The Geological Society of America
Memoir 220

Formation of the Green Mountain anticlinorium in northern Vermont at ca. 420 Ma

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ABSTRACT

The Appalachian Mountains in northern Vermont host a complex rock record of the tectonic evolution of eastern Laurentia, from the opening of the Iapetus Ocean to the subsequent formation of a convergent Paleozoic margin involving multiple phases of orogenesis. Prior $^{40}Ar/^{39}Ar$ studies in Vermont and northern Massachusetts have generally interpreted two major events associated with a dominantly Ordovician Taconic orogeny and a Devonian Acadian orogeny; intermediate ages were considered to reflect Taconic metamorphism and/or deformation that was "partially reset" during the Acadian orogeny. However, recent studies have documented Salinic ages in northern Vermont, aligning with multiple lines of evidence in southern Quebec for an intervening Salinic orogeny during the Silurian.

This study reports integrated microstructural and $^{40}Ar/^{39}Ar$ geochronological analyses of samples collected across the Green Mountain anticlinorium in northern Vermont. The dominant S_2 and S_3 foliations are defined in thin section by predominantly white mica/quartz microlithons and aligned mica cleavage domains in schist to graphitic schist that formed under greenschist-facies conditions. Correlation of microstructures across the field area and associated $^{40}Ar/^{39}Ar$ plateau ages reveal a spatial pattern associated with microstructural development across the anticlinorium. In the eastern limb, the oldest plateau age, 457.6 ± 2.0 Ma (1σ), is interpreted to reflect the timing of formation of S_2. The youngest plateau age, 419.0 ± 2.4 Ma, comes from the western limb of the anticline near the trace of the Honey Hollow fault, where

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Tam, E., Webb, L.E., Aiken, C., Kim, J., and Klepeis, K., 2023, Formation of the Green Mountain anticlinorium in northern Vermont at ca. 420 Ma, *in* Whitmeyer, S.J., Williams, M.L., Kellett, D.A., and Tikoff, B., eds., Laurentia: Turning Points in the Evolution of a Continent: Geological Society of America Memoir 220, https://doi.org/10.1130/2022.1220(27).

S_2 is completely transposed by S_3. Intermediate ages were obtained across the axis of the anticline, where S_3 is a crenulation cleavage. While the Green Mountain anticlinorium has been previously interpreted to have formed in the Devonian during the Acadian orogeny, the typical ca. 386–355 Ma ages are notably absent in the data set, except in locally disturbed spectra.

The results of this work are closely aligned with published results of $^{40}Ar/^{39}Ar$ dating in southern Quebec that reflect deformation during Taconic and Salinic orogenesis. These new data, together with recently reported ages of west-directed transport on Taconic thrusts along the western Green Mountain front at ca. 420 Ma, suggest a phase of mountain building in the New England Appalachians that has been previously unreported in Vermont. The formation of the Green Mountain anticlinorium coincided with a complex tectonic interval that overlapped temporally with (1) the transition from Salinic thrusting to normal faulting, (2) magmatism attributed to slab breakoff, and (3) syntectonic deposition in the Connecticut Valley–Gaspé Basin.

INTRODUCTION

Vermont's tectonic history spans more than 1 b.y. and records the formation and rifting of the supercontinent Rodinia—creating Laurentia, Gondwana, and the Iapetus Ocean (Ratcliffe et al., 1991; McLelland et al., 2010; Cawood et al., 2001). The collision between Laurentia and the Shelburne Falls arc constituted the first stage of the Taconic orogeny (D_1, ca. 470–465 Ma; Karabinos et al., 2017; Macdonald et al., 2014, 2017), closing the Iapetan Ocean and accreting rift and basin sediments, ophiolites, and island arcs onto Laurentia as part of east-directed subduction involving a foreland-propagating thrust system associated with prograde metamorphism (St-Julien and Hubert, 1975; Sasseville et al., 2008; van Staal et al., 2009; Stanley and Ratcliffe, 1985). Consensus on a model representing the second phase of metamorphism during the Middle Ordovician (D_2) has not been reached (Dorais et al., 2017), with some researchers advocating for a change in polarity of subduction, with subduction proceeding westward under the Laurentian margin (Karabinos et al., 1998; Macdonald et al., 2014), and others supporting continued eastward subduction throughout the orogeny (Ratcliffe et al., 1998, 1999). Regardless, structural and metamorphic overprinting due to the Salinic and Acadian orogenies have obscured a full understanding of the Taconic orogenic cycle (e.g., Laird et al., 1984, 1993; van Staal et al., 1998; Thompson and Thompson, 2003; Honsberger et al., 2017; Castonguay et al., 2001, 2012). This study aimed to examine the timing and orogenic affinity of deformation in northern Vermont by examining the Green Mountain anticlinorium, a key feature that has been regionally correlated with structures in southern Quebec (Castonguay et al., 2012). New $^{40}Ar/^{39}Ar$ ages constrain the timing of deformation and metamorphism in the northern Green Mountain anticlinorium and reveal its formation at ca. 420 Ma, overlapping temporally with the late stages the Salinic orogeny in Quebec (Tremblay and Pinet, 2016) and the early stages of northwestward propagation of the Acadian orogenic front in Maine (Bradley et al., 2000).

