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Rise and fall of the Acadian altiplano: Evidence for a Paleozoic orogenic plateau in New England

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A B S T R A C T

High elevation orogenic plateaus are formed by a complex interplay of deep and surficial processes and influence a variety of Earth systems. However, few exposures of plateau mid-crust are presently recognized, hindering understanding of the deeper processes. We present evidence for the existence of an orogenic plateau during and after the Devonian Acadian orogeny whose mid-crustal roots are exposed in the New England Appalachians. The four-dimensional crustal evolution of this paleo-plateau is constrained by the integration of new petrologic and geochronologic databases, petrochronology, and geophysical imaging. Doubly thickened crust, widespread amphibolite to granulite-facies metamorphic conditions, a paleo-isobaric surface, and protracted mid-crustal anatexis indicate the development of a high elevation, low relief plateau by 380 Ma. $^{40}Ar/^{39}Ar$ thermochronology shows a distinct thermochronologic signature with very slow cooling rates of 2–4 °C/m.y. following peak metamorphic conditions. Thermochronologic data, trace element and Nd isotope geochemistry, and monazite petrochronology suggest a 50 m.y. lifespan of the plateau. Orogen parallel ductile flow and extrusion of gneiss domes resulted in plateau collapse, crustal thinning, and homogeneous exhumation at ca. 330–300 Ma. Thinning and exhumation of the plateau crust may have led to the sharp 12–15 km step in Moho depth in western New England, possibly by reactivating the suture between Laurentia and accreted Gondwanan-derived terranes. The formation of the Acadian altiplano may have influenced Li-pegmatite genesis, foreland basin evolution, and Paleozoic paleoclimate, while its recognition may provide a window into the deeper processes of orogenic plateaus including partial melting, plutonism, and collapse by ductile extension.

1. Introduction

Orogenic plateaus are integral to many modern collisional orogens (e.g. the Tibetan Plateau, the Andean Altiplano-Puna plateau, and the Anatolian-Zagros plateau) and the mechanism(s), rates, and timing of uplift and collapse are critical data for models of collisional tectonics (Garzione et al., 2017; Kapp and DeCelles, 2019). The creation and destruction of orogenic plateaus affect global geodynamics (Hatzfeld and Molnar, 2010), climate (Raymo and Ruddiman, 1992), atmospheric circulation (Molnar et al., 1993), and the genesis of critical resource deposits (Bradley, 2019). Current models of plateau evolution are generally informed by studies of modern orogens, which provide a field-based record of predominantly upper crustal processes. Deeper geodynamic processes are inferred from numerical models, petrogenetic studies, and geophysical imaging. The recognition of paleo-plateaus, and especially, the deeper levels of paleo-plateaus, has been hindered by overprinting events, complex deformational histories, and the limitations of geochronologic techniques. Yet, a mid-crustal perspective on the processes, kinematics, and timescales of plateau evolution may be key for placing observations made in modern orogens into a broader context, testing the predictions of numerical models, and in building four dimensional models of plateau evolution.

We present evidence for the existence of an orogenic plateau during and after the Acadian Orogeny (*sensu lato*), ca. 380-330 Ma, the exhumed mid-crustal roots of which are exposed in the New England Appalachians. The extent of the region of homogeneous uplift and exhumation are defined by thermobarometric and thermochronologic data. We constrain the timing and nature of crustal thickening, mid-crustal residence, and orogenic collapse with the integration of structural fabrics and monazite petrochronology. Our results are consistent with, and may help to explain, a wide variety of geologic observations from the history of the foreland basin to modern Moho structure while providing a four-dimensional perspective on plateau evolution.

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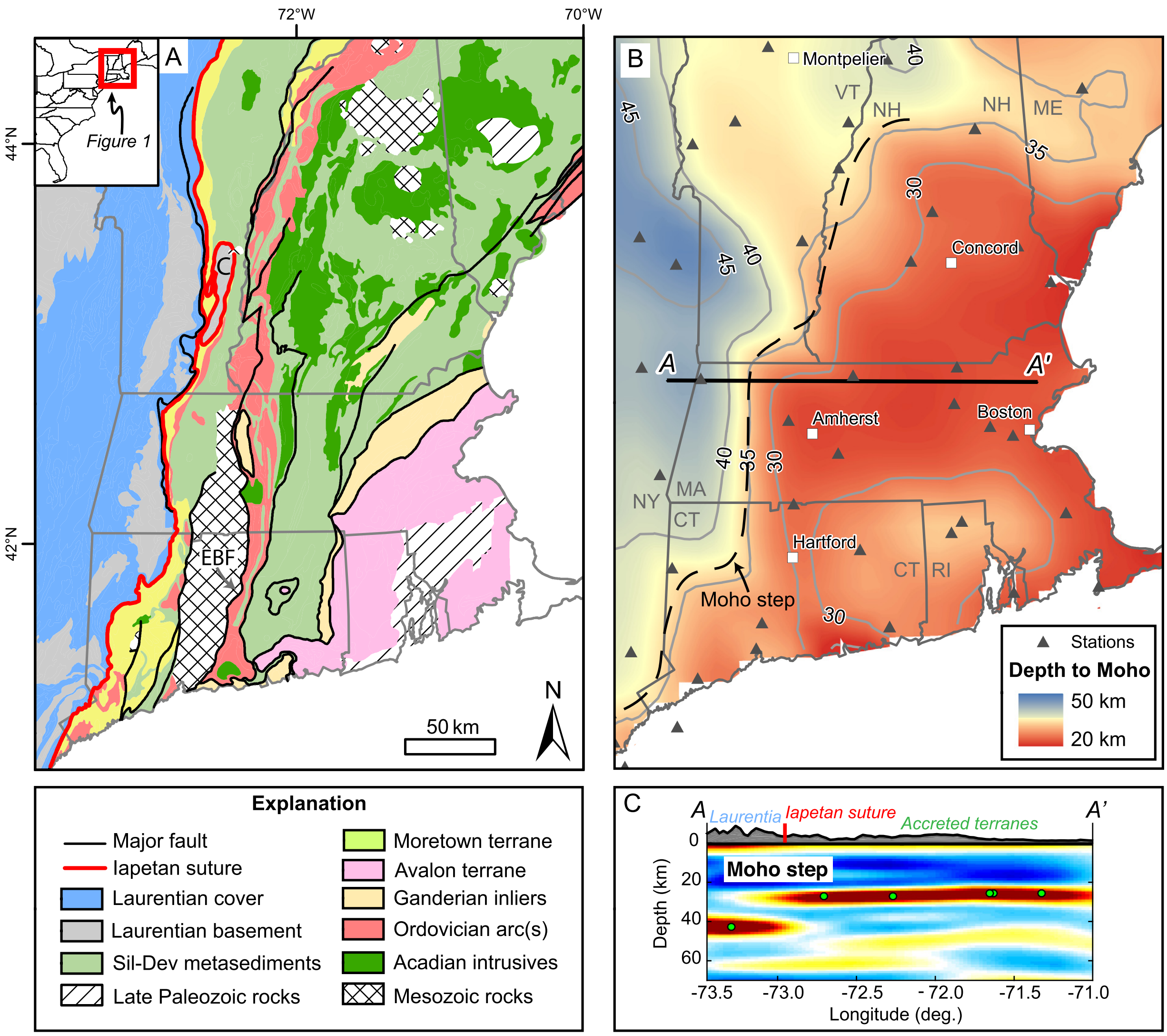

Fig. 1. A: Tectonic map of the Appalachian Mountains (modified from Hibbard et al., 2006). Black lines indicate major faults. C: Chester Dome. Red lines mark the Iapetan Suture, interpreted to mark the boundary between tectonic elements of Laurentian and Gondwanan affinity (Karabinos et al., 2017). Inset: Location map of Figs. 1A and 1B. B: Distribution of Moho depth (in kilometers) from Li et al. (2018). Triangles indicate stations used to constrain Moho depth using teleseismic P-to-S receiver functions. Dashed line represents approximate trace of the Moho step. State abbreviations: CT – Connecticut; MA – Massachusetts; ME – Maine; NH – New Hampshire; NY – New York; RI – Rhode Island; VT – Vermont. C: Cross section A–A′ showing Moho depth and 12-15 km step. Circles indicate projected location of seismic stations used to constrain the Moho step. Note that apparent overlap in the Moho across the step is a processing artifact not suggested by receiver functions (Li et al., 2018).

