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The deep magmatic cumulate roots of the Acadian orogen, eastern North America

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ABSTRACT

The dearth of cumulate magmatic roots in accretionary orogens is a cornerstone of models that postulate redistribution of mass and energy within the crust for the genesis of intermediate to silicic magmatism. Likewise, the origin of the evolved Acadian (Devonian) plutonism in the New England Appalachians (northeastern USA) has long been explained by closed-system crustal melting due to the absence of associated coeval deep mafic counterparts. Here, we report the discovery of Acadian hydrous ultramafic cumulate rocks that formed by deep-seated (~1.1 GPa) fractional crystallization processes from a mantle-derived parental melt (Connecticut, southern New England, USA). These rocks are the first of their kind identified in the Appalachian orogen, and one of only a handful of preserved deep subarc hydrous cumulates worldwide. We propose a genetic link between the studied rocks and the evolved coeval plutonism in central-southern New England, where the former represent the missing deep cumulate roots of the same magmatic arc. Our findings support the hypothesis that differentiation of mantle-derived hydrous magmas by fractional crystallization and assimilation processes in the deep crust is a fundamental process in the production of intermediate to silicic magmatism and the geochemical evolution of the continental crust.

INTRODUCTION

Whereas basaltic magmas constitute the main flux of material through the mantle-crust boundary in subduction zones, the bulk continental crust displays a more felsic, andesite-like composition (Rudnick and Gao, 2014). Resolving this paradox requires a comprehensive understanding of the genesis of intermediate to silicic magmas in accretionary orogens. An enduring model holds that significant evolved magmatism is produced in lower-crustal zones of anatexis, where the main mass contributor is preexisting crustal rocks (White and Chappell, 1983; Davidson and Arculus, 2005; Sisson et al., 2005; Collins et al., 2020). An alternative view is that fractional crystallization of mantle-derived basalts following the formation of subarc ultramafic cumulates coupled with melting and assimilation processes in the lower crust are largely responsible for the production of evolved magmatism (Gill, 1981; Ague and Brimhall, 1988; Hildreth and Moorbath, 1988; Annen et al., 2006; Jagoutz and Kelemen, 2015). However, direct testing of the crystal-fractionation linkage of deep ultramafic and/or mafic roots complementary to evolved magmatism has proven challenging because terranes exposing deep subarc magmatic crust are scarce.

Recent studies in the exhumed arc sections of Talkeetna (Alaska, USA), Kohistan (Pakistan), and Famatina (Argentina) as well as xenolith-based crustal reconstructions and experimental results have demonstrated that subarc magmatic cumulates that formed by fractionation of hydrous magmas display distinctive geochemical signatures (Greene et al., 2006; Jagoutz et al., 2011; Nandedkar et al., 2014; Walker et al., 2015; Müntener and Ulmer, 2018; Melekhova et al., 2019). For instance, whereas cumulates produced after fractional crystallization of dry magmas at mid-crustal levels display a continuous decrease of Mg# [Mg# = 100 × MgO / (MgO + FeO) molar proportions] with increasing SiO_2 content, the cumulate line of descent (CLD) of hydrous parental magmas at subarc pressures (0.7–1.3 GPa) exhibits a Z-shaped trend in Mg# versus SiO_2 space (Müntener and Ulmer, 2018). Thus, these geochemical signals allow better testing of the links between ultramafic/mafic and evolved magmatic rocks in more complex settings such as accretionary orogens, where field relations are commonly obscured by intense tectonism.

The Acadian orogen of the northern Appalachians (New England, USA, and eastern Canada) is related to the collision of the microcontinent Avalonia with the Eastern margin of Laurentia (ca. 423–385 Ma) (Van Staal et al., 2009). Classic studies in New England attribute much of the orogen's associated intermediate to silicic plutonism to closed-system partial melting of a metasedimentary crust triggered by crustal thickening and the associated radiogenic and shear heating (Lux et al., 1986; Chamberlain and Sonder, 1990; Brown and Pressley, 1999). The paucity of identified mafic roots is a key argument in favor of such models. In contrast, Dorais and Paige (2000) and Dorais (2003) argued for the need of a mantle-derived component in the genesis of the Acadian plutonism in New England. Thus, this controversy embodies the debate on the processes behind the production of intermediate to silicic magmatism in accretionary orogens.