In Vermont, series of lithotectonic slices (Fig. 1), including the Green Mountain slice, Hinesburg and Underhill slices, and Rowe/Prospect Rock slice (considered to be structurally equivalent along strike because they contain imbricated rocks associated with an early Paleozoic accretionary wedge; Stanley and Ratcliffe, 1985; Stanley et al., 1985; Stanley and Hatch, 1988; Honsberger et al., 2019), represent rift-drift sequences deposited onto the Laurentian margin during Neoproterozoic opening of the Iapetus Ocean that were ultimately deformed as a part of the Laurentian margin (Thompson and Thompson, 2003; Coish et al., 2012; Ratcliffe et al., 2011). In southern Quebec, the Humber zone represents the same peri-Laurentian metasediments and volcanics and has been correlated to the aforementioned slices in Vermont (Ratcliffe et al., 2011; Macdonald et al., 2014; Castonguay et al., 2012). Further east, the Moretown slice is interpreted as peri-Gondwanan volcanics and sediments accreted onto the Laurentian basement and carbonates of the passive Laurentian margin, which were subsequently metamorphosed during the Ordovician Taconic orogeny (Fig. 1; Thompson and Thompson, 2003; Stanley and Ratcliffe, 1985; Honsberger et al., 2017). The Dunnage zone of southern Quebec has been similarly identified as correlative to the peri-Gondwanan volcanics and sediments of the Moretown slice (Coish et al., 2012; Ratcliffe et al., 2011; Macdonald et al., 2014). The boundary between the Rowe/Prospect Rock slice and the Moretown terrane is the Red Indian Line, a boundary stretching from Canada into New England that represents the main Iapetan suture between Laurentian- and Gondwanan-correlative terranes (Macdonald et al., 2014; van Staal et al., 1998; Williams et al., 1988).

These slices are also interpreted to have been overprinted by the Acadian orogeny (between 386 and 355 Ma in Vermont; Laird et al., 1984, 1993), which was caused by a collision between composite Laurentia and the microcontinent Avalonia in the Devonian (van Staal and Barr, 2012; Tremblay and Pinet, 2016). Evidence for the Salinic orogeny has been recognized in parts of the northern Appalachians, including in Newfoundland (Dunning et al., 1990; van Staal et al., 2014), New

Brunswick (van Staal and De Roo, 1995), Maine (West et al., 1992; Hibbard, 1994), and southern Quebec (Castonguay et al., 2001, 2007, 2012). Regionally, ages defining both the Salinic and Acadian orogenic cycles are diachronous and occasionally overlap, though structural overprinting relationships (i.e., discrete generations of folding and foliation development) have shown them to be distinct, sequential events where they occur together (van Staal et al., 2009; van Staal and De Roo, 1995; Wilson and Kamo, 2012).

The Salinic orogeny has been interpreted in southern Quebec (van Staal et al., 2012; Tremblay and Pinet, 2016) to have resulted from the collision of the Gondwanan terrane called Ganderia with composite Laurentia following a subduction flip (southeast to northwest) at the end of the Taconic orogeny (Robinson et al., 1998; Tucker et al., 2001). Here, early Salinic deformation started around 440 Ma involving northwest-directed thrusting and subsequent southeast-directed back thrusting, and later Salinic crustal-scale extension occurred between ca. 434 and 405 Ma on southeast-dipping faults (Castonguay et al., 2001, 2007; Long, 2007; Tremblay and Pinet, 2016; Perrot and Tremblay, 2021).

Correlations of structures in northern Vermont to Salinic structures in southern Quebec have been proposed (e.g., Kim et al., 2003; Castonguay et al., 2012), though studies in central New England have also argued against a definite Salinic event (Rankin et al., 2007). Castonguay et al. (2007) and Castonguay et al. (2001) documented $^{40}Ar/^{39}Ar$ ages from rocks in southern Quebec associated with the Sutton Mountains anticlinorium and its northern counterpart, the Notre-Dame Mountains anticlinorium, respectively. These studies constrained a Salinic (D_3) deformation event associated with southeast-directed back thrusting (ca. 433–420 Ma) and east-directed normal faulting (ca. 417–405 Ma); associated faults can be traced to the Honey Hollow and Burgess Branch faults in Vermont, respectively. The Green Mountain anticlinorium (overall trend of 015°; Thompson et al., 1999) in Vermont has been correlated with the Sutton Mountains anticlinorium and the Notre-Dame Mountains anticlinorium in southern Quebec (Fig. 1; Castonguay et al., 2007). Salinic ages

