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Paleozoic evolution of crustal thickness and elevation in the northern Appalachian orogen, USA

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ABSTRACT

The Acadian and Neoacadian orogenies are widely recognized, yet poorly understood, tectono-thermal events in the New England Appalachian Mountains (USA). We quantified two phases of Paleozoic crustal thickening using geochemical proxies. Acadian (425–400 Ma) crustal thickening to 40 km progressed from southeast to northwest. Neoacadian (400–380 Ma) crustal thickening was widely distributed and varied by 30 km (40–70 km) from north to south. Doubly thickened crust and paleoelevations of 5 km or more support the presence of an orogenic plateau at ca. 380–330 Ma in southern New England. Neoacadian crustal thicknesses show a strong correlation with metamorphic isograds, where higher metamorphic grade corresponds to greater paleo-crustal thickness. We suggest that the present metamorphic field gradient was exposed through erosion and orogenic collapse influenced by thermal, isostatic, and gravitational properties related to Neoacadian crustal thickness. Geobarometry in southern New England underestimates crustal thickness and exhumation, suggesting the crust was thinned by tectonic as well as erosional processes.

INTRODUCTION

Present-day variations in crustal thickness are relatively well known (Laske et al., 2012), but the timing and magnitude of crustal thickening and surface uplift variations in ancient mountain belts are poorly constrained (Molnar et al., 1993; Garzione et al., 2017). Traditionally, episodes of crustal thickening have been interpreted from geobarometry and the geometry of metamorphic isograds (Carmichael, 1978; Spear et al., 1984). However, these methods cannot constrain the thickness of crust below the current exposure, and interpretations can be complicated by later overprinting. The geochemistry of syncollisional igneous rocks has recently been proposed as a paleo–crustal thickness proxy (Hu et al., 2017; DePaolo et al., 2019), offering a promising tool with which to study the crustal evolution of ancient convergent margins.

The Appalachian Mountains (eastern United States) are a classic example of accretionary tectonics, yet first-order questions abound in the New England section of the orogen. The nature, timing, and significance of the Acadian and Neoacadian tectono-thermal events and the potential existence of an orogenic plateau are not well constrained due to polyphase deformation, high-grade metamorphism, along-strike heterogeneity, and an apparent continuum of geochronologic dates (Robinson et al., 1998; Hillenbrand et al., 2019). Constraints on crustal thickness during Appalachian orogenesis are essential for testing tectonic models and for drawing conclusions about large-scale Earth system processes.

We investigated the magnitude and spatial pattern of crustal thickening during the Acadian and Neoacadian orogenies in New England using geochemical proxies. The data suggest two stages of thickening that culminated in the formation of an orogenic plateau in southern New England. Variations in crustal thickness are strongly correlated with exposed metamorphic isograds, suggesting that the amount and style of orogenic collapse and isostatic rebound played a major role in the development of the modern metamorphic field gradient.

GEOLOGIC BACKGROUND

The tectonic elements of the Appalachian orogen record multiple phases of Phanerozoic tectonism (Fig. 1). Orogenesis began with the Taconic orogeny (475–445 Ma), interpreted to represent collision between Laurentian and Ordovician island arc(s) built on the Gondwanan-derived Moretown terrane in New England (Macdonald et al., 2014). The Salinic orogeny (440–430 Ma) involved accretion of Ganderia, a peri-Gondwanan domain, to Taconic-modified composite Laurentia (van Staal et al., 2009). The Acadian orogeny is marked by nappe emplacement and magmatism and is attributed to collision between composite Laurentia and Avalonia, a Gondwanan-derived domain (423–385 Ma, Robinson et al., 1998; 425–400 Ma, van Staal et al., 2009). The enigmatic Neoacadian orogeny (366–350 Ma, Robinson et al., 1998; 400–340 Ma, van Staal et al., 2009) has been characterized on the basis of geochronology, high-grade metamorphism, plutonism, and the overprinting of Acadian structures. It has been associated with accretion of the peri-Gondwanan Meguma terrane (van Staal et al., 2009). The 325–260 Ma Alleghanian orogeny is interpreted to record collision of Gondwana with Laurentia and the final assembly of Pangea, although its effects are restricted primarily to southeastern New England (Robinson et al., 1998; Wintsch et al., 2014). Mesozoic extension associated with the breakup of Pangea led to magmatism, normal faulting, and the development of rift basins (Zen, 1991).