2. Geologic background

The tectonic elements of the Appalachian orogen record multiple phases of Paleozoic to Mesozoic tectonism (Fig. 1A). The Paleozoic record is dominated by episodic collision and accretion of terranes to the margin of Laurentia followed by a Mesozoic history of continental extension and the birth of the Atlantic Ocean.

Orogenesis began with the Ordovician Taconic orogeny (475–450 Ma). It has been interpreted to represent closure of the Iapetus ocean due to collision between the Laurentian passive margin (basement massifs and cover rocks) and Ordovician island arc(s) built on the Gondwana-derived Moretown terrane in New England (Karabinos et al., 2017). Taconic orogenesis is marked by the emplacement of thrust sheets and ophiolites onto the Laurentian margin, foreland basin sedimentation, and amphibolite facies metamorphism in western New England. The end of the Taconic orogeny has been interpreted to have involved a reversal in subduction polarity, creating a west-dipping subduction zone under Laurentia (Karabinos et al., 2017) and subsequent accretion of the Gander terrane in the Salinic orogeny (van Staal et al., 2009).

The subsequent Silurian Salinic orogeny (430–422 Ma), in many recent models, involved accretion of the peri-Gondwanan Gander terrane to the post-Taconic margin of Laurentia. Salinic orogenesis involved dominantly sinistral oblique convergence although the effects of Salinic tectonism have not been well documented in southern New England (van Staal et al., 2009). A thick succession of clastic rocks were deposited in deep, syn-tectonic marine basins of the Central Maine and Connecticut Valley-Gapsé troughs in the Silurian through the earliest Devonian (Fig. 1A).

The late Silurian to Carboniferous Acadian orogeny (*sensu lato*; 420 to 350 Ma) was the dominant tectonic event in the northern Appalachian Mountains, producing polyphase deformation and high-grade metamorphism (Robinson et al., 1998; van Staal et al., 2009). Presently, Acadian orogenesis in southern and central New England is understood to be marked by the emplacement of east- and west-directed thrust nappes and sheet-like intrusions (Robinson et al., 1998). The Acadian deformational front has been shown to have propagated from the southeast to northwest in the late Silurian and Devonian (Robinson et al., 1998; van Staal et al., 2009), and has been attributed to collision between composite Laurentia and the peri-Gondwanan Avalon terrane. Prolonged deformation, metamorphism, and magmatism between 380 and 350 Ma has been interpreted to be related to progressive accretion of the Meguma terrane to Laurentia, designated by some workers as the Neoacadian orogeny (Robinson et al., 1998; van Staal et al., 2009). Alternatively, oblique subduction of the Rheic Ocean beneath composite Laurentia may have driven tectonic interactions between Laurentia and the accreted Meguma terrane and promoted prolonged transpression (Kuponiyi et al., 2017).

Recently, researchers have recognized a phase of 350 to 300 Ma tectonism characterized by dextral transpression in southern New England (Massey et al., 2017). The earlier stages of this event apparently involved dextral shearing with sub-horizontal stretching lineations. Later deformation involved the development of isoclinal folds, localization of high strain zones, and a component of vertical extrusion. Massey et al. (2017) suggested that the transpressional event may have been related to continued convergence between Meguma and Laurentia. We associate this protacted period of late Silurian to Carboniferous tectonism with the Acadian orogeny (*sensu lato*) because of the apparent continuity of geochronologic dates and deformation at the mid-crustal level in the central and southern New England Appalachians.

The 325–260 Ma Alleghanian orogeny is interpreted to record collision of Gondwana with Laurentia and the final assembly of the supercontinent Pangea (Robinson et al., 1998). However its effects are restricted primarily to Rhode Island and southeastern Connecticut at the latitude of southern New England (Robinson et al., 1998). The Mesozoic breakup of Pangea led to continental extension, magmatism, and the development of thin-skinned normal faults with associated sedimentary basins (Roden-Tice et al., 2009).

3. Methods

We have compiled a new geospatial database of geologic, petrologic, and thermochronologic data to investigate the 4D Paleozoic to Mesozoic crustal evolution of the New England Appalachians. Maps of petrologic and thermochronologic data (supplementary material) were constructed by interpolating between data points using the Spline with Barriers tool (in ArcMap 10.6). Barriers were constructed to correct for offset along fault traces documented to have experienced brittle, post-orogenic displacement (Hibbard et al., 2006; Roden-Tice et al., 2009). This dataset was integrated with geophysical P-to-S receiver function results of Li et al. (2018) who recognized a sharp (12–15 km high) step in the Moho under western New England (Fig. 1B-C). We compiled published monazite geochronology and compositional data and expanded this dataset with new monazite and xenotime petrochronology. U–Th–Pb_{total} geochronology and full compositional data were acquired in-situ with the Cameca SX100 Ultrachron electron microprobe at the University of Massachusetts Amherst. The analytical protocol follows that described by Williams et al. (2019, 2017). Detailed analytical procedures, compositional maps and data, backscattered electron images, sample localities and lithologic descriptions are provided in the supplementary material.

4. Results

Calculated metamorphic pressures (Fig. 2A) document a large region of consistent ∼0.6 GPa (6 kbar) pressures across central New England. They are interpreted to represent Acadian amphibolite to granulite-facies metamorphic conditions and the region has been referred to as the “central Massachusetts metamorphic high” (Robinson et al., 1998). The total area of ≥0.6 GPa metamorphism exceeds 20,000 km^2. The western boundary of the 0.6 GPa region roughly corresponds with the trace of the Moho step (Li et al., 2018) and Iapetan suture (Figs. 1, 2A). Lower grade (and older) conditions are preserved farther west (Robinson et al., 1998; Zen, 1991). Locally, higher-P regions occur near the trace of the Moho step (Fig. 2A), with pressures of 0.8 to ≥1.0 GPa reported from gneiss-cored domes and thrust slices (Karabinos et al., 2010; Keller and Ague, 2018).

$^{40}Ar/^{39}Ar$ hornblende, muscovite, and biotite dates show distinct gradients near the trace of the Moho step (Figs. 1B, 2B–D). All three mineral systems yield dates that are on the order of 900 to 420 Ma west of the Moho step and can likely be attributed to cooling from the Grenvillian, Taconic, and/or Salinic orogenies. East of the step, hornblende dates are 380–340 Ma over an area corresponding to the 0.6 GPa “metamorphic high” and can be attributed to cooling from the Acadian orogeny. Muscovite dates throughout the same area are 40 to 50 m.y. younger, between 340 and 300 Ma. Biotite dates show a similar spatial trend, but the dates are less consistent near the trace of the Moho step (Fig. 2D), probably due to a combination of excess ^{40}Ar, alteration, composition, variable diffusion radii, and/or analytical methods (e.g. Roberts et al., 2001). Within each mineral system, $^{40}Ar/^{39}Ar$ dates are consistent and show little variability across the 0.6 GPa domain.

Low temperature thermochronometers show a different pattern of dates with little to no difference across the trace of the Moho step (Fig. 3). $^{40}Ar/^{39}Ar$ K-feldspar analyses generally display upper intercept or total gas dates that are greater than 360 Ma west of the Green Mountains and 325-310 Ma across Vermont to New Hampshire (Fig. 3A). Dates are less than 250 Ma east of the New Hampshire-Vermont border along the eastern border fault of the Mesozoic Hartford Basin (Fig. 1A). Apatite fission track dates show no discernable gradient near or across the trace of the Moho step (Fig. 3B). A notable north-to-south gradient in fission track dates (80 Ma to 160 Ma) exists from central to southern New England. As with K-feldspar dates, there is an offset in apatite fission track dates along the trace of the eastern Connecticut Valley/Hartford Basin border fault, but this Mesozoic offset is likely relatively minor. Thus, unlike higher-T thermochronometers, low-T thermochronometers are relatively unchanged across the trace of the Moho step and throughout the area of 0.6 GPa metamorphism.