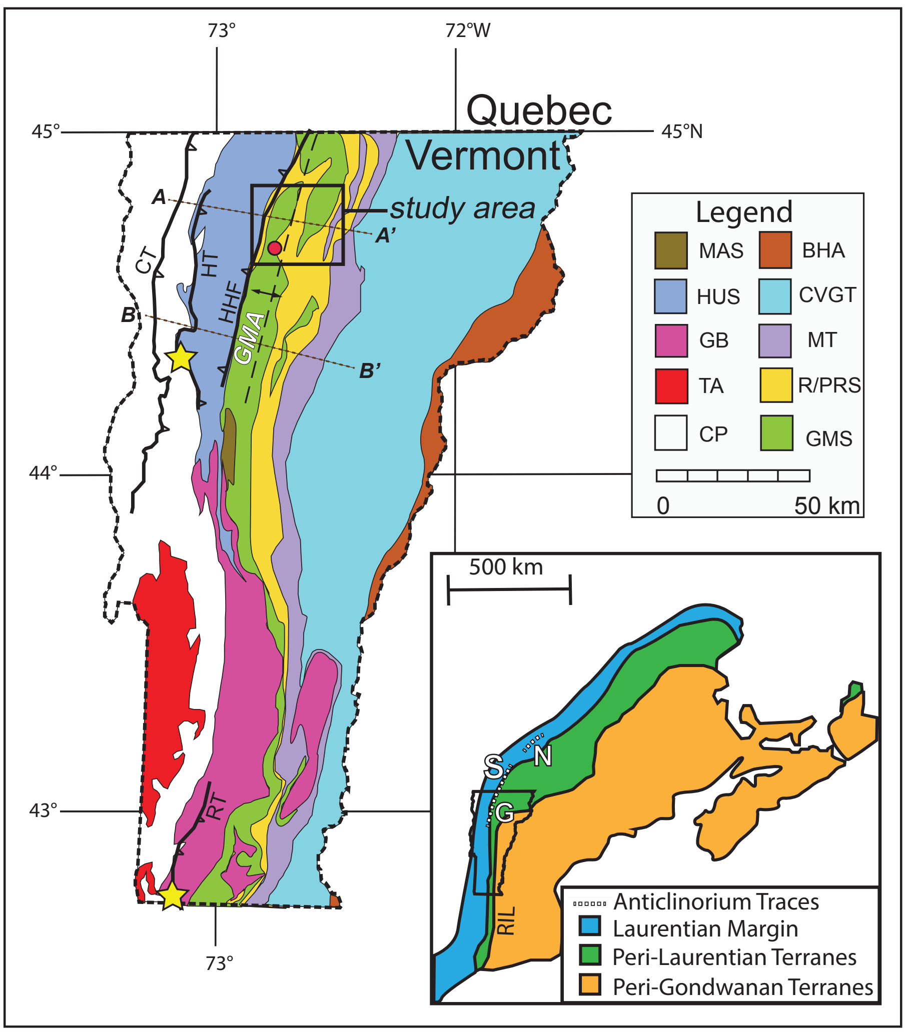

Figure 1. Regional map of Vermont and its major lithotectonic divisions, modified from Honsberger et al. (2017), Castonguay et al. (2012), and Kim et al. (2003). MAS—Mount Abraham slice; HUS—Hinesburg and Underhill slices; GB—Grenvillian basement; TA—Taconic allochthon; CP—carbonate platform; BHA—Bronson Hill arc; CVGT—Connecticut Valley–Gaspé Trough; MT—Moretown terrane; R/PRS—Rowe/Prospect Rock slice; GMS—Green Mountain slice; CT—Champlain thrust; GMA—Green Mountain anticlinorium; HHF—Honey Hollow fault; HT—Hinesburg thrust; RT—Rattlesnake thrust. The study area is denoted within the box and shown in Figure 2. Yellow stars show the general locations of the $^{40}Ar/^{39}Ar$ data from the Rattlesnake (RT; Webb et al., 2019) and Hinesburg thrust (HT; Kim et al., 2019). The red circle shows the location of Prospect Rock. Inset depicts the extent of terranes associated with Laurentia and Gondwana in the northern Appalachians, modified from Honsberger et al. (2017) and Castonguay et al. (2012); RIL—Red Indian Line. Anticlinorium traces are shown as small white dashed lines: G—Green Mountain anticlinorium; S—Sutton Mountains anticlinorium; N—Notre-Dame Mountains anticlinorium.

in northern Vermont have been shown to follow similar trends as those of southern Quebec (ca. 433–405 Ma), with an overall southeastward younging of D_2 ages suggesting southeast-directed deformation (Castonguay et al., 2001, 2007, 2012).

Workers in Quebec have delineated a detailed structural chronology that includes an intervening Salinic orogeny (for a recent summary, see Tremblay and Pinet, 2016). In contrast, the long-held view in Vermont and Massachusetts was that $^{40}Ar/^{39}Ar$ ages intermediate between the Taconic (ca. 470–440 Ma) and Acadian (ca. 385–355 Ma) orogenies reflect the partial resetting of Taconic fabrics during the Acadian event (Laird et al., 1984; Sutter et al., 1985; Stanley and Ratcliffe, 1985; Spear and Harrison, 1989). However, studies have shown that the geology of Vermont, southern Quebec, and other regions of New England represents different structural levels of the Taconic orogeny (Thompson and Thompson, 2003; Castonguay et al., 2012; Ratcliffe et al., 2011), consistent with the intensity of Acadian deformation and metamorphism generally increasing from north to south (Laird et al., 1984).