METHODS

We applied crustal thickness and paleoelevation proxies to a newly compiled geochemical database for the northern Appalachian Mountains. Hu et al. (2017, 2020) developed trace-element proxies from global correlations of crustal thickness, elevation, Sr/Y, and chondrite-normalized La/Yb (La/Yb_n) values in syncollisional igneous rocks. This has been interpreted to reflect magma generation, assimilation, and differentiation occurring near the Moho. As the crust thickens, garnet and amphibole are increasingly stable, sequestering Y and Yb, while plagioclase breaks down, releasing Sr and La, which results in increasing Sr/Y and La/Yb ratios in the melt phase. The thermo-isotopic neodymium crustal index (NCI) of DePaolo et al. (2019) uses the degree of crustal assimilation as a proxy for crustal thickness. It operates on the assumption that most melt hybridization occurs at or near the base of the crust and that higher degrees of assimilation are

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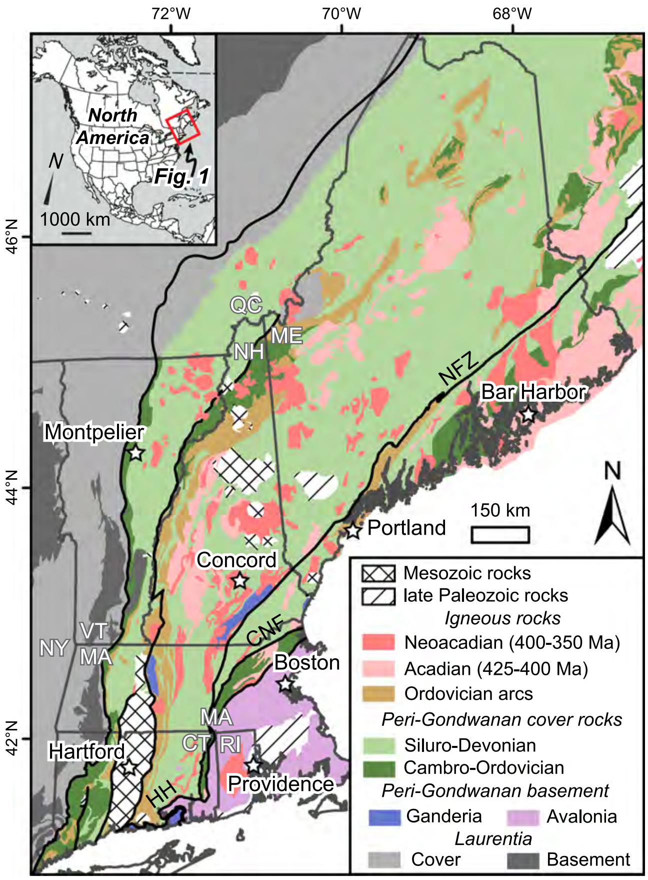


Figure 1. Tectonic map of the northern Appalachians, modified from Hibbard et al. (2006). NFZ—Norumbega fault zone, CNF—Clinton-Newbury sfault, HH—Honey Hill fault. State abbreviations: CT—Connecticut, ME—Maine, MA—Massachusetts, NH—New Hampshire, NY—New York, RI—Rhode Island, VT—Vermont, QC—Québec (Canada).

associated with higher wall-rock temperatures. Our complete geochemical database ($n = 17{,}000$) is archived at https://sites.google.com/umass.edu/ned. Samples used in this study (i.e., passing filters summarized below) are presented in the Supplemental Material[1], where additional details about methods are also provided.

