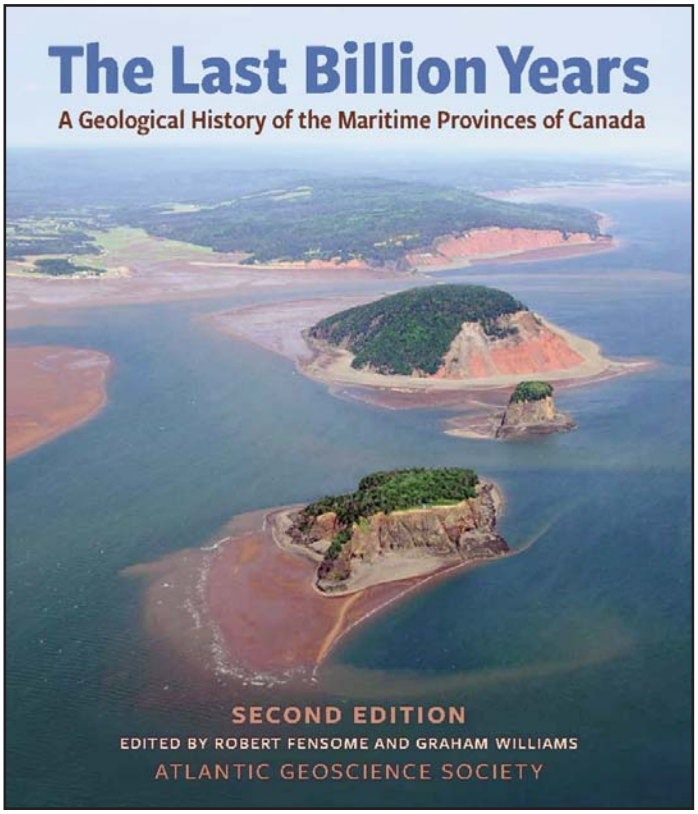
REVIEW



The Last Billion Years: A Geological History of the Maritime Provinces of Canada

Robert Fensome and Graham Williams (editors)

Co-Published by: Nimbus Publishing Limited and the Atlantic Geoscience Society
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Reviewed by Tracy Webb
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The much-anticipated second edition has arrived, just in time for its grand unveiling at the GAC-MAC-IAH-CNC-CSPG conference recently held in Halifax, Nova Scotia, in May 2022. A wonderfully informative book, it covers the intriguing geological history of New Brunswick, Nova Scotia, and Prince Edward Island. These provinces are recognized also as the traditional unceded territory of the Wolastoqiyik (Maliseet) and the Mi'kmaw Peoples. This book is intended to enhance the understanding of the geological development and evolution of the Maritime Provinces for all readers, whether the reader has a formal background in the earth sciences, or is generally interested about the land around them, and how it has changed.

Over the past two decades since the first edition was published, new technologies have enabled geologists to collect more data, and further develop the stories captured in the rocks and new fossil discoveries. These stories create a more comprehensive understanding of what has happened over time – in millions and billions of years! To set the stage for exploring these stories, the authors have divided the book into chapters that describe aspects of the given topic. Terms are well-explained and easy to grasp, as the writing style is informative and appealing. Between some of the chapters, additional information is highlighted by supplementary discussions, such as *Box 2: From Crystals to Rocks*, for those who are particularly curious about the given topic.

The first three chapters provide a foundational background that cover the concepts of geological processes. The first chapter, *The Dynamic Earth*, includes discussions of plate tectonics, from the life cycles of mountain ranges and orogenic belts, to folding and faulting. The rock cycle is presented with many examples of how this process affected present day landforms, such as describing the formation of the South Mountain Batholith in southwestern mainland Nova Scotia (as seen at Peggy's Cove), and the formation of Mount Carleton, New Brunswick. The impact of time is considered in Chapter 2, *The Fourth Dimension*, and provides the reader with an appreciation of how we view time. New technologies improve the ability to relate time and events through correlation and using tools such as radiometric dating, helium thermochronology, fission track dating, and dendrochronology. Chapter 3, aptly titled *Tales of Trails and Ancient Bodies* is an excellent introduction into understanding the development and evolution of life forms, and their place and role throughout the evolving Earth over time. Together, the Maritime Provinces have an amazing variety of fossil sites, with many representatives of fossil life over the periods of time. Fossils provide a wealth of information about the paleoclimate, the diversity of populations and their distributions, to extinctions and the evolution of new fauna. Even astronomical information can be determined, such as the daily

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Typical subhorizontal joints (prominent fractures) in granite at Pabineau Falls, New Brunswick, caused by release of pressure over time as overlying rocks were removed by erosion. Photo credit: R. Fensome.