Yttrium (Y) in monazite from metapelitic rocks in central New England is systematically zoned and can be categorized into three compositional groups. Group I domains typically define the cores of zoned monazite grains and are locally found as inclusions in garnet. They are characterized by high Y content (commonly >1 wt%) and yield 400–380 Ma dates (Fig. 4C). Group II domains typically mantle group I cores and form a continuum of dates between 380 and 330 Ma. They are characterized by distinctly lower Y than Group-I domains, typically less than 0.5 wt% (Fig. 4C). Y-enriched Group-III domains form thin rims around group II mantles and are dated to 330–300 Ma.

In addition to monazite, xenotime was found in a sample of pelitic garnet-biotite-sillimanite schist from the core of the central Massachusetts metamorphic high (sample P101A). Xenotime is found in two microstructural domains distinct from monazite: as inclusions in monazite-free cores of garnet and along late fractures in garnet. Xenotime grains present as inclusions in garnet cores are relatively enriched in Yb and heavy rare earth elements and depleted in middle rare earth elements, and yield a weighted mean of 382.5 ± 11.2 Ma ($n = 4$, MSWD = 1.6). Xenotime along fractures in garnet were dated to ca. 325 to 305 Ma. These domains are relatively depleted in Yb and heavy rare earth elements and enriched in middle rare earth elements.

5. Discussion

Petrologic and thermochronologic data presented here are consistent with observations from extant and ancient orogenic plateaus and also with the results of numeral modeling studies.

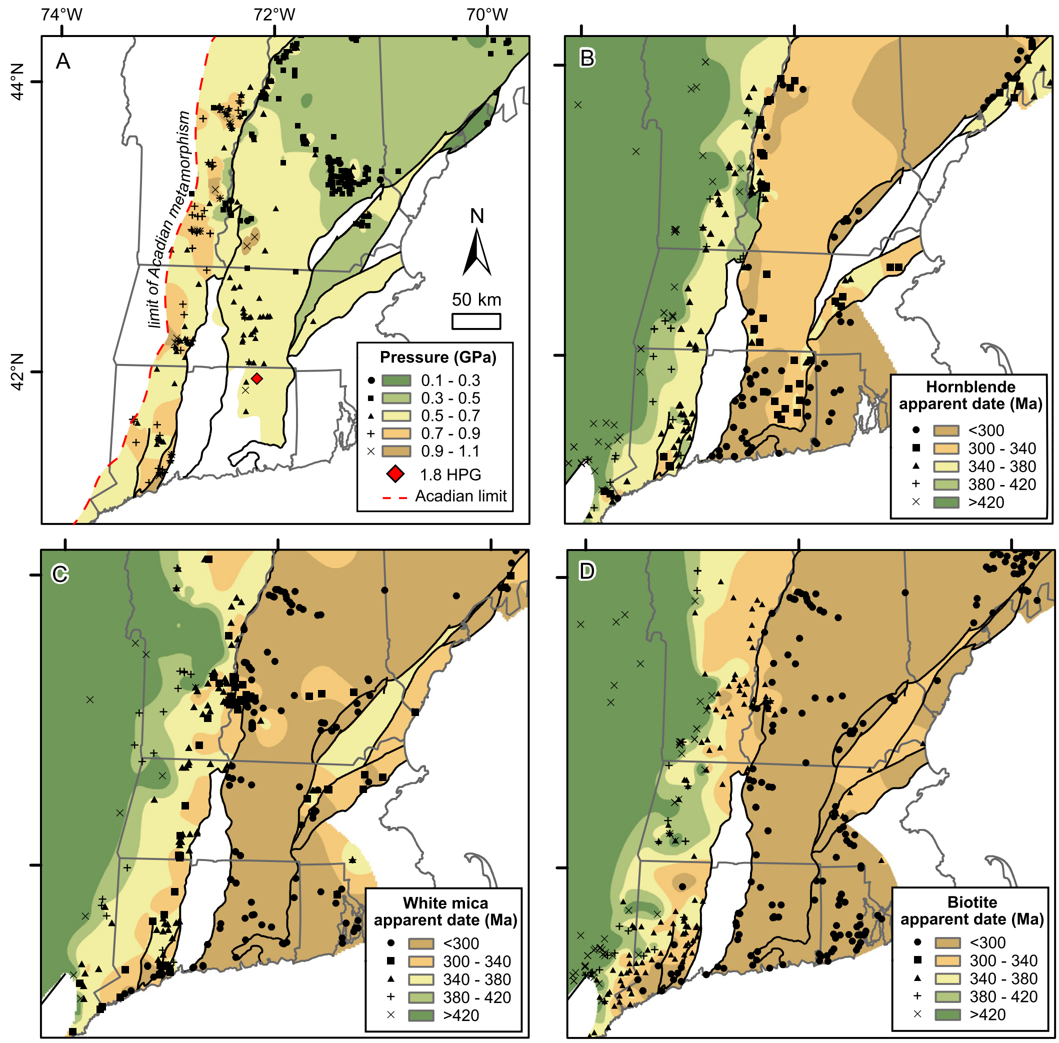

Fig. 2. Maps of metamorphic pressure and high temperature thermochronologic dates. Metamorphic pressure during the Acadian orogeny (ca. 380 Ma) (A), hornblende dates (B), muscovite dates (C), and biotite dates (D). Dates are interpreted to represent regional cooling. Dark symbols represent individual data points. See supplemental material for complete data set. The limit of Acadian metamorphism is modified from Robinson et al. (1998) to the region with hornblende dates between 420 and 300 Ma. (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)

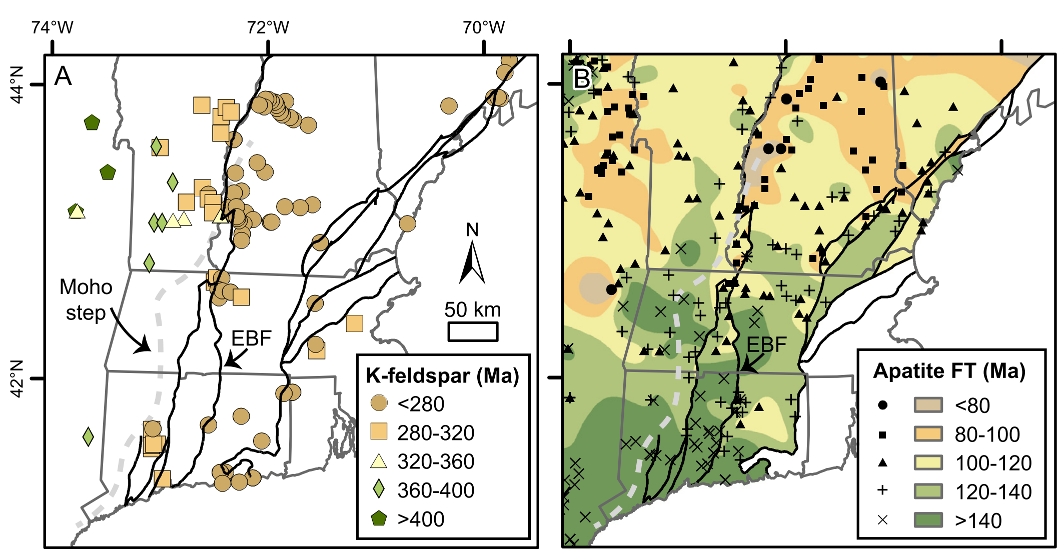

Fig. 3. Distribution of low temperature thermochronologic dates. K-feldspar upper intercept and plateau dates are shown in A and apatite fission track dates in B. K-feldspar dates are represented by 40 Ma bins as data coverage is insufficient for contour mapping. Black symbols mark individual data points on B. Details of individual data points are available in the supplement. Dashed gray line represents approximate location of Moho step shown in Fig. 1B. (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)