This study presents findings from $^{40}Ar/^{39}Ar$ step-heating analyses and microstructural observations of samples collected from the Green Mountain slice, within the footwall of the Prospect Rock fault and spanning the Green Mountain anticlinorium (Figs. 2 and 3). The Prospect Rock fault is mapped as a folded Taconic thrust fault, with the footwall of the Prospect Rock fault defining the Green Mountain anticlinorium (Thompson and Thompson, 2003). The Prospect Rock fault has been interpreted as having undergone deformation in association with motion on the thrust fault (ca. 470–460 Ma; Stanley and Ratcliffe, 1985; Karabinos et al., 1998), with additional deformation and folding occurring as part of the Green Mountain anticlinorium during the Acadian orogeny (Laird et al., 1984; Thompson and Thompson, 2003). In contrast, our new results correlate well with the data published from southern Quebec (Castonguay et al., 2007, 2012) and with recent $^{40}Ar/^{39}Ar$ pilot data revealing a ca. 420 Ma age from other "Taconic" thrusts delineating the western front of the Green Mountains—the Hinesburg thrust (Kim et al., 2014, 2019) and the Rattlesnake thrust in southern Vermont (Webb et al.,

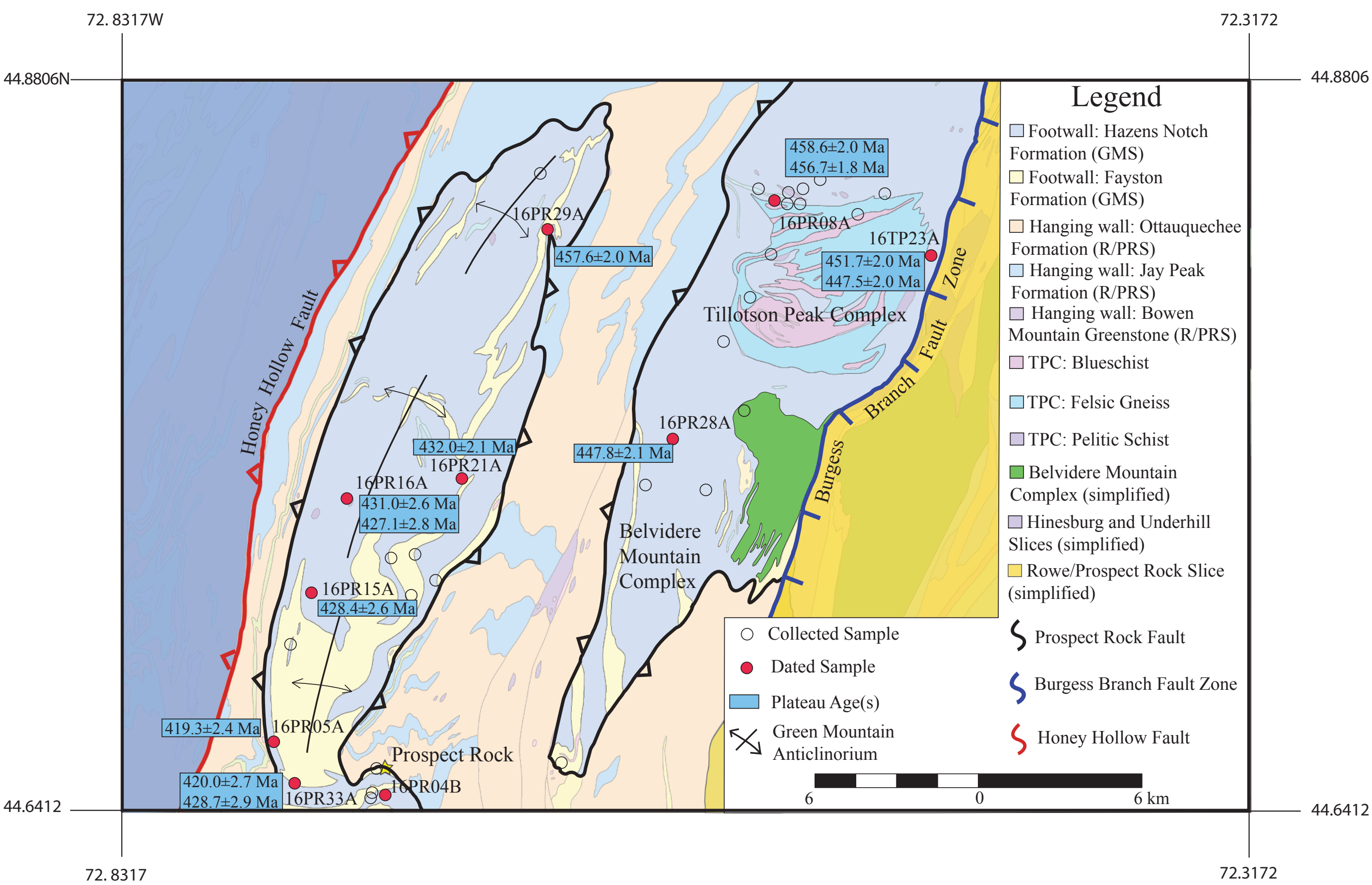

Figure 2. Lithological and tectonic structural map of the Prospect Rock fault footwall, modified from Ratcliffe et al. (2011). Map extent corresponds to the study area bounding box in Figure 1. Dated sample locations (red circles) with corresponding ages from $^{40}Ar/^{39}Ar$ dating are listed. The axis of the Green Mountain anticlinorium is denoted throughout the Prospect Rock fault footwall. The location of Prospect Rock is noted as a yellow star. GMS—Green Mountain slice; R/PRS—Rowe/Prospect Rock slice; TPC—Tillotson Peak Complex.