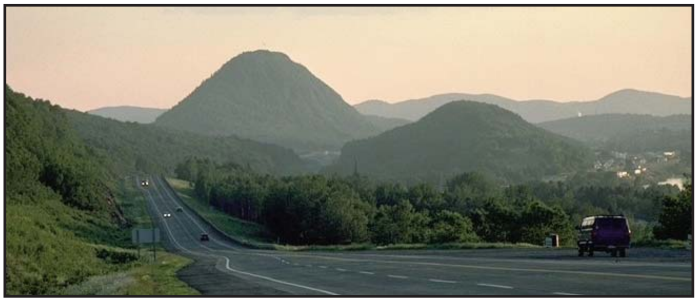
Sea stacks formed from Carboniferous sedimentary rocks under attack from stormy weather, Pokeshaw, New Brunswick. Photo credit: R. Fensome.

Trackway of a Permian tetrapod (a four-legged animal) on a sandstone block discovered in Lord Selkirk Provincial Park, Prince Edward Island, dating from about 290 million years ago. Photo credit: M. Stimson.

Aerial view of the cliffs at Five Islands Provincial Park, Nova Scotia, showing a faulted block of Late Triassic North Mountain Basalt (dark grey), Early Jurassic fluvial and lacustrine red sedimentary rocks (left of the faulted block) and Late Triassic lacustrine red sedimentary rocks (right of the faulted block) overlain by North Mountain Basalt. Photo credit: L. Podor.

growth rings of Devonian corals indicating that the length of a day was then only 22 hours long!

The puzzle pieces of the geological stories are pulled together starting in Chapter 4, *Into Deepest Time*. The processes involved in producing the first land masses, to the first life forms and banded iron formations, build on previously explained concepts. The growth and demise of supercontinents to microcontinents, along with changing oceans are framed within the rock formations of the Maritime Provinces over time, with many local examples given. *Box 4: Rock Stars* illustrates the key discoveries and life stories of several prominent individuals who made exceptionally noteworthy contributions to Maritime geology and geoscience education. Chapter Five, *The Pieces Come Together*, further explores the significant tectonic, climatic, and biotic changes from the Proterozoic and Cambrian to the Devonian, setting the stage for the introduction of the Carboniferous – a particularly rich period of the ancient Maritimes. *Box 5: Granite* is an analysis of the granite batholiths and related features found as distinct landforms, such as the South Mountain Batholith in Nova Scotia, and the Pokiok Batholith in New Brunswick. *Box 6: Fish Tales* goes through the evolution and classifications of fishes, linking certain specimens to various Maritime localities. Chapter Six, *Basins and Ranges*, describes the development of the coal fields, from the changing seas and climate – producing a great "drying off" (creating the red soils of Prince Edward Island for example) to the greatest known extinction of approximately 90% of all living organisms. *Box 7: Old Salt and Lime* relates to the impacts of these times of great aridity, while *Box 8: Flowing Through Time* describes the effects of fluvial environments on both landforms and organisms, including human habitation impacts. Chapter Seven, *An Ocean is Born*, shows how the North Atlantic Ocean grew over time during the breakup of Pangea, and makes connections to the Mesozoic to Cenozoic rocks formed across the region. Some of the basalt flows that heralded the birth of the Atlantic Ocean contain many types of zeolites, and the Bay of Fundy is a world-famous site for collecting these minerals. Several extinction events took place during these times and the extraordinary fossil evidence for one of them is found in several key locations in the Maritimes, especially the "Fundy Fossils" section. During the Cenozoic,