Here we present the discovery of a hydrous ultramafic/mafic mélange complex in the Acadian orogen (southern New England, USA). Textural relations, whole-rock and *in situ* mineral geochemistry, and zircon U-Pb and Lu-Hf isotopic data reveal that the rocks represent the missing subarc hydrous cumulate roots of the Acadian orogen in the New England Appalachians. We suggest that the segregation of hydrous ultramafic cumulates from mantle-derived parental melts in a deep crustal hot zone was a fundamental process driving the genesis of evolved Acadian plutonism.

GEOLOGICAL AND PETROLOGICAL BACKGROUND

The field area lies within the Brimfield Schist in the Central Maine terrane, a lithotectonic unit of the Acadian orogen in New England (Figs. 1A and 1B). Ultrahigh-temperature (~1000 °C, ~1 GPa) and high-pressure (~1040 °C, ~1.8 GPa) metamorphic rocks of the Brimfield Schist indicate that the thrust sheets of the southern Central

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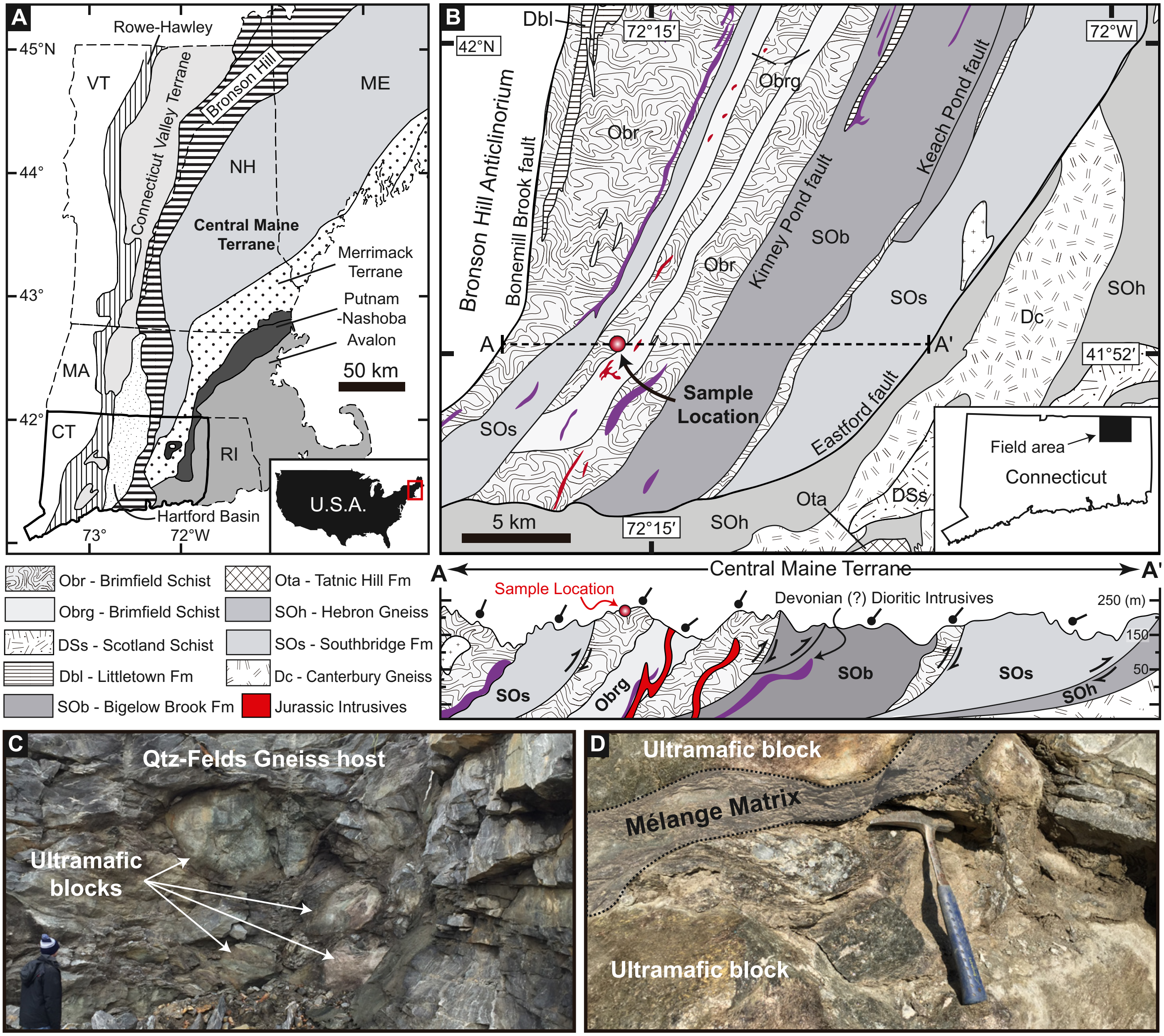