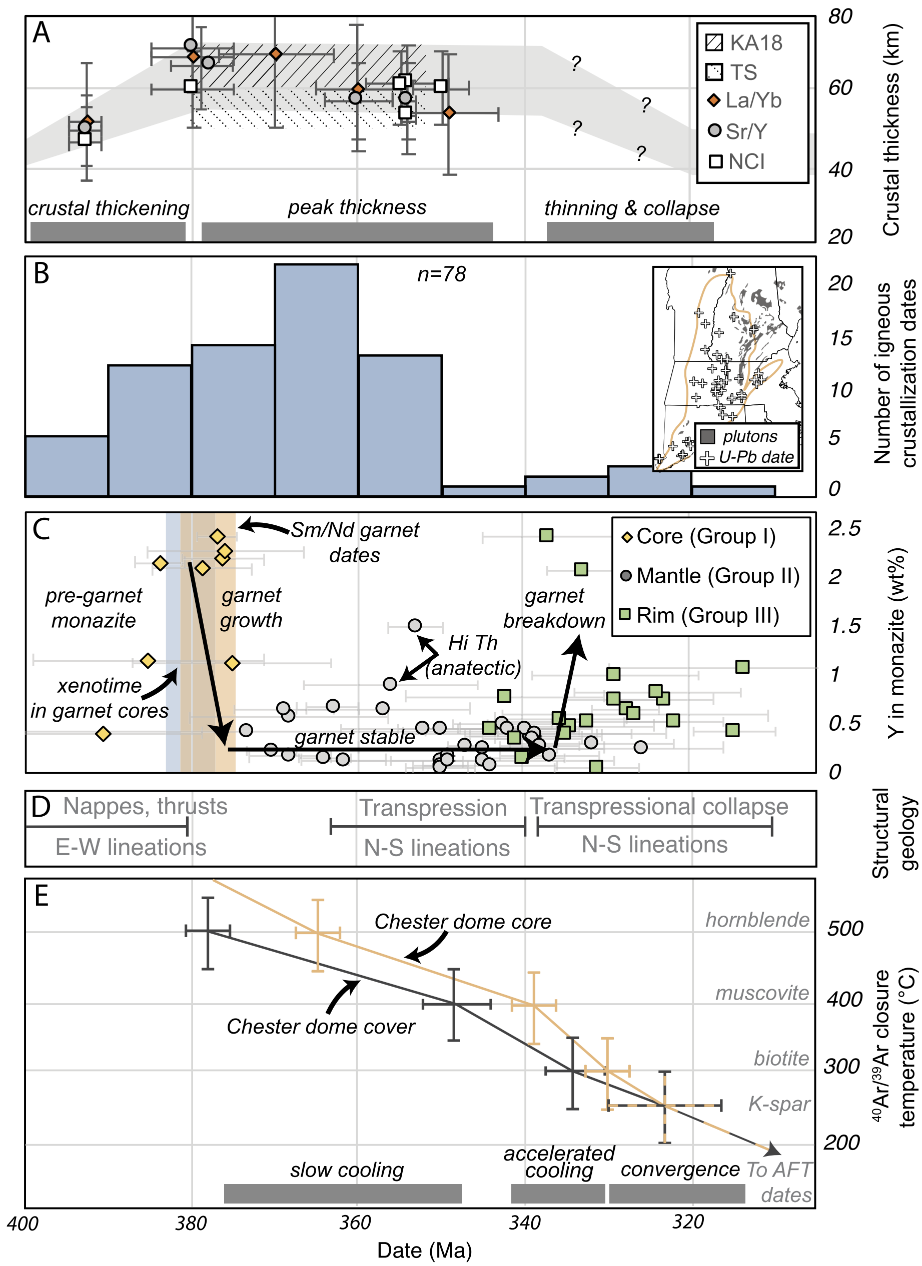

Fig. 4. Synthesis of petrologic, geochemical, geochronologic, and structural data A: Crustal thickness estimates from Keller and Ague (2018) (KA18; solid lines), the integration of thermobarometers with modern crustal thickness (TS; stippled lines) and geochemical crustal thickness estimates (La/Yb, Sr/Y, and NCI (Neodymium crustal index; DePaolo et al., 2019) thermo-isotopic proxies) from Hillenbrand (2020). Gray region indicates the interpreted crustal thickness evolution. B) Histogram of the compiled U–Pb dates of monazite and zircon interpreted to record the time of igneous crystallization shown as 10 m.y. bins. Inset: Location of 400–350 Ma plutons in gray modified from Hibbard et al. (2006) and dated localities used in compilation shown as crosses, with outline of 0.6 GPa region shown for reference. Outline indicates region of ∼0.6 GPa pressure. C: Yttrium content in monazite vs. date of core, mantle, and rims domains from representative samples from central Massachusetts. Samples used in the compilation are EB14-002, 9-1-L, 219-3-L, P14-005A-5B of McCulla (2016), CBSZ-104-L of Massey et al. (2017), and P101A and IWH20-6 from this study. These samples show consistent trends with a decrease in Y ca. 380 Ma, low values of less than 0.5 wt% Y between 380 and 330 Ma, and an increase in Y after 330 Ma. The decrease in Y corresponds with regional Sm–Nd dates and U-Th-Pb xenotime dates in core of P101A garnet cores, shown as blue and orange boxes, respectively. D: Temporal evolution of regional structural geology and rock fabrics compiled from Robinson et al. (1998) and Massey et al. (2017). E: Cooling curves of $^{40}Ar/^{39}Ar$ dates from the core and cover rocks of the Chester Dome. Temperature-time paths are distinct until they converge at ca. 325 Ma and subsequently experience the same cooling history. Note increase in cooling rate ca. 340–320 Ma. (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)

In the following paragraphs, we integrate a range of data and evaluate the evidence for the development of an orogenic plateau (the Acadian altiplano) and for the persistence of this plateau for at least 50 m.y. As discussed below, the recognition of this feature has important implications for Appalachian crustal evolution, foreland basin evolution, and Li-bearing pegmatite genesis, and provides an analogue for processes deep below modern plateaus.

Modern orogenic plateaus are characterized by high elevation, thickened crust, and broad regions of low topographic relief (Garzione et al., 2017; Hatzfeld and Molnar, 2010; Laske et al., 2013; Molnar et al., 1993). A broad zone of ∼0.6 GPa metamorphic pressure characterizes much of central and western New England (Fig. 2A). This suggests that rocks at the modern erosional surface were buried by at least 20–30 km of overburden. The regionally sub-horizontal nature of the 0.6 GPa isobar combined with the consistent and homogeneous cooling ages across the same large region suggests that the region was buried by a similar amount of overburden and exhumed homogeneously. A first order estimate of minimum syn-orogenic crustal thickness of 50-60 km can be derived from combining the burial depth with the ~30 km modern crustal column (Fig. 2B, 4A; Li et al., 2018). Keller and Ague (2018) suggested that Acadian crustal thickness may have been as great as 60–70 km based on thermobarometric analysis of lower crustal granulites from north-central Connecticut (Fig. 2A, 4A).

Inferences of a greatly thickened crust are further supported by the geochemistry of syn-Acadian igneous rocks. Recent studies have shown a correlation between crustal thickness and the trace element and isotope geochemistry of Phanerozoic convergent margin magmas (e.g. Chapman et al., 2015; DePaolo et al., 2019), and that this relationship can be applied to estimate paleo-crustal thickness. Hillenbrand (2020) used recent trace element (Sr/Y; La/Yb) and thermo-isotopic (Nd) calibrations to estimate the temporal and spatial evolution of crustal thickness in the northern Appalachians. Results from each of these proxies are consistent and indicate crustal thicknesses of 55-70 km in the ~0.6 GPa region by 380 Ma (Fig. 4A). Furthermore, they suggest that these crustal thicknesses were sustained for at least 30 m.y. (Fig. 4A).