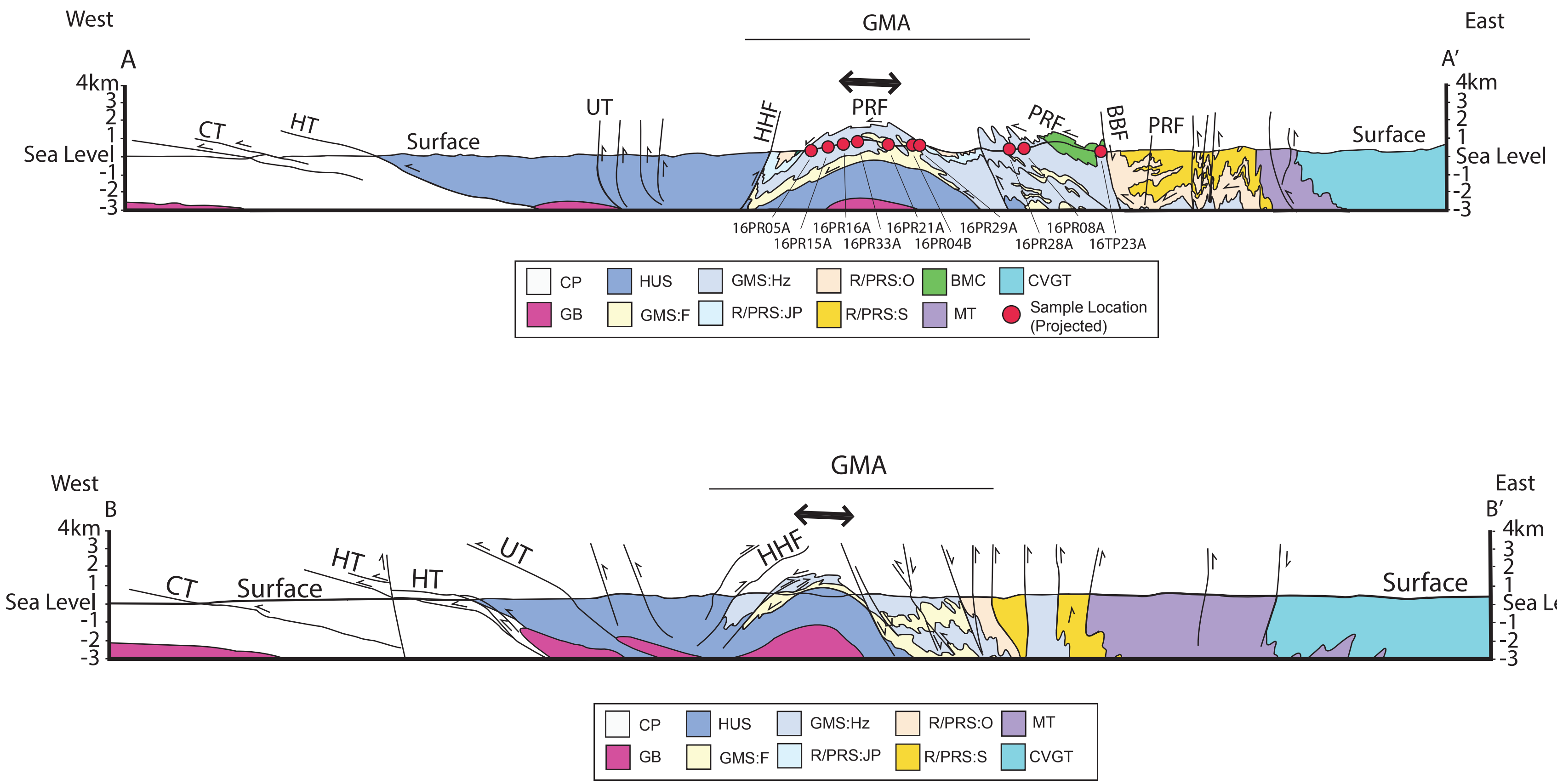

Figure 3. Cross section modified from Ratcliffe et al. (2011). Structures above the surface are projected. Lines of section are shown in Figure 1. Stratigraphic units were simplified using lithotectonic units as defined in Figure 1, except for stratigraphic units related to the Prospect Rock fault. Collection locations of samples are projected onto the cross section. BMC—Belvidere Mountain Complex; CP—carbonate platform; GB—Grenvillian basement; HUS—Hinesburg and Underhill slices; MT—Moretown terrane; CVGT—Connecticut Valley–Gaspé Trough; R/PRS—Rowe/Prospect Rock slice; GMS:F—Green Mountain slice, Fayston Formation; GMS:Hz—Green Mountain slice, Hazen's Notch Formation; R/PRS:JP—Rowe/Prospect Rock slices, Jay Peak Formation; R/PRS:O—Rowe/Prospect Rock slices, Ottauquechee Formation; R/PRS:S—Rowe/Prospect Rock slices, Stowe Formation; GMA—Green Mountain anticlinorium; CT—Champlain thrust; HT—Hinesburg thrust; UT—Underhill thrust; HHF—Honey Hollow fault; PRF—Prospect Rock fault; BBF—Burgess Branch fault.

2019). Altogether, these findings suggest that a phase of mountain building in Vermont ca. 420 Ma drove the formation of the Green Mountain anticlinorium.