Figure 1. (A) Geologic map of the major terranes of New England, USA (Aleinikoff et al., 2007). ME—Maine; NH—New Hampshire; VT—Vermont; MA—Massachusetts; CT—Connecticut; RI—Rhode Island. (B) Detailed geologic map and cross section of the study area (Rodgers, 1985). Major thrust faults are labeled. (C,D) Field relations of ultramafic/mafic mélange rocks. Qtz—quartz; Felds—feldspar.

Maine terrane sampled the Acadian orogenic roots during the assembly of composite Laurentia (Ague et al., 2013; Keller and Ague, 2018). The studied rocks are olivine-pyroxene hornblendites, olivine-hornblende pyroxenites, norites and/or orthopyroxenites, hornblendites (hereafter ultramafic rocks), and gabbros and common anorthosite veins (hereafter mafic rocks). They occur as a mélange of decimeter to multi-meter blocks along thrust faults within a sequence of metasedimentary and metavolcanic rocks (Figs. 1C and 1D). The mélange matrix preserves a carbonate-bearing amphibole-chlorite-talc assemblage (Fig. 1D). The rocks are generally fresh with rare olivine serpentinization and phlogopite chloritization. They dominantly consist of large amphibole (<3 cm) and orthopyroxene (<20 cm) oikocrysts enclosing submillimeter cumulus olivine, orthopyroxene, phlogopite, and rare clinopyroxene (Figs. 2A–2C). Hornblendites and anorthosites display subhedral to idiomorphic granoblastic textures (Fig. 2D). In the most differentiated norites and gabbros, plagioclase appears as an intercumulus phase (Fig. 2E). Detailed petrographic descriptions are provided in Section S1 of the Supplemental Material[1].

[1]Supplemental Material. Detailed petrographic descriptions, methods, modeling, and tables. Please visit https://doi.org/10.1130/GEOL.S.12921599 to access the supplemental material, and contact editing@geosociety.org with any questions.

RESULTS

Bulk-Rock Geochemistry

The ultramafic rocks display elevated Mg# (70.4–83.5) at variable SiO_2 contents (41.4–53.4 wt%) (Fig. 2F). Their Al_2O_3 contents are relatively low (5.6–10.3 wt%, excepting hornblendites) and correlate with increasing SiO_2 (Fig. 2G). The lower Al_2O_3 concentrations in the SiO_2-poorer samples correspond to lower CaO (1.4–9.8 wt%). This is consistent with Al_2O_3 and CaO being dominantly hosted by amphibole and with the scarcity or absence of clinopyroxene and plagioclase. In contrast, the mafic rocks display a wider range of Mg# values (77.3–41.8) that correlate directly with SiO_2 (47–51.8 wt%) and inversely with Al_2O_3