We applied Sr/Y and La/Yb proxies for syncollisional magmas as indicated by (1) published interpretations of the tectonic setting (Robinson et al., 1998; Bradley et al., 2000), (2) petrogenetic studies (Wones, 1980), and/or (3) discrimination diagrams (Fig. S1 in the Supplemental Material). The calibration was applied to samples passing the filters of Hu et al. (2017): SiO_2 = 55–72 wt%, MgO = 0.5–6.0 wt%, Rb/Sr <0.35, Sr/Y <60, and La <60 ppm. The Rb/Sr filter removes samples that experienced high degrees of intracrustal fractionation (Hu et al., 2017). Mineralized, highly altered, and/or cumulate samples were removed. In total, 289 samples from 44 units passed these filters, and for these, the median Sr/Y and La/Yb ratios were calculated.

The NCI proxy extends our constraints to more felsic magmas, although the model saturates at a crustal thickness of 60 km (DePaolo et al., 2019). We chose representative values for both juvenile and evolved end members based on terrane analysis and petrologic studies, as described in the Supplemental Material (Fig. S2). Samples with potentially significant upper-crustal contamination (e.g., elevated $^{87}Sr/^{86}Sr$ or $\delta^{18}O$) were removed. Crustal thickness estimates were calculated using 89 samples from 24 plutons.

RESULTS

Calculated crustal thicknesses and elevations are shown in Figure 2 and tabulated in the Supplemental Material. Paleo–crustal thickness estimates, regardless of method, were consistent within systematic error (10–20 km) and are here interpreted together. Following Hu et al. (2017, 2020), La/Yb values are generally preferred over Sr/Y for crustal thicknesses >50 km and elevations >3 km due to the greater sensitivity of the La/Yb proxy above these values.

We present the spatial distribution of thickness and elevation using present-day locations in order to facilitate comparisons with geophysical observations. Rocks analyzed here postdate terrane accretion and major faulting (Bradley et al., 2000). Thus, palinspastic considerations are likely to be relatively minor (for reference, our data are plotted on the proposed reconstructions of Waldron et al. [2015] in Fig. S3). While faulting has presumably occurred in the eastern portion of the study area along the Norumbega, Clinton-Newbury, and Honey Hill fault systems (Robinson et al., 1998), no major differences are observed in crustal thickness across these faults.

Plutons dated to 425–400 Ma yielded a consistent record of crustal thickness and elevation, but they showed a distinct temporal trend (Fig. 2A). Geochemical proxies suggest crustal thicknesses of 35–45 km, consistent with estimates from ca. 410 Ma lower-crustal cumulates (Tassara et al., 2020), and elevations of ~1–2.5 km. The ages of plutons become systematically younger from the southeast to northwest, from 425 to 400 Ma.

Crustal thicknesses derived from 400 to 350 Ma plutons increase from northeast to southwest. They range from ~40 km in much of Maine to ~50 km in Vermont to western Maine, and to 55–70 km in Massachusetts, Connecticut, and southern New Hampshire (southern New England; Fig. 2B; Fig. S4). Notably, the values from southern New England are similar to thermobarometric estimates from lower-crustal blocks (Keller and Ague, 2018). Thus, crustal thickness differed by up to 30 km along strike. Calculated elevations increase from 1–2 km in Maine to 2–4 km in Vermont, and to 4–7 km in southern New England (Fig. 2B). No correlation is apparent between the ages of Neoacadian plutons and spatial distribution or crustal thickness.

Time-series plots (Fig. 3) highlight the evolution of the orogen along and across strike and, in particular, the similarity of values prior to ca. 400 Ma and the subsequent north to south differences. Maine remained relatively constant at 40 km after initial southeast-northwest thickening. Vermont reached 50 km at 375–350 Ma, corresponding to elevations of 2–4 km. Southern New England achieved crustal thicknesses of 60–70 km and elevations of 5–7 km by 380 Ma. After this peak, crustal thickness and elevation decreased to 55–60 km and 4–5 km, respectively, by 360 Ma.