GEOLOGIC SETTING

Geologic Context

The Prospect Rock fault footwall is synonymous with the Green Mountain slice (Figs. 2 and 3). It includes the Fayston Formation, the Hazens Notch Formation, and the Pinney Hollow Formation (Fig. 2; Walsh and Aleinikoff, 1999; Thompson and Thompson, 2003; Cady et al., 1963; Doll et al., 1961), and it represents metamorphosed rift-clastic and slope-rise sediments deposited onto the Laurentian margin (Thompson and Thompson, 2003; Ratcliffe et al., 2011; Coish et al., 2012). The Green Mountain slice is considered to be correlative to the internal Humber zone in southern Quebec, which similarly represents peri-Laurentian metasediments and volcanics (Castonguay et al., 2012; Coish et al., 2012). Rocks in the hanging wall of the Prospect Rock fault are a part of the Rowe/Prospect Rock slice, which includes the Jay Peak, Ottauquechee, and Stowe Formations (Thompson and Thompson, 2003; Cady et al., 1963).

On the eastern limb of the Green Mountain anticlinorium, the Tillotson Peak Complex occurs structurally between the Green Mountain slice and the Rowe/Prospect Rock slices (Ratcliffe et al., 2011) and is composed of albite gneiss of the Hazens Notch Formation, with blueschist (sourced from both metapelitic and mafic rocks), eclogite, and small ultramafic lenses (Laird and Albee, 1981a; Bothner and Laird, 1999, 1987; Gale, 1986). The Belvidere Mountain Complex occurs in the same structural position as the Tillotson Peak Complex and contains a sequence of serpentinized ultramafic rocks, amphibolite, and metapelites (Gale, 1980; Laird et al., 1984). These complexes are considered regionally key units due to their use in $^{40}Ar/^{39}Ar$ studies constraining regional metamorphism (Laird et al., 1984; Castonguay et al., 2012). Recent studies have documented coesite in the metapelitic sequence of the Tillotson Peak Complex, indicating these rocks were exhumed from ultrahigh-pressure conditions of over 28 kbar and 530 °C within a Taconic subduction zone (Gonzalez et al., 2020).

Structural Context

Three sets of foliations have been recorded previously throughout the Green Mountain anticlinorium (Figs. 1 and 2), not including bedding (S_0; see Table 1). Occurrences of S_0 are rare and typically appear to have been transposed by later foliations (Kim et al., 1999). Distinguishing among foliations can be challenging, as different combinations form composite foliations. S_1 is found locally as compositional layering and axial planar to rootless isoclinal F_1 folds (Castonguay et al., 2012). S_1 is associated with early Taconic deformation (Thompson and Thompson, 2003) and is folded by a second generation of transposed isoclinal folds with an axial planar spaced cleavage (S_2; Castonguay et al., 2012).

S_2 foliations are associated with peak metamorphism during the Taconic orogeny (Thompson et al., 1999; Laird and Albee, 1981a, 1981b). The dip direction of S_2 varies across the Green Mountain anticlinorium, dipping southeast on the eastern limb of the anticlinorium and curving toward the southwest traveling west over the anticlinorium (Thompson and Thompson, 2003). S_3 foliations have previously been interpreted to have formed during the Acadian orogeny (Laird et al., 1984; Thompson and Thompson, 2003). S_3 foliations are generally defined as spaced cleavages or crenulation cleavages and are parallel to axial planes of F_3 folds. In some areas, such as east of the Burgess Branch fault zone, S_2 and S_3 form a composite foliation (Kim et al., 1999, 2003).

The Prospect Rock fault is folded by F_2 folds and the Green Mountain anticlinorium, with axial planes matching regional N-S–striking folds (Fig. 3; Thompson and Thompson, 2003; Ratcliffe et al., 2011). The Prospect Rock fault dips moderately to the east, as much of the Prospect Rock fault is found on the eastern side of the Green Mountain anticlinorium fold axis. The fault dips more steeply to the southeast on the short D_2 limb than on the long limb (Thompson and Thompson, 2003). The fault itself was recognized through observations of the hanging-wall phyllites of the Rowe/Prospect Rock slice, which are draped over the footwall albitic schists of the Green Mountain slice (Fig. 2; Thompson and Thompson, 1998). Thompson and Thompson (2003) interpreted overall westward transport of the hanging wall along the Prospect Rock fault, with the Prospect Rock fault representing the basal thrust of the Taconic accretionary prism, with local east-directed normal reactivation occurring during the Acadian orogeny. Eastward fault movement along the Prospect Rock fault could be indicative of tectonic wedging, with the Prospect Rock fault acting as a roof thrust under the Rowe/Prospect Rock slice (Lamon and Doolan, 2001).

West of the Green Mountain anticlinorium, the Prospect Rock fault is truncated by the steeply west-dipping Honey Hollow fault, which is interpreted as a major late Taconic back thrust (Hinesburg and Underhill thrusts in Fig. 3B; Thompson and Thompson, 2003; Ratcliffe et al., 2011). The Honey Hollow fault is not well located in the vicinity of our westernmost samples; rather, it is inferred from zones of east-vergent folds with sheared limbs (Thompson and Thompson, 2003). The fault has a similar relationship to the Green Mountain anticlinorium as do the Brome, Stukely Sud, and St-Étienne faults to the Sutton Mountains anticlinorium in southern Quebec (Colpron, 1990; Rose, 1993). Faults in southern Quebec have exhibited Salinic D_3 southeast-directed back thrusting and later east-directed normal faulting; associated faults can be traced to the Honey Hollow and Burgess Branch faults in Vermont, respectively. This east/southeast-directed movement has been attributed to imbrication upon the Grenvillian basement underneath the Sutton and Notre-Dame Mountains anticlinoria (Castonguay et al., 2001, 2007).