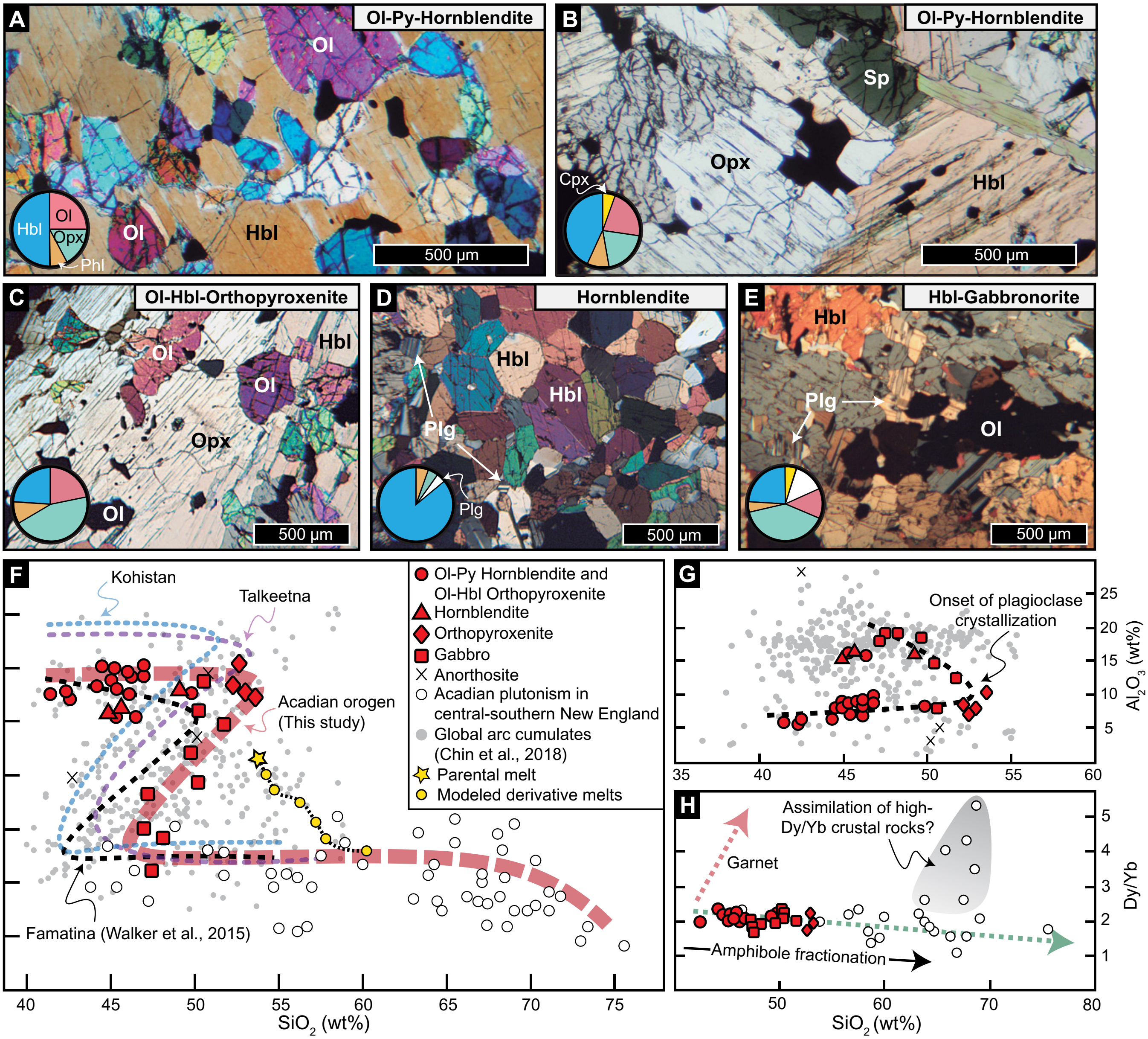

Figure 2. (A–E) Photomicrographs of representative textures in studied rocks from New England, USA. Pie charts depict relative modal abundances. Ol—olivine; Opx—orthopyroxene; Cpx—clinopyroxene; Phl—phlogopite; Plg—plagioclase. (F,G) Bulk-rock Mg# [Mg# = 100 × MgO / (MgO + FeO) molar proportions] and Al_2O_3 concentrations plotted against SiO_2. Also shown in F are schematic trajectories of cumulate lines of descent (CLDs; dashed lines) of subarc natural exposures (Kohistan [Pakistan] and Talkeetna [Alaska, USA] CLD after Jagoutz et al. [2011]). (H) Dy/Yb versus SiO_2 for available data (symbols as in panel F) on the New Hampshire Plutonic Suite (Dorais, 2003). Acadian plutonic rocks in central-southern New England (white circles) after Emerson (1917), Snyder (1964), Watts et al. (2000), and Dorais (2003).