DISCUSSION

Geochemical data suggest distinct spatial patterns in crustal thickness and thickening histories before and after ca. 400 Ma. The apparent southeast-northwest trend in pluton ages (425–400 Ma), along with sedimentological and structural data, was interpreted by Bradley et al. (2000) in terms of a northwest-migrating Acadian deformational front. Our results are compatible with this model, and with models involving west-directed shortening (Fig. 2A; Robinson et al., 1998). Crustal thicknesses of 40 km and elevations of 1–2 km are similar to other nappe-style orogenic belts such as the Alps (Lombardi et al., 2008).

In contrast, crustal thicknesses and elevations after 400 Ma varied significantly along strike. Thickening apparently occurred simultaneously and in a short time period across southern New England and Vermont between 400 and 375 Ma, an observation also supported by the timing of rapid foreland basin subsidence and regional shortening (Fig. 4D; Robinson et al.,

[1]Supplemental Material. Geochemical and isotopic data, detailed descriptions of methods, and Figures S1–S4. Please visit https://doi.org/10.1130/XXXXX to access the supplemental material, and contact editing@geosociety.org with any questions.

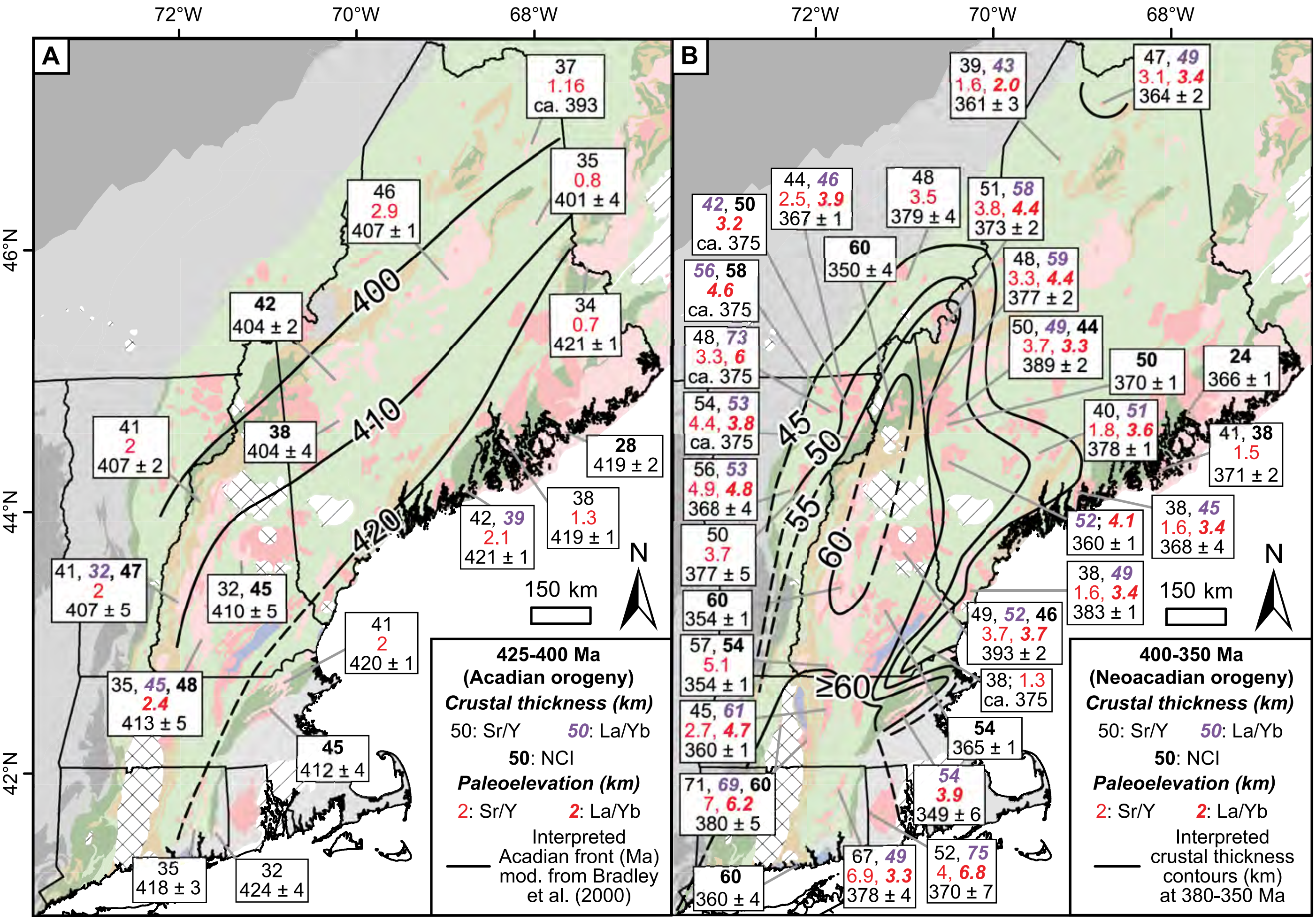


Figure 2. (A) Crustal thickness and paleoelevation data for the period 425–400 Ma and interpreted age trend. (B) Crustal thickness and paleoelevation data for the period 400–350 Ma. NCI—neodymium crustal index of DePaolo et al. (2019).