The consistency between petrologic and geochemical estimates provide compelling evidence for syn-Acadian crustal thicknesses akin to those of modern and ancient orogenic plateaus (55 to 70 km; Chapman et al., 2015, 2020; DePaolo et al., 2019; Laske et al., 2013; Rivers, 2012), on the order of twice the modern global average of ~35 km (Laske et al., 2013). Similarly, paleo-elevation estimates of 3 to 5 km derived from Airy Isostacy and empirically derived equations (Hillenbrand, 2020) are similar to estimates for modern and ancient orogenic plateaus (2 to 5 km; Chapman et al., 2020; Ernst, 2010; Garzione et al., 2017; Hatzfeld and Molnar, 2010). While paleoelevation studies have not been carried out in the northern Appalachians due to the deep level of exposure, sedimentological evidence from the foreland basin for alpine glaciation at subtropical latitudes indicate significant (at least several km) of elevation in the Acadian hinterland (Ettensohn et al., 2019).

Numerical models suggest that rheological weakening caused by a hot, weak, low viscosity mid-crust is responsible for the signature low topographic relief of orogenic plateaus (e.g. Jamieson et al., 2004). Thermal-mechanical experiments designed to model orogenic plateaus predict mid-crustal amphibolite to granulite facies metamorphic conditions at temperatures of 600 to 800 °C, accompanied by widespread partial melting (e.g. Jamieson et al., 2004). Mid-crustal exposures in New England record regional amphibolite to granulite facies conditions at temperatures of 600 to 825 °C (e.g. Robinson et al., 1998; Thomson, 2001; Tracy and Dietsch, 1982). The rocks also record widespread and prolonged anatexis (e.g. Massey et al., 2017; Robinson et al., 1998; Thomson, 2001). Compilation of U–Pb dates from anatectic rocks in the ~0.6 GPa region shows a continuum of dates between 380 and 330 Ma, with a broad peak between 380 and 350 Ma (Fig. 4B). Further, the composition and zoning of some Group II monazite domains from migmatitic rocks are consistent with crystallization from anatectic melts (Kohn et al., 2005). The wide range of these dates and lack of systematic distribution suggests that, regionally, the mid-crust of central New England was hot and, because of the high-temperatures and presence of partial melt, had relatively low viscosity. This hot, at least episodically partially molten, crust was likely too weak to support significant topographic relief favoring the existence of a low relief plateau, in accord with the consistent 0.6 GPa pressures across the large region.

Quantitative models of plateaus predict metamorphic temperatures of in excess of 900 °C in the lower crust (Jamieson et al., 2004). Ultra-high temperature (>1000 °C) metamorphic conditions have been observed in xenoliths from the Tibetan plateau (reviewed in Kapp and DeCelles, 2019). Rocks recording similar conditions have been reported in this region of the New England Appalachians. Disaggregated blocks and xenoliths of granulite facies gneiss locally record ultra-high temperature conditions in excess of 1000 °C at pressures of 1 to 1.8 GPa (Ague et al., 2013; Keller and Ague, 2018). While precise timing of extreme metamorphic conditions and the emplacement history of these rocks remains poorly constrained, they provide evidence of a hot Acadian lower crust.

Thermochronologic data show that the central New England region of 0.6 GPa pressures cooled slowly and homogeneously after the peak of Acadian activity. The systematic trends of $^{40}Ar/^{39}Ar$ dates and lack of sharp differences between plutonic and metamorphic rocks indicate that they probably represent the ages of regional cooling. The lack of sharp gradients in $^{40}Ar/^{39}Ar$ hornblende, muscovite, and biotite dates, cooling rates, and thermobarometric conditions throughout central New England support the inference that the region was exhumed homogeneously. Slow cooling, at integrated rates of 2–4 °C/m.y., is shown by the 40 to 50 m.y. lag between the time of the closure of Ar diffusion in hornblende (500 ± 50 °C, Harrison, 1982) and muscovite (400 ± 50 °C; Harrison et al., 2009). A maximum cooling rate of 5 °C/m.y. is constrained by geospeedometry (Tracy and Dietsch, 1982). A wide range of petrologic studies have suggested a nearly isobaric retrograde P–T path for central New England including evidence from conventional thermobarometry of retrograde shear zones, fluid inclusions, and petrogenetic grid analysis (Robinson et al., 1998; Thomson, 2001; Tracy and Dietsch, 1982). This P–T path indicates that the rocks were buried in the mid-crust for a prolonged period of time before being exhumed in a later event. Prolonged mid-crustal residence and slow cooling would be predicted for rocks buried in the core of a long-lived plateau.

Monazite geochemistry and geochronology provide an additional record of metamorphic and structural evolution. Monazite compositional domains can be linked with silicate reactions and deformation fabrics to place temporal constraints on the P–T history (Williams et al., 2017 and references therein). In particular, the Yttrium content in monazite can be linked to reactions involving garnet, a key metamorphic index mineral, especially if other Y-bearing phases are absent. Garnet incorporates significant Y and, hence, is typically associated with low-Y monazite (Williams et al., 2017).

Group I domains (400–380 Ma), generally enriched in Y, are interpreted to have crystallized before significant garnet growth (Massey et al., 2017). These domains are temporally linked with fabrics related to early Acadian orogenesis involving west-directed folding, thrust faulting, and nappe emplacement (Fig. 4D; Robinson et al., 1998).

Group II domains (380–330 Ma) are characterized by distinctly lower Y than Group I domains (Fig. 4C), suggesting monazite growth in the presence of garnet. The decrease in Y in monazite is consistent with ca. 380 Ma xenotime in garnet cores and published garnet Sm–Nd dates (Fig. 4C; Gatewood et al., 2015; Sullivan, 2014). The latter have been interpreted to represent garnet growth during prograde metamorphism and crustal thickening (Gatewood et al., 2015; Sullivan, 2014). This interpretation is supported by geochemical evidence for crustal thickening between 400 and 380 Ma (Fig. 4A; Hillenbrand, 2020) as well as contemporaneous rapid subsidence and black shale deposition in the adjacent foreland basin (Ettensohn et al., 2019). Further evidence for monazite growth during high grade metamorphism comes from domains characterized by high Th/U ratios, slightly elevated Y values, and weak oscillatory Th zoning, suggestive of their crystallization from anatectic melts (Kohn et al., 2005). Low-Y monazite continued to grow until ca. 330 Ma suggesting that garnet was stable in these rocks for as much as 50 m.y. This is also consistent with geochemical evidence for the persistence of thickened crust for a minimum of 30 m.y. (Fig. 4A). Massey et al. (2017) linked Group II monazite domains to dextral transpressive fabrics, orogen