(8.2–19.2 wt%) and CaO (6.1–11.4 wt%), consistent with a modal increase of intercumulus plagioclase (Figs. 2F and 2G). The entire suite has elevated FeO (mean ~11 wt%) and TiO_2 concentrations (mean ~0.85 wt%; Table S1 in the Supplemental Material).

Zircon U-Pb and Lu-Hf Isotope Constraints

Zircons from an olivine-pyroxene hornblendite and an orthopyroxenite were analyzed for their U-Pb (Figs. 3A–3G; Table S2) and Lu-Hf isotopic compositions (Fig. 3H; Table S3) to constrain their timing of crystallization and the source of the parental magmas. Most zircons have subhedral to anhedral forms and inner domains with typical oscillatory magmatic zonation (Figs. 3C–3F). The zircons from the olivine-pyroxene hornblendite record four main episodes at 410 ± 4.6, 392.6 ± 4.4, 360.7 ± 4.2, and 337.4 ± 3.9 Ma (2σ) (Fig. 3A). The zircons from the orthopyroxenite record two dominant episodes at 406.6 ± 5.5 and 359.2 ± 4.2 Ma (2σ) (Fig. 3B). Several individual grains have older cores and significantly younger overgrowths (Figs. 3D and 3F). The range of $\varepsilon_{Hf(t)}$ values for all zircons is between 4.2 and −3.7 (Fig. 3H). Whereas the $\varepsilon_{Hf(t)}$ values for zircons from the olivine-pyroxene hornblendite are always positive (0.4–4.2; *n* = 29), zircons from the orthopyroxenite range from −3.7 to 1.5 (*n* = 43), with 74% of the zircons having negative values.

Temperature, Pressure, and Nature of the Parental Magma

We use *in situ* mineral compositions from a high-Mg# and low-SiO_2 ultramafic rock to constrain the petrogenesis of the studied rocks. Two-pyroxene thermobarometry (Putirka, 2008, and references therein) indicates equilibration temperatures of $1025\pm^{116}_{58}$°C and pressures of $1.1\pm^{0.24}_{0.27}$ GPa (Fig. 4A; Tables S4, S5).