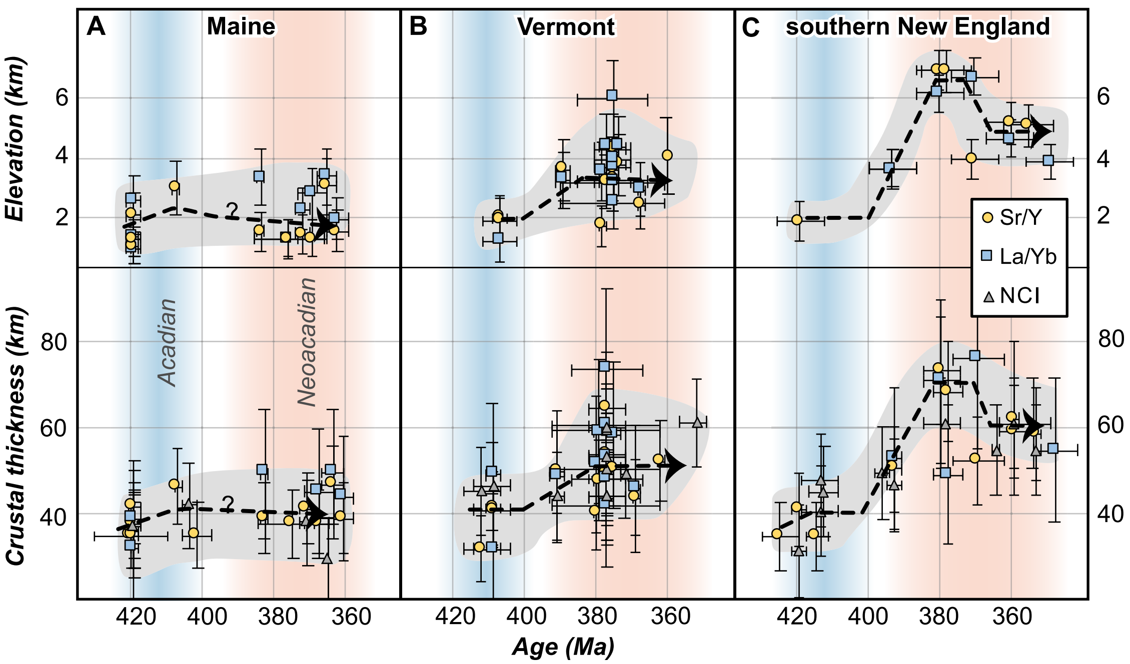
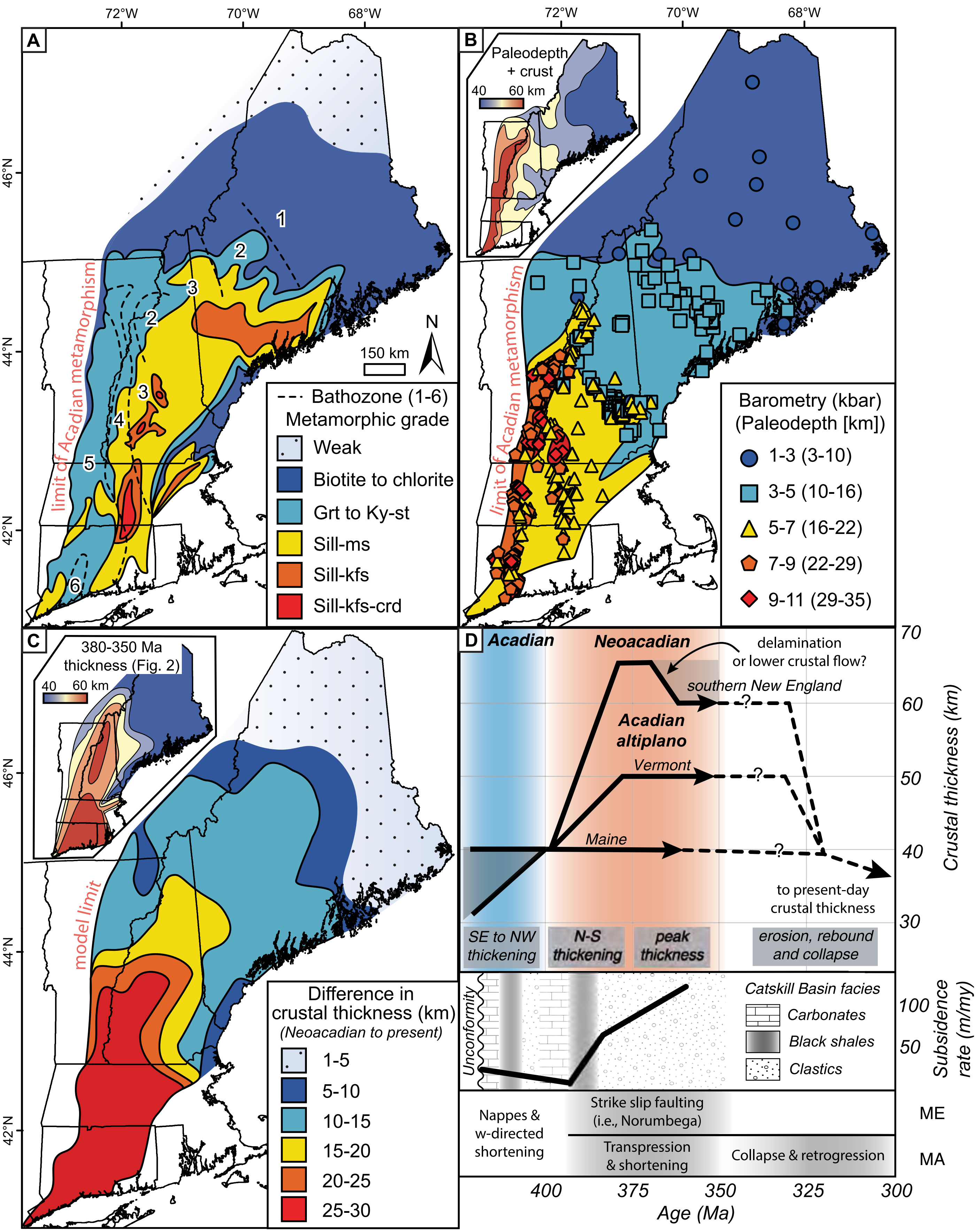


Figure 3. Time series of crustal thickness and paleoelevation (km) for (A) Maine, (B) Vermont to western Maine, and (C) southern New England, USA. NCI—neodymium crustal index of DePaolo et al. (2019).