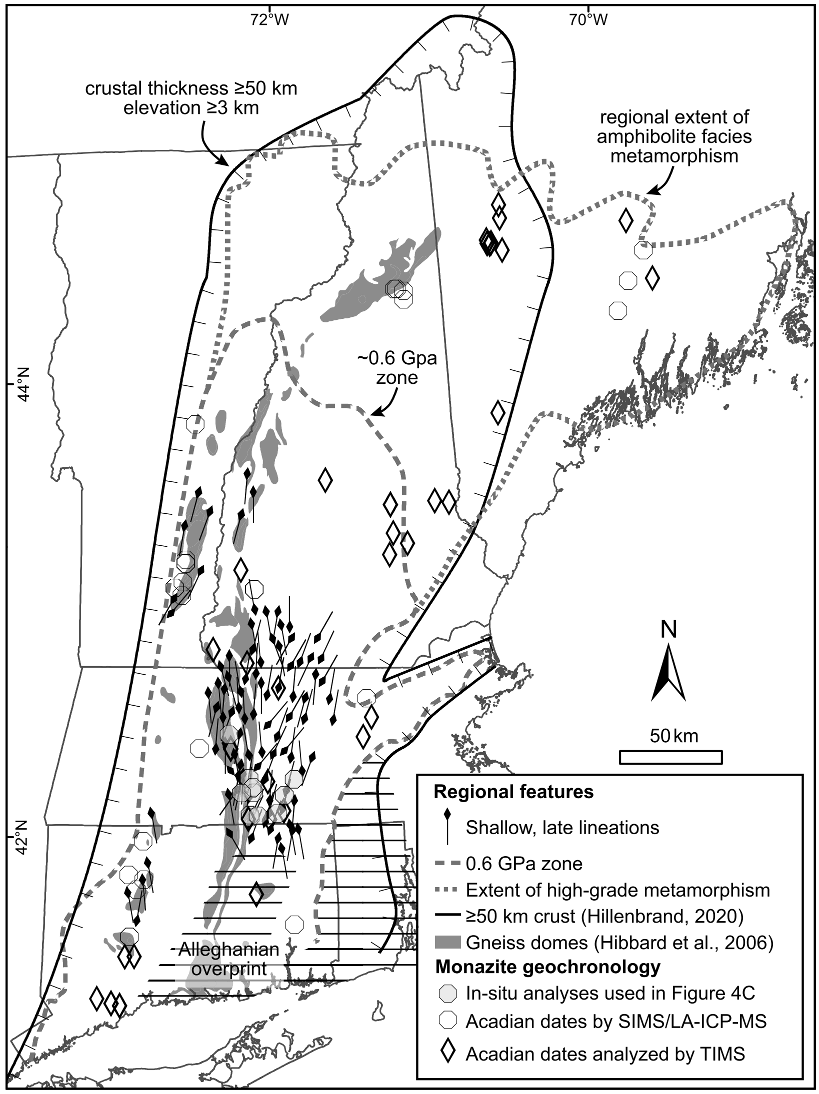

Fig. 5. Spatial distribution of features discussed in text. Arrows indicate the location and orientation of late, shallow N–S lineations. Shaded regions indicate the areal extent of gneiss domes (Hibbard et al., 2006). Long and short dashed lines indicate approximate regions of ∼0.6 GPa pressures and upper amphibolite facies or higher metamorphism, respectively (adapted from Robinson et al., 1998). Hachured line represents the region of thickened (≥50 km) crust (adapted from Hillenbrand, 2020). Locations of monazite geochronology are symbolized by the type of analysis. Sources of lineation data and monazite geochronology are available in the supplementary data.

parallel flow, and interpreted the continuous range of dates to indicate protracted deformation at mid-crustal conditions (Fig. 4D).

We interpret the Y-enriched monazite of Group III to record the breakdown of garnet, releasing Y during decompression and/or cooling ca. 330–300 Ma (Fig. 4B). This interpretation is corroborated by growth of ca. 325–305 Ma xenotime along fractures in garnet. The microstructural setting and composition of group III monazite also constrain the timing of development of the strong, shallowly plunging N-S lineations (Massey et al., 2017). These fabrics, the orientations of which are shown in Fig. 5, are reflective of orogen parallel mid-crustal flow and a component of vertical thinning which characterize (post-)Acadian orogenic collapse in southern New England (Fig. 4D; Massey et al., 2017).

Together, monazite geochemistry and geochronology and Sm-Nd garnet dates suggest that garnet may have been stable in these rocks for upwards of 50 m.y (ca. 380 Ma – ca. 330 Ma). This Y-monazite-garnet relationship has been observed in other terranes which have also experienced prolonged residence in the mid- to deep crust of orogenic plateaus (Kohn et al., 2005; Williams et al., 2019). We interpret period of low-Y monazite (i.e., garnet stability at 0.6 GPa) to correspond with thickened crust and the duration of the orogenic plateau (Fig. 4A, C). Further, as the stability of garnet is largely pressure dependent, 330–300 Ma monazite rims provide a constraint on the timing of exhumation, and thus, orogenic collapse in rocks that have previous experienced periods of isobaric cooling (Fig. 4C–D). These observations are in agreement with geologic and geophysical observations from both modern and ancient orogenic plateaus and with the predictions of numerical models (DeCelles, 2004; Garzione et al., 2017; Jamieson et al., 2004; Kapp and DeCelles, 2019). This hypothesized paleo-plateau likely existed for approximately 50 m.y. (380 to 330 Ma) based on petrologic evidence, $^{40}Ar/^{39}Ar$ thermochronology, the prolonged stability of garnet, and the dates and composition of igneous rocks.

The minimum region of this hypothesized plateau is constrained by the region of ∼0.6 GPa pressures, slow cooling, and thickened crust. The present east-west extent, or width (perpendicular to strike), of the 0.6 GPa zone is approximately 150 to 200 km and is roughly similar to much of the width of the Andean Altiplano and Puna plateau (Garzione et al., 2017). This value is similar to the 200-300 km width of the Iranian plateau and the 350 km width of the Tibetan Plateau at its thinnest (Hatzfeld and Molnar, 2010), although significantly thinner than widest portions of the Tibetan Plateau (≥1000 km). The north-south extent of the 0.6 GPa zone is approximately ∼300 km, somewhat smaller to the 400–500 km length of the Pamir salient, approximately half of the length of the Altiplano (∼700 km), and an order of magnitude smaller than the ∼2,500 km long Tibetan Plateau. However, neither the northern nor the southern extents of the hypothesized plateau region in New England can be as well constrained. The smooth gradation of pressures along strike to the north does not present a clear boundary. Geochemical evidence suggests that thickened Acadian crust (greater than 50 km) and elevations of ≥3 km extended perhaps as far as northern Vermont and as far east as western Maine (Fig. 5; Hillenbrand, 2020). Hillenbrand (2020) suggested that this region may represent an extension of the Acadian altiplano or a transitional region to the thinner (∼40 km) crust of Maine. The southern limit of the ∼0.6 GPa zone is not presently exposed, being buried under sediments of the coastal plain (Hibbard et al., 2006). Sedimentological data suggest that high elevations and crustal loading continued south along orogenic strike (Ettensohn et al., 2019). Similarities in petrologic observations and thermal histories to New England, and tectonic models suggesting channel flow, observed in the Inner Piedmont of the southern Appalachians (Huebner et al., 2017) may be compatible with the plateau hypothesis. Together, these suggest the plateau may have extended significantly farther south. Plateau collapse, Alleghanian shortening and deformation, and Mesozoic rifting have also have reduced the present aerial extent of plateau exposure in New England. Considering these factors, the hypothesized Acadian altiplano was perhaps on the scale of the Altiplano, Puna or Pamir plateaus but smaller than the modern Tibetan Plateau.

Sustaining a thickened, rheologically weak crust likely requires continued compressional stress. Structural and geochronologic studies in central New England have shown protracted shortening and transpression through the Devonian and Carboniferous (Massey et al., 2017; Robinson et al., 1998). We envision that this was produced by continued collisional orogenesis during accretion of the Avalon and/or Meguma terranes to composite Laurentia (Massey et al., 2017; Robinson et al., 1998; van Staal et al., 2009). Meguma may have accreted as a distinct terrane or as a promontory of Gondwana (Kuponiyi et al., 2017; van Staal et al., 2009). Alternatively, an oblique, advancing, or progressively flattening subduction zone, following step-back behind the accreted Avalon and/or Meguma terrane(s), could have supported the hypothesized plateau (Kuponiyi et al., 2017), reminiscent of some models for the formation of the Nevadaplano (DeCelles, 2004).

Orogen-parallel extension and north-south domal extrusion juxtapose high-P (0.8 to ≥1 GPa; Fig. 2A) cores of gneiss domes with 0.6 GPa cover rocks (Fig. 2A, 5; Karabinos et al., 2010; Massey et al., 2017; Thompson et al., 1968). Thermochronologic evidence from the Chester Dome of western Vermont (C on Fig. 1A) constrains the timing of juxtaposition of high-P rocks of the dome core against 0.6 GPa cover rocks. Pre-325 Ma cooling ages from the core of the dome are consistently younger than those of the cover rocks implying the core rocks were hotter and more deeply buried (Fig. 4E). However, thermochronologic dates from core and cover rocks converge at 325 Ma (Fig. 4E). This suggests that they were in thermal equilibrium and at the same structural level by ∼325 Ma. Corollary evidence for exhumation of the core Chester Dome at this time comes from 340–310 Ma xenotime halos around garnet (Gatewood et al., 2015). These halos are interpreted to have formed during garnet-consuming reactions during decompression (Williams et al., 2017), i.e. during Carboniferous orogenic collapse. The structural and kinematic similarities between the Chester Dome and other New England gneiss domes (Karabinos et al., 2010) and their compatibility with 330-310 Ma fabrics in central New England (Massey et al., 2017), suggest that these constraints may be broadly applicable to many of the core-complex like domal structures.