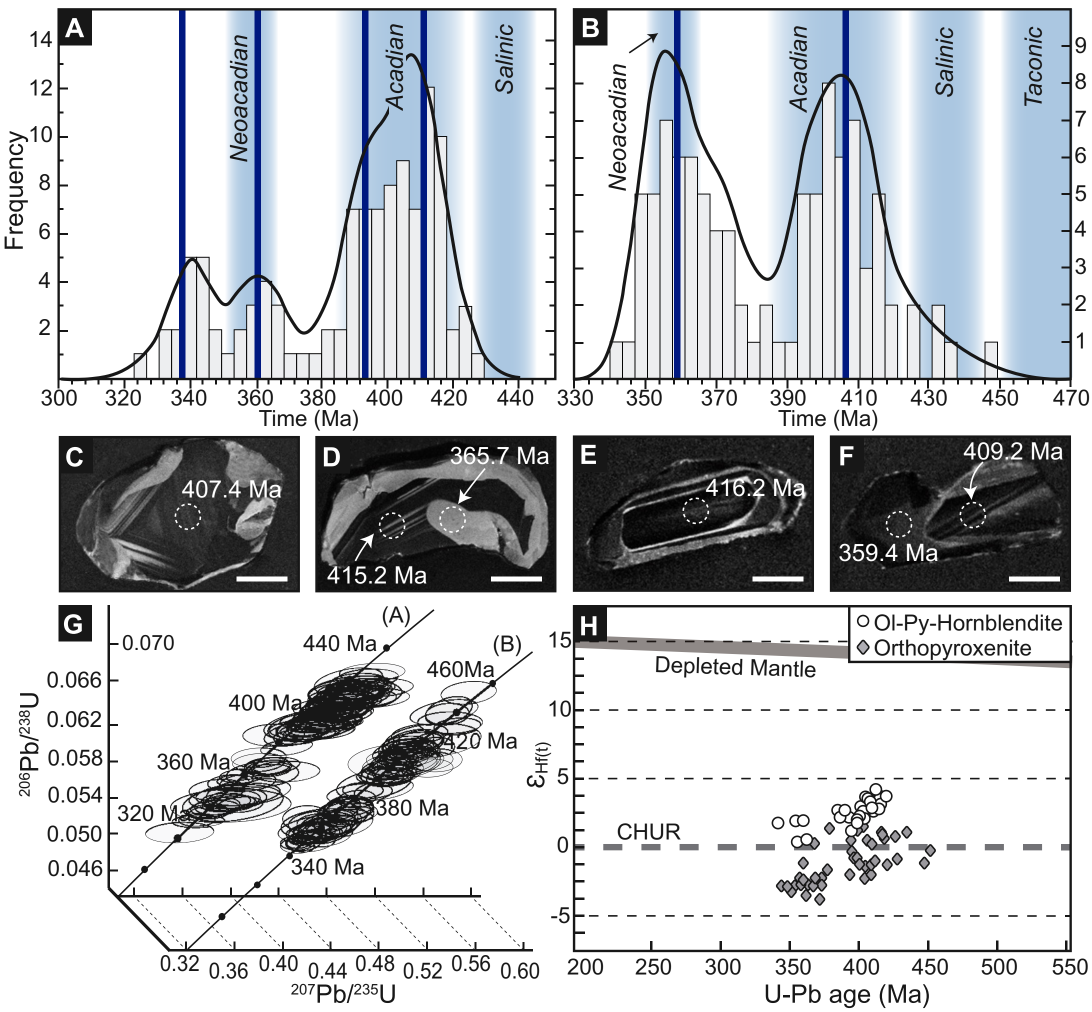

Figure 3. (A,B) U-Pb population (gray bars) and age-probability curves (black lines) for olivine-pyroxene hornblendite (A) and orthopyroxenite (B). (C–F) Cathodoluminescence images of zircons from olivine-pyroxene hornblendite (C,D) and orthopyroxenite (E,F). Dashed circles indicate selected spots for U-Pb dating. Scale bars are 70 μm in length. (G) U-Pb concordia plot of analyzed zircon for both samples. (H) $\varepsilon_{Hf(t)}$ versus U-Pb age for zircons from both samples. Ol-Py—olivine-pyroxene; CHUR—chondritic uniform reservoir.

Thermobarometric estimates based on the composition of pristine and clearly magmatic amphibole using the approaches of Ridolfi and Renzulli (2012) and Larocque and Canil (2010) yield consistent values at $995\pm^{7}_{11}$ °C and $1.13\pm^{0.06}_{0.08}$ GPa, and ~1.2 ± 0.1 GPa, respectively (Fig. 4A; Table S6). These estimates indicate depths of 40–45 km and are compatible with those obtained for the associated ultrahigh-temperature metamorphic rocks (>1 GPa; Ague et al., 2013).

Considering our petrographic observations (Figs. 2A and 2B), we assume that the parental