A
B
C
D
72°W
70°W
68°W
46°N
44°N
42°N
limit of Acadian metamorphism
Bathozone (1-6)
Metamorphic grade
Weak
Biotite to chlorite
Grt to Ky-st
Sill-ms
Sill-kfs
Sill-kfs-crd
150 km
N
Paleodepth
+ crust
40
60 km
Barometry (kbar)
(Paleodepth [km])
1-3 (3-10)
3-5 (10-16)
5-7 (16-22)
7-9 (22-29)
9-11 (29-35)
380-350 Ma
thickness (Fig. 2)
model limit
Difference in
crustal thickness (km)
(Neoacadian to present)
1-5
5-10
10-15
15-20
20-25
25-30
Acadian
Neoacadian
delamination
or lower crustal flow?
southern New England
Acadian
altiplano
Vermont
Maine
to present-day
crustal thickness
SE to NW
thickening
N-S
thickening
peak
thickness
erosion, rebound
and collapse
Crustal thickness (km)
Unconformity
Catskill Basin facies
Carbonates
Black shales
Clastics
Subsidence
rate (m/my)
Nappes &
w-directed
shortening
Strike slip faulting
(i.e., Norumbega)
Transpression
& shortening
Collapse & retrogression
ME
MA
Age (Ma)

Figure 4. (A) Metamorphic zones simplified from Robinson et al. (1998) and bathozones of Carmichael (1978). Grt to Ky-st—garnet to kyanite-staurolite; Sill-ms—sillimanite-muscovite; Sill-kfs—sillimanite–K-feldspar; Sill-kfs-crd—sillimanite–K-feldspar–cordierite. (B) Distribution of metamorphic pressures and paleodepth. (Inset) Paleodepth added onto modern crustal thickness. (C) Difference between Neoacadian and modern crustal thickness. (D) Crustal evolution synthesized from geochemical, sedimentological, and structural data. MA—Massachusetts; ME—Maine.

1998; Ettensohn et al., 2019). We speculate that the slight decrease in crustal thickness in southern New England at 370–360 Ma may have been related to the foundering of dense (eclogitized?) lower crust (Moecher et al., 2020) or outward ductile flow of mid- or lower crust (Beaumont et al., 2004). If the former is correct, it may have been associated with ca. 365–355 Ma "Neoacadian" magmatism in southern New England (Robinson et al. (1998; Moecher et al., 2020).

The distinct crustal thickening histories shown here may provide a basis for refining the timing of the Acadian and Neoacadian orogenies in New England. We prefer to associate 425–400 Ma thickening with the Acadian orogeny, based upon its link with the Acadian front of Bradley et al. (2000). The 400–340 Ma tectonism may be better associated with Neoacadian orogenesis, based on the distinctively different crustal thickening style and its connection with classic Neoacadian plutonism in central Massachusetts.

Hillenbrand et al. (2019) hypothesized the existence of an orogenic plateau in southern New England at 380–330 Ma based on petrologic, geochronologic, and thermochronologic data. They argued that subhorizontal isobars, granulite-facies metamorphism, widespread anatexis, and slow cooling indicate the existence of a high-elevation, low-relief plateau. Our geochemical estimates of crustal thicknesses (55–70 km) and paleoelevations (5–7 km) from southern New England closely match those of the Tibetan-Pamir and Altiplano-Puna plateaus (Fig. S4; Garzione et al., 2017; Hacker et al., 2017). Values for Vermont (50 km thickness; 3 km elevation) are similar to the hypothesized Cretaceous Arizonaplano and Nevadaplano (Coney and Harms, 1984; Chapman et al., 2015, 2020). Thus, we suggest that the results provide strong independent evidence for the proposed "Acadian altiplano" in southern New England. The somewhat thinner crust of Vermont may have involved a lower-elevation segment of the hypothesized plateau or a transitional region to the thinner crust of Maine. The synchronous uplift may be suggestive of the distributed shortening that is characteristic of weak plateau crust (Hacker et al., 2017).