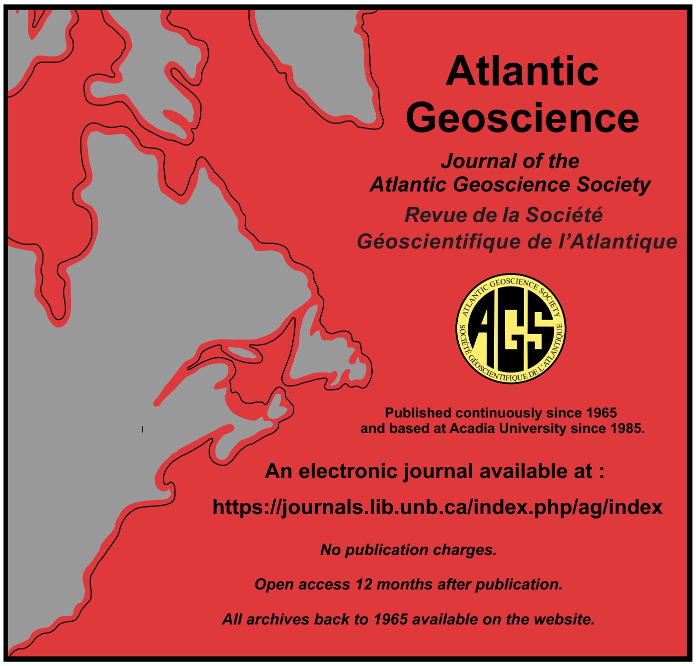


The erosional remnants of an Early Devonian volcanic pipe from the Tobique-Chaleur Bay Belt, Sugarloaf Mountain, Campbelton, New Brunswick. Photo credit: R. Fensome.

the Earth began cooling, leading into Chapter 8, *Into the Quaternary Ice Age*. In addition to the effects of the Ice Age on landscapes and life forms, another factor to consider is the rise and fall of sea level and our changing coastlines. The earliest humans arrived about 12,500 to 9500 years ago, and left behind several important archeological sites, mainly along waterways. *Box 9: Between Land and Sea* describes the ever-changing coastline, including the significant environmental role of coastal marshes, and how humans are affected by and play a role in causing erosion and altering the coastlines.

The last three chapters present a more in-depth look at geology and how it influences society and our daily lives. The diverse and plentiful mineral resources found in the Maritime Provinces are covered in Chapter 9, *From Rocks to Resources*. This chapter discusses the earliest Indigenous use of resources for tools and paints, to the earliest (1604) European discovery of iron in the North Mountain Basalt, to the present-day roles of mining and resources extraction, including water. *Box 10: Carved in Stone* takes the reader on an interesting journey exploring the many buildings throughout the Maritimes that have been constructed using local stone. Many homes built in the early 1800s, from churches, various government and municipal buildings to bridges and railway stations illustrate the wonderful use of stone. This section highlights structures made of sandstone, granite, limestone, quartzite, and slate, as well as the use of stones in cemeteries and graveyards. Chapter 10, *Nature's Challenges* considers the damage that can be caused by natural processes, such as earthquakes, tsunamis, submarine slides and surficial landslides, toxins in rocks and soils that leach into groundwater, to local concerns with radioactive minerals producing radon gas. Chapter 11, *The Human Factor,* is a critical look at the impacts of resource extraction and human actions. It highlights coal mining, from the tragic loss of human life to the long-term effects of coal-burning processes on the global environment, mine tailings and the toxins left over from extraction of gold from ores. For example, arsenic from old mining sites locally affects the water supply and people's health. Garbage and landfills are discussed, with emphasis on efforts to mitigate their impacts more effectively and utilizing more green technologies to help reduce negative results of climate change. Very fittingly, the last synthesis of information is found in *Box 11: Milestones*. This frames the changes over the last four billion years with colour-coded information indicating geological changes (plate tectonics and rock formations; mountain building and orogenies), mass-extinction events, to climate, oceans, atmosphere, and space events, modern landscapes, and life events. There is also a very comprehensive list of resources for those who wish to find out more information about earth sciences – from museums, pamphlets, books, websites, maps, videos, UNESCO Geoparks, earth science organizations, universities and colleges, to places and events to explore.

For those who have the First Edition, the Second Edition is well worth adding to the collection, with its updated scientific information, additional chapters and boxes, and spectacular photographs, maps, diagrams, and illustrations. The wonderful collaboration and contributions by the authors have produced a book that is both a thoroughly researched and well-written description of the topics presented, and an engaging and eye-catching volume to have gracing one's coffee table in a prominent location! From budding younger earth scientists to university geology students to general interest for those of all ages, this is a book that will foster and enhance an understanding of our planet and give Maritimers much appreciation of the geological and human prehistory of where they live.



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