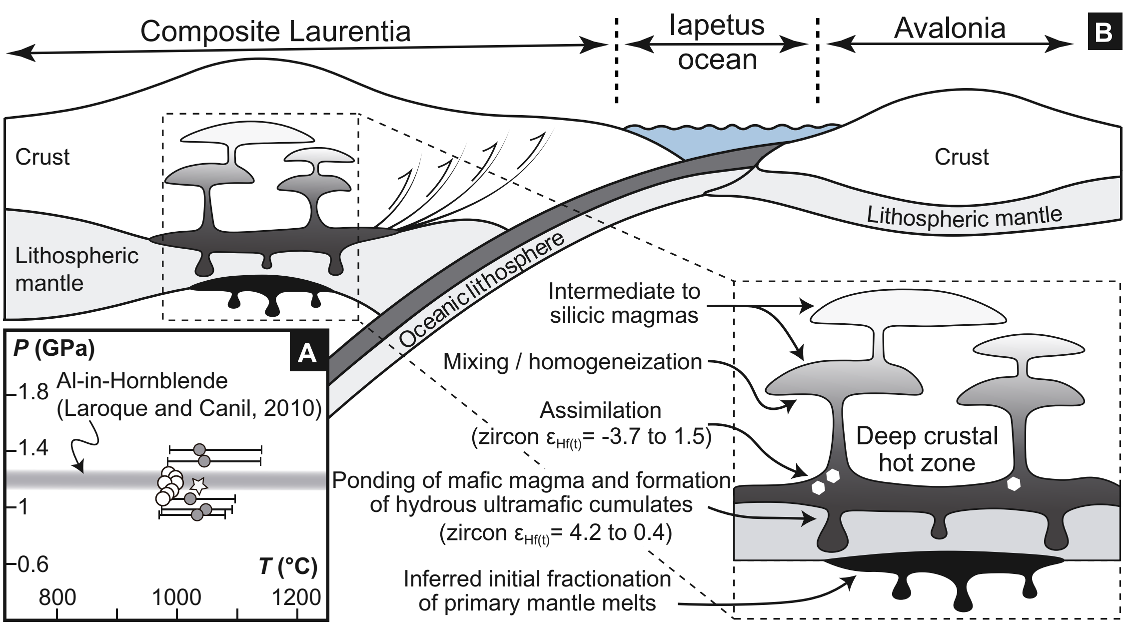

Figure 4. (A) Two-pyroxene (gray circles) and amphibole (white circles) thermobarometry. Star indicates mean two-pyroxene pressure-temperature (*P-T*) value. (B) Simplified geological model of tectonic and petrogenetic processes for genesis of evolved Acadian plutonism in central-southern New England, USA.

melt was in equilibrium with amphibole. Thus, we estimate the parental magma composition by means of the Fe/Mg partitioning between amphibole and basaltic melt. Calculated equilibrium parental melts using representative hornblende (Mg# 81–82) have a Mg# between 56 and 63 ($Kd^{Fe/Mg}_{amph/liq}$ [Fe/Mg partition coefficient between amphibole and liquid] = 0.31 to 0.38; Pichavant and Macdonald, 2007; Table S6).

DISCUSSION

Deep Subarc Hydrous Magmatic Cumulates

The elevated Mg# of the ultramafic rocks (Mg# ~77 and as much as 28.2 wt% MgO) as well as their distinctive orthocumulate to adcumulate textures are best explained by the accumulation of a liquidus assemblage of a primitive parental melt. In contrast to the FeO- and TiO_2-poor cumulates formed at mid-ocean ridges, the elevated FeO and TiO_2 concentrations of the cumulates studied here are similar to those formed in subarc settings (Chin et al., 2018).

Cumulates from hydrous parental magmas at subarc pressures define three distinctive segments in the Mg# versus SiO_2 and Al_2O_3 versus SiO_2 spaces (Jagoutz et al., 2011; Walker et al., 2015; Müntener and Ulmer, 2018). The first segment denotes an increase in SiO_2 at high Mg# and relatively low Al_2O_3 (Figs. 2F and 2G). The second segment is characterized by a SiO_2 and Mg# decrease and a significant increase in Al_2O_3 (Figs. 2F and 2G). The third segment represents an increase in SiO_2 at low Mg# and high Al_2O_3. The suite of cumulate rocks studied here clearly reproduce the first and second segments of this CLD (Fig. 2F). Thus, the major-element systematics and CLD of the studied ultramafic/mafic rocks also reveal a deep (~1.1 GPa) subarc hydrous origin.

Although the most primitive ultramafic cumulates studied here display lower Mg# and higher Al_2O_3 contents compared to those of the Talkeetna and Kohistan sections, their CLD closely resembles that of the Famatina arc section (Walker et al., 2015; Fig. 2F). Such compositions could result after differentiation of primary melts prior to the segregation of the cumulate rocks via earlier fractional crystallization or melt-rock reaction. This is consistent with the relatively low Mg# nature (56–63) of the parental melt, which matches the parental melts in Famatina (Walker et al., 2015).