TABLE 1. FOLIATIONS AND DEFORMATION EVENTS FOR ROCKS OF THE GREEN MOUNTAIN SLICE AND CORRELATIVE ROCKS OF SOUTHERN QUEBEC

	Field-defined foliations within the Green Mountain slice, from Thompson and Thompson (2003), Thompson et al. (1999), and Kim et al. (1999)	Deformation events of northern Vermont Appalachians, from Castonguay et al. (2012)	Deformation events of southern Quebec Appalachians, Canada, from Castonguay et al. (2007, 2012)	$^{40}Ar/^{39}Ar$ and microstructure-defined foliations and deformation time span from the Tillotson Peak Complex, from Aiken (2018)	$^{40}Ar/^{39}Ar$ and microstructure-defined foliations and deformation time span from this study
Pre-Taconic	S_0: Bedding. Rare, often transposed.				
Taconic orogenic cycle (Phase 1)	S_1: Compositional layering, poorly preserved, quartzite beds. Commonly parallel to S_2. Taconic orogeny.	Deformation of the Belvidere Mountain Complex: Ca. 505–473 Ma (pre–Taconic deformation).	D_{1-2}: Penetrative foliation and metamorphic differentiation/layering. Regionally associated with west-directed motion on shear zones. Ophiolite emplacement, prograde metamorphism. 496–471 Ma, 469–456 Ma, early to peak Taconic metamorphism.	D_1/S_1: Crenulated inclusions within garnet porphyroblasts, prograde–peak Taconic metamorphism. Ca. 485–480 Ma.	S_1: Mica-defined foliations truncated by S_2. No definite dates, early Taconic orogeny.
Taconic orogenic cycle (Phase 2)	S_2: Spaced cleavage, dominant foliation over the Green Mountain anticlinorium. Peak Taconic metamorphism.	Early deformation (D_e): Ca. 471–460 Ma (Taconic orogeny).		D_2/S_2: E-W–trending spaced crenulation cleavage, related isoclinal F_2 folds. Exhumation of the Tillotson Peak Complex. Ca. 471–456 Ma, including titanite age (from U/Pb dating) of 460 ± 17 Ma.	S_2: Quartz and mica microlithons, truncated mica grains. Greenschist-facies Taconic metamorphism. Ca. 458–447 Ma.
Continued Taconic deformation				D_3/S_3: Spaced crenulation cleavage axial planar to E-W–trending F_3 folds. Ca. 455–445 Ma, possible continuation of D_2/Taconic deformation.	
Salinic orogenic cycle	S_3: Spaced or crenulation cleavage. Average strike is 015° (azimuth). Previously interpreted as the Acadian orogeny.	Middle deformation (D_m): Ca. 446–415 Ma (Salinian orogeny).	D_3: Heterogeneously developed S_3 crenulation cleavage or penetrative foliation, mylonitic schistosity. Retrograde metamorphism. 431–405 Ma, Salinian orogeny.	D_4/S_4: S_4 as locally preserved spaced crenulation cleavage axial planar to NW-trending Gilmore antiform. Ca. 435–405 Ma, Salinian orogeny.	S_3: Crenulation cleavage deforming S_2, and spaced foliation/samples exhibiting dynamic recrystallization under greenschist-facies conditions. Ca. 420–419 Ma, Salinian orogeny.
Acadian orogeny		Late deformation (D_l): Ca. 386–355 Ma (Acadian orogeny).	D_4: Steeply dipping to vertical spaced or crenulation cleavage, axial planar to NE/SE-trending folds. 390–376 Ma, Acadian orogeny.		

Similarly, the presence of Grenvillian basement in northern Vermont (i.e., north of the mapped extent of the Green Mountain Massif), including under the Green Mountain anticlinorium (see Fig. 3; Stanley and Wright, 1997; Coish, 2010; Thompson, 2010; Ratcliffe et al., 2011), has been noted, implying Grenvillian basement slices were involved in D_1 and D_2 Taconic events (Castonguay et al., 2005). These updated maps additionally show a lack of east-directed thrusting south of the Green Mountain anticlinorium, instead moving to west-directed motion (Castonguay et al., 2012).

RESULTS

Forty oriented rock samples were collected from the footwall of the Prospect Rock fault between Prospect Rock and the