Rivers (2012) proposed that plateau collapse may produce a characteristic thermochronologic signature due to the juxtaposition of regions of colder, upper crust with hotter, deeper crust. The signature was interpreted in the Grenville province where low-grade upper crustal blocks preserving $^{40}Ar/^{39}Ar$ hornblende apparent dates that predate metamorphism in the Ottawan orogeny (ca. 1080 Ma) are juxtaposed against middle crustal blocks yielding post-Ottawan dates (Rivers, 2012). Fig. 2B shows a 200 km, N-S trending belt from northern Massachusetts to eastern Vermont of rocks with anomalously old, pre-Acadian $^{40}Ar/^{39}Ar$ hornblende apparent dates. In this belt, Ordovician to Silurian dates are preserved in rocks that are commonly thought to have undergone Acadian (Devonian) metamorphism. A possible explanation is that they represent a block of Acadian upper crust that was down-dropped during the collapse. Ar release spectra from in this belt are complex and suggestive of one or more trapped Ar components (Spear and Harrison, 1989). Similar Ar release spectra are observed in $^{40}Ar/^{39}Ar$ hornblende dates of the Ottawan orogenic lid, which also preserves anomalously old dates relative to the orogen (Rivers, 2012). Rivers (2012) attributed this to incomplete diffusion of radiogenic Ar as the cool orogenic lid came into contact with hot mid-crust during collapse of the Ottawan orogenic plateau.

Collapse of overthickened crust in New England apparently occurred with continued compressional tectonic stress (Massey et al., 2017). We suggest that collapse may have initiated as convergence rates decreased between composite Laurentia and accreting terranes or as a result of plate reorganization due to the changing stress field associated with approach of Gondwana (Robinson et al., 1998). Kuiper (2016) proposed that subduction of an oceanic ridge and associated transform fault and development of a Mendocino-style triple junction could explain concurrent patterns of collisional and strike slip tectonics in the New England Appalachians. Southwestward propagation of strike-slip motion and associated changes in plate motion in this model could have decreased stress that sustained the plateau and led to the initiation of orogenic collapse. If models suggesting a flattening subduction zone outboard of the accreted Avalon and Meguma terranes are correct (Kuponiyi et al., 2017), then steepening or breakoff of the slab may have initiated collapse. These models, in which collapse of the Acadian altiplano is related to a change in subduction style, are reminiscent of hypotheses for collapse of the Nevadaplano in the western U.S.A. (Ernst, 2009).

The widespread occurrence of 0.6 GPa pressures at the present ground surface indicates that, since the mid-late Paleozoic, approximately 20 to 30 km have been stripped from the crust in central New England versus 3–7 km in eastern New York (Zen, 1991). Intriguingly, this apparent ∼15 to 25 km difference in the current erosional surface is similar to the magnitude of offset of the Moho step (Fig. 1B–C; Li et al., 2018). We suggest that thinning of the overthickened crust of the orogenic plateau was associated with the development or amplification of the Moho step and the dramatic differences in Moho depth beneath these two domains. The location and initiation of the Moho step are probably related to accretionary tectonics (i.e. Gondwanan terranes against Laurentia) but it reached its present state during collapse of the Acadian altiplano.

Low temperature thermochronology can place a lower bound on the timing of plateau collapse and exhumation and also on the establishment of the Moho step. The absence of an east to west gradient across the Moho step in K-feldspar $^{40}Ar/^{39}Ar$ and apatite fission track dates (Fig. 3) contrasts strongly with the large offset recorded by high temperature thermochronometers (Fig. 2B–D). The lack of a discontinuity suggests that rocks on either side of the Moho step were juxtaposed by the time of cooling through the closure temperature of the K-feldspar and apatite fission systems. Cooling histories compiled for rocks to the east and west of the

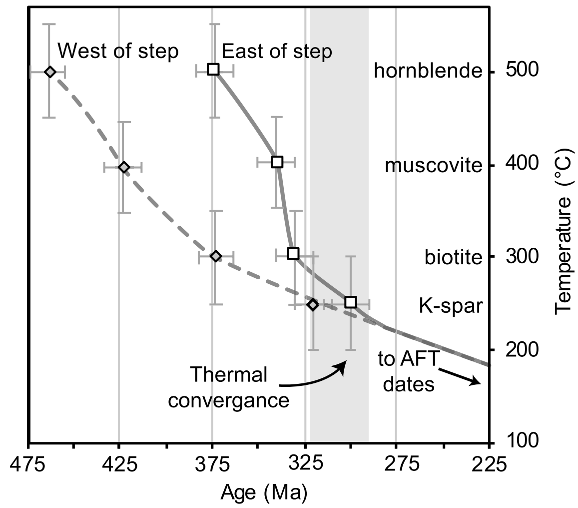

Fig. 6. Representative thermal histories for regions east and west of the Moho step. The full thermochronologic dataset is available in the supplementary material.

Moho step converge between ca. 300 and 280 Ma (Fig. 6). This indicates that rocks east and west of the step were juxtaposed, and thus, the Moho step likely existed, by at least this time.

A break in apatite fission track and K-feldspar dates is observed 40–60 km east of the trace of the Moho step along the eastern border fault of the Mesozoic Hartford rift basin (Fig. 3B; Roden-Tice et al., 2009). This discontinuity is likely related to a few (∼1-3) km of vertical offset along the border fault (Haugerud, 1990; Thompson et al., 1968). However, the relatively minimal amount of offset and listric nature of the border fault are inconsistent with the steepness and magnitude of the Moho step (Thompson et al., 1968). Further, detrital apatite (U–Th)/He dates suggest that New England has likely experienced relatively uniform Mesozoic to present exhumation and that terrane boundaries have not been significantly reactivated (McKeon, 2012). Consequently, the Moho step is unrelated to Mesozoic continental extension or younger processes.

One additional constraint on the crustal evolution may come from Triassic to Cretaceous magmatic rocks that are exhumed to relatively shallow levels (2–5 km) across New England and adjacent New York State (Zen, 1991). The uniform level of exposure, despite the wide spatial distribution of these rocks, may be evidence that the major crustal offset occurred prior to this magmatic episode.

Our age constraints indicate that the steep Moho step (Li et al., 2018) has been preserved for at least 300 m.y. Thermobarometric and thermochronologic discontinuities, and the Moho step, all follow the trend of the Iapetan suture between Laurentian- and Gondwanan-derived tectonic elements (Figs. 1, 2; Karabinos et al., 2017), suggesting that the suture may have been reactivated in forming the Moho step. The steepness of the present-day step may reflect the reactivation, during collapse, of a steeply dipping, pre-existing structure. This may reflect an initially shallow tectonic boundary which was progressively steepened during collisional events or an originally steep boundary, such as that described by Klepeis et al. (2019). In addition, lithospheric differences between more rigid Laurentian lithosphere and the more juvenile lithosphere of the accreted terranes (Li et al., 2018) would help to localize later deformation (reactivation) along the tectonic boundary.

Isostatic compensation from the relatively more buoyant, juvenile lithosphere underneath New England may have contributed to differential uplift/exhumation and thus, to the Moho discontinuity. Towards the north, the dip of the Moho step decreases but continues to correspond to the 0.6 GPa terrane boundary and the gradient in Acadian cooling ages (Fig. 2). Notably the gradient in metamorphic pressures from north to south in central New Hampshire is also more gradual than the east-west gradient in western New England (Fig. 2A). This may be due to smaller differences in crustal rheology between accreted terranes than between these terranes and the Laurentian craton. Alternately, it may be related to differences in Acadian crustal thickness and shortening along orogenic strike (Hillenbrand, 2020).