Crystallization Age and Source of Magmas

The zircon U-Pb ages record the Acadian, Neoacadian, and early Alleghanian orogenies of the northern Appalachians (Figs. 3A and 3B). Magmatic cores indicate that the cumulate suite formed during the Acadian crust-forming event ca. 410 Ma. Mantling overgrowths represent recrystallization processes during the subsequent orogenic events (Figs. 3D and 3F). Positive $\varepsilon_{Hf(t)}$ values for the zircons in the olivine-orthopyroxene hornblendite indicate that the parental magma derives from a Lu-Hf radiogenic source (Fig. 3H). Thus, although the parental melt was evolved with respect to a primary mantle melt during the crystallization of the cumulates (Table S6), the $\varepsilon_{Hf(t)}$ shows that it originated from a mantle source. Conversely, the range of $\varepsilon_{Hf(t)}$ values found in zircons from the orthopyroxenite (−3.7 to 1.5) suggests that the mantle-derived parental magmas underwent assimilation of crustal material during evolution in the deep crust (Fig. 3H).

Linkage to Evolved Acadian Plutonism in New England

The Acadian plutonism in central-southern New England was emplaced within the same magmatic arc and includes calc-alkaline plutons of the Merrimack belt (ca. 400 Ma; Watts et al., 2000), the New Hampshire Plutonic Suite (e.g., Kinsman Granodiorite: 411 ± 19 Ma; Bethlehem Granodiorite: 410 ± 5 Ma; Spaulding Tonalite: 393 ± 5 Ma; Dorais, 2003), and other metaigneous (e.g., Canterbury Gneiss), gabbroic (e.g., Lebanon gabbro), and related intrusions (Emerson, 1917; Snyder, 1964; Fig. 2F).

Our zircon U-Pb data reveal a remarkable temporal link with the evolved Acadian plutonism in central-southern New England (Fig. 3), indicating a potential genetic relationship. Importantly, Dorais (2003) showed that the genesis of much of the Acadian plutonism involved a mantle and/or lower crust magmatic component. One possibility is that the ultramafic/mafic hydrous cumulates represent a source of fluids that triggered fluxed-crustal melting of the overlying crust (Collins et al., 2020). Alternatively, they could represent the residues left after fractional-crystallization processes that led to the production of derivative evolved Acadian magmas. Available data for the New Hampshire Plutonic Suite shows decreasing Dy/Yb with increasing SiO_2 weight percent, suggesting amphibole fractionation during differentiation (excepting some samples with SiO_2 >65 wt%; Fig. 2H; Davidson et al., 2007). This trend converges well with that of the rocks studied here, and in view of their amphibole-dominated CLD, a crystal-fractionation linkage to the evolved Acadian plutonism in central-southern New England is plausible.

To test this, we provide a fractional crystallization-assimilation model adopting the approach of Jagoutz (2010). The composition of the parental melt, fractionated cumulates, and assimilated material are provided in Table S7. Results show that fractionation of the studied hydrous cumulates, including some crustal assimilation, can produce significant SiO_2-rich (~60 wt%) derivative magmas (Fig. 2F). Further SiO_2 enrichment would require additional fractionation, assimilation, and/or partial melting at shallower crustal levels. The above discussion supports a genetic relationship between the hydrous cumulate rocks and the evolved coeval plutonism in New England, where the former constitutes the missing cumulate roots of the same Acadian magmatic arc (Fig. 4B).

CONCLUSIONS AND IMPLICATIONS

We report the discovery of a hydrous ultramafic/mafic mélange complex in the southern Central Maine terrane of the New England Appalachians. Textural relations, whole-rock and mineral major-element systematics, and zircon U-Pb and Lu-Hf isotope geochemistry reveal that the rocks are ultramafic/mafic magmatic cumulates crystallized from a mantle-derived hydrous parental melt in the lower crust (40–45 km depth) during the Acadian orogeny. We suggest that they represent the missing subarc cumulate roots complementary to much of the Acadian plutonism in New England. Our findings indicate that the production of the intermediate to silicic Acadian magmatism involved the differentiation of mantle-derived parental melts after the segregation of hydrous ultramafic cumulates and concurrent assimilation processes in a deep crustal hot zone (Fig. 4B), in contrast to models involving only closed-system crustal melting. Our results are consistent with the hypothesis that the formation of subarc ultramafic magmatic cumulates is a necessary step in the genesis of evolved magmatism and the geochemical evolution of the continental crust.

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