The variation in Neoacadian crustal thicknesses suggests differences in the regional strain field or in tectonic setting along orogenic strike. Structural data indicate a transpressional regime in Neoacadian time, with greater shortening in southern New England relative to Maine (Robinson et al., 1998; Moecher et al., 2020). This difference may have been controlled by the geometry of the collision zone and basement architecture (Massey et al., 2017) or contrasting collisional styles (Kuiper, 2016).

Many studies have inferred crustal thickening on the basis of metamorphic assemblages and thermobarometry (Spear et al., 1984). Petrologic studies have identified a distinct metamorphic field gradient in New England in which both metamorphic grade and paleodepth (at the present erosional surface) increase from northeast to southwest (Fig. 4A; Carmichael, 1978; Zen, 1991; Robinson et al., 1998). Pressures are lowest in Maine (1–2 kbar) and increase to southern New England (6–11 kbar; Fig. 4B). Together, these observations show a striking, and not entirely surprising, correlation with Neoacadian crustal thicknesses (Fig. 2B).

To assess the magnitude of change in crustal thickness, Neoacadian to present, we compared the results of Figure 2B to the present-day values of Li et al. (2018). Models calculated in ArcGIS show the greatest difference in crustal thicknesses (20–30 km, Neoacadian versus present) and, by inference, crustal thinning/exhumation, in southern New England (Fig. 4C). Differences decrease to the northeast, to as little as 3–10 km in Maine. This pattern broadly approximates thermobarometric data and inferences from metamorphic assemblages (Fig. 4A). Notably, metamorphic pressures underestimate paleo–crustal thickness and exhumation relative to geochemical proxies in Massachusetts and southern New Hampshire. This suggests that crustal thinning involved both erosional and tectonic processes. The 330–300 Ma, shallowly dipping stretching lineations and the condensing of structural levels (Massey et al., 2017) suggest ductile thinning played an important role (Long and Kohn, 2020). Other processes such as delamination (Levin et al., 2000) may also have contributed to crustal thinning. This analysis would not be applicable to areas that experienced significant Alleghanian tectonism, such as southeastern Connecticut and Rhode Island (Robinson et al., 1998; Wintsch et al., 2014).

The greatly thickened crust and high topography of southern New England may have created high gravitational potential energy, isostatically instability, and a hot thermal structure, which favored tectonic thinning (Dewey, 1988; Bird, 1991; Beaumont et al., 2004). Ultimately, erosion, thermal weakening, gravitational collapse, and isostatic rebound of the thickened crust and high topography of southern New England served to exhume deeper levels of the crust relative to the thinner crust of Maine, resulting in the present-day metamorphic field gradient (Fig. 4D).

CONCLUSIONS

We quantified the crustal thickness and elevation history of the New England Appalachians, 425–350 Ma, using geochemical proxies. Our results show distinct spatiotemporal patterns in crustal thickness related to the Acadian and Neoacadian orogenies. Acadian orogenesis progressed from southeast to northwest and resulted in a 40-km-thick crust. Neoacadian thickening occurred synchronously but varied by 30 km from north to south (40–70 km). The magnitude and pattern of crustal thickening in southern New England suggest an orogenic plateau formed by 380 Ma. Neoacadian crustal thickness strongly correlates with metamorphic petrology. We propose that contrasts in gravitational, isostatic, and thermal properties related to crustal thickness likely influenced erosion and ductile thinning, which exposed the present metamorphic field gradient.

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