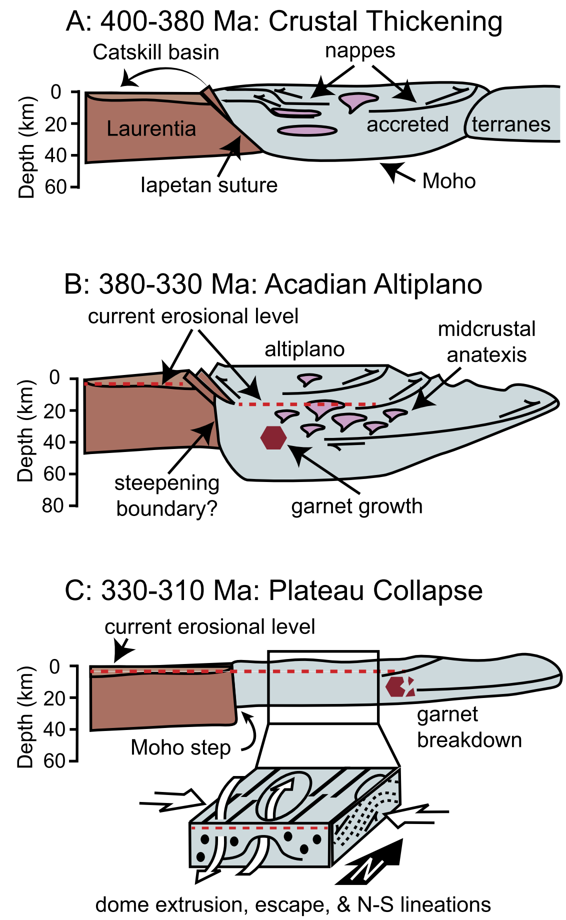

Fig. 7. Simplified model for the tectonic evolution of the Acadian Orogeny and the Acadian altiplano at approximately the latitude of section A–A′ in Fig. 1B. Horizontal distances and garnet are not to scale. A: Early Acadian (400–380 Ma) crustal thickening involving east-west shortening, divergent nappe emplacement, and magmatic additions. B: Establishment of the Acadian altiplano ca. 380 Ma from continued thickening. Dashed red line represents the modern erosional surface. C: Collapse of the plateau, ca. 330–310 Ma. The crust of the altiplano is significantly thinned relative to Laurentian crust forming the Moho step, perhaps by reactivation of the suture between Laurentian and Gondwanan tectonic elements. Inset: Kinematic model of plateau collapse involving the northward extrusion of gneiss domes and orogen parallel escape (adapted from Karabinos et al., 2010 and Massey et al., 2017). (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)

These results and interpretations are summarized in Fig. 7. Crustal thickening involving east-west shortening, divergent nappe emplacement, and magmatic additions occurred between ca. 400 and 380 Ma (Fig. 7A). Crustal thickening resulted in the formation of a high elevation, low relief orogenic plateau due to a hot and rheologically weak mid-crust (Fig. 7B). Continued convergence of terranes with composite Laurentia sustained the plateau for ca. 50 m.y. until collapse began ca. 330 Ma. Plateau collapse was orogen parallel, involving the formation of core complex-like gneiss domes and development of the steep Moho step (Fig. 7C).

6. Implications

The 50 m.y. duration of the Acadian altiplano in New England is within the range interpreted for the Tibetan Plateau (DePaolo et al., 2019; Kapp and DeCelles, 2019) and for several proposed paleoplateaus (Chapman et al., 2020, 2015; Rivers, 2012; Williams et al., 2019). The long duration suggests a balance of forces involving tectonic convergence, ductile (gravitational) flow, and erosion. The balance was apparently disrupted at ca. 330 Ma when N-S ductile flow and erosion led to crustal thinning and exhumation. The lifespan of the plateau places constraints on tectonic models by requiring sustained plate convergence during and after the Acadian orogeny (*sensu lato*).

A suite of lithium-cesium-tantalum (LCT) pegmatites, dated to 370–325 Ma (Bradley et al., 2016), lie along the edge of the proposed plateau and the trace of the Moho step, suggesting a relationship to the altiplano. LCT pegmatites are interpreted to be the product of plate convergence and paleoclimate, commonly occurring in orogenic belts with salars perched along the orogenic axis, as deeply circulating brines interact with magma (Bradley, 2019). The uplift of orogenic plateaus have strong orographic effects (Ernst, 2010; Molnar et al., 1993) which potentially facilitate enrichment of Li in brines (Bradley, 2019). This may be applicable to the Acadian altiplano hypothesis, where arid conditions are indicated by nearby concurrent deposition of climate-sensitive redbeds and other paleobotanic evidence (Ettensohn et al., 2019). The current erosion level may provide insight into deeper processes ongoing today in the Li-rich districts such as the modern Andean salars and, specifically, into the primary (igneous?) source of Li to the surficial brines.

Crustal thickening of the Acadian hinterland led to the development of the large Catskill foreland basin (Ettensohn et al., 2019; Robinson et al., 1998). A currently unexplained aspect of the Catskill basin is the lack of Gondwanan-derived Neoproterozoic detrital zircon, common in the Acadian hinterland, and the dominance of Mesoproterozic, Grenville-sourced zircon (Thomas et al., 2020). The orogenic plateau model may help to explain this conundrum. Orographic effects localize erosion to the edges of plateaus while simultaneously decreasing erosion from the plateau interior (Ernst, 2010). Gondwanan-derived detrital zircon is first noted in midcontinent basins at approximately the time of collapse of the plateau (Thomas et al., 2020), perhaps due to increased erosion rates and/or drainage reorganization. It is also intriguing to note that the Acadian sedimentary wedge is thickest adjacent to southern New England and the region of thickened crust of the hypothesized plateau (Ettensohn et al., 2019).

Numerous studies have noted connections and implications of orogenesis for global carbon flux and climate on million year time scales (Raymo and Ruddiman, 1992). Orogens can serve as a source of carbon, from volcanic degassing or degassing of carbonate-bearing rocks during metamorphism, or as a sink during silicate weathering or carbon burial. Stewart and Ague (2018) calculated a total flux of $0.5*10^{18}$ to $1.7*10^{18}$ $\mathrm{mol\,CO_2\,Myr^{-1}}$ for prograde metamorphism of the Acadian orogeny. These values are on the other of those which can drive global climate change and consistent with global temperature increases in the early Devonian (Stewart and Ague, 2018). However, the mid and late Devonian are characterized by a decrease in global temperature and mass extinction (Averbuch et al., 2005; Ettensohn et al., 2019). It has been noted that the uplift of Cenozoic orogenic plateaus may have driven cooling through chemical weathering processes (e.g. Raymo and Ruddiman, 1992). Paleogeographic models place the Acadian orogen in the subtropics (Bradley, 2019) where carbon sequestration via chemical weathering is relatively enhanced. Speculatively, enhanced silicate weathering of the Acadian altiplano may have been one of the factors contributing to late Devonian global cooling and biotic instability.

7. Conclusions

Petrologic, geochronologic, and geologic data from central New England are consistent with the signature of an exhumed orogenic plateau. We propose that the crust of the Acadian altiplano was thickened to 55 to 70 km by 380 Ma and remained so through continued plate convergence for ca. 50 m.y until it underwent orogen-parallel collapse ca. 330–300 Ma. Our model is consistent with geologic observations and may help to explain enigmatic features of the foreland basin, Moho structure, and paleoclimate, while perhaps providing a window into the deeper processes of orogenic plateaus including partial melting, plutonism, ductile extension, and Li mineralization.

CRediT authorship contribution statement

Ian W. Hillenbrand: Investigation, Methodology, Visualization, Writing – original draft. **Michael L. Williams:** Funding acquisition, Resources, Visualization, Writing – review & editing. **Cong Li:** Visualization, Writing – review & editing. **Haiying Gao:** Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2021.116797.

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