TABLE 2. SAMPLE INFORMATION, INCLUDING OBSERVED FOLIATIONS, KEY MICROSTRUCTURES, AND A BRIEF INTERPRETATION

Sample name (ordered from west to east)	Sample location (°N, °W)	Rock type	Minerals dated	$^{40}Ar/^{39}Ar$ plateau age (Ma ± 1σ error)	Foliations (dominant foliation in bold)	Key microstructures	Grouped interpretation
16TP23A	44.8173, 72.4731	Schist, HNF	Muscovite, single-grain aliquots	451.7 ± 2.0 447.5 ± 2.0	S_1, **S_2**	*TM*, *AIT*, **CL**	Plateau ages date S_2 foliation formation at ca. 458 Ma
16PR08A	44.8419, 72.5362	Schist, HNF	Muscovite, single-grain aliquots	458.6 ± 2.0 456.7 ± 1.8	S_1, **S_2**	*TM*, **SF**	
16PR29A	44.8314, 72.6467	Schist, HNF	Muscovite, single-grain aliquot	457.6 ± 2.0	**S_2**	**SF**, **S-C′**	
16PR28A	44.7638, 72.5859	Schist, HNF	Muscovite, two-grain aliquot	447.8 ± 2.1	S_1, **S_2**, S_3	*TM*, *AC*, **SF**, MC; PQ	Mixed ages due to incomplete resetting of micas defining S_2 foliation during S_3 development
16PR21A	44.7499, 72.6858	Schist, HNF	Muscovite, single-grain aliquot	432.0 ± 2.1	S_1, **S_2**, S_3	*TM*, *MC*, **SF**, MC; PQ	
16PR16A	44.7439, 72.7410	Schist, HNF	Muscovite, single-grain aliquots	431.0 ± 2.6 427.1 ± 2.8	S_1, **S_2**, S_3	*TM*, **CL**, MC, AC; PQ	
16PR15A	44.7120, 72.7565	Schist, HNF	Muscovite, single-grain aliquot	428.4 ± 2.6	S_1, **S_2**	*AIT*, *TM*, **SF**	
16PR04B	44.6466, 72.7211	Schist, HNF	Muscovite, single-grain aliquot	No plateau achieved	**S_3**	**SF**; GBM	Plateau ages date S_3 foliation formation via dynamic recrystallization at ca. 420 Ma
16PR33A	44.6489, 72.7634	Schist, HNF	Muscovite, single-grain aliquots	420.0 ± 2.7 428.7 ± 2.9	S_2, **S_3**	TM, **SF**; GBM, SGR	
16PR05A	44.6633, 72.7759	Schist, HNF	Muscovite, single-grain aliquot	419.3 ± 2.4	**S_3**	**SF**, **S-C′**; GBM	

Note: HNF—Hazens Notch Formation. For foliations and key microstructures, italicized text indicates S_1, regular text indicates S_2, underscored text indicates S_3, and bold text indicates the dominant foliation and features thereof: TM—truncated mica domains/grains; AIT—albite inclusion trails; CL—compositional layering; SF—spaced foliation; S-C′—S-C′ shear fabric; AC—albite crenulations; MC—mica crenulations. Quartz microstructures are listed after semicolons: PQ—polygonal quartz; GBM—grain boundary migration; SGR—subgrain rotation.

Tillotson Peak Complex area (Fig. 2). Samples were collected to broadly represent the Prospect Rock fault footwall in this region. Following initial petrographic evaluations for the potential to date K-bearing phases from a range of microstructures across the strike of the Green Mountain anticlinorium (Fig. 3), 10 samples were selected for use in microstructural analyses and $^{40}Ar/^{39}Ar$ dating. Details on these 10 samples, including summaries of microstructural analyses, $^{40}Ar/^{39}Ar$ dating results, and summarized interpretations can be found in Table 2 (full details are provided in the Supplemental Material[1]).

[1]Supplemental Material. Full descriptions of methods for microstructural and $^{40}Ar/^{39}Ar$ geochronology analyses, apparent age spectra for all samples, microphotographs of all samples detailing observed microstructures, data tables with locations, and summaries for each sample (including microstructural and $^{40}Ar/^{39}Ar$ geochronological results and full $^{40}Ar/^{39}Ar$ data tables). Please visit https://doi.org/10.1130/MWR.S.21291453 to access the supplemental material, and contact editing@geosociety.org with any questions.

Microstructures

Detailed methods on microstructural analytical methods are provided in the Supplemental Material, and detailed microstructural features per sample can be examined in Table 2 and in the Supplemental Material. Foliation generations identified were designated initially as S_n, S_{n+1}, S_{n-1}, etc. Generations were then correlated between locations and evaluated in light of associated $^{40}Ar/^{39}Ar$ apparent age spectra, with three generations of foliations (S_1–S_3) being identified (Table 1). For the easternmost samples (16PR29A, 16PR08A, 16TP23A, 16PR28A), the dominant foliation (S_2) was observed as spaced foliation and compositional layering of quartz and mica domains (Fig. 4A). Evidence for an older foliation (S_1) was found as truncated mica domains and albite inclusion trails/crenulations (Fig. 4B). Nontruncated mica crenulations (S_3) were observed to deform the dominant foliation in sample 16PR28A. Sample 16PR29A exhibited S-C′ shear fabric with a top-to-the-west sense of movement (Fig. 4A).

Samples proximal to the axis of the Green Mountain anticlinorium (16PR15A, 16PR16A, and 16PR21A) showed a dominant foliation defined by spaced foliation and compositional layering of quartz and mica domains (S_2; Fig. 4C). S_3 was observed as mica and albite crenulations of the dominant foliation, and S_1 appeared as mica crenulations truncated by S_2 and as crenulations in albite inclusion trails (Figs. 4C and 4D). Samples in this grouping exhibited polygonal quartz grains (Fig. 4C), suggesting either that elevated temperatures outlasted deformation, allowing for grain boundary area reduction to occur, or that quartz growth due to dissolution precipitation creep occurred during crenulation cleavage development (cf. Ashley et al., 2013). Both processes could alter argon concentrations, resulting in larger step ranges in apparent age spectra. The westernmost samples (16PR05A, 16PR33A, 16PR04B) exhibited a dominant, spaced S_3 foliation (Figs. 4E and 4F). S_2 was found as mica domains truncated by the dominant foliation (Fig. 4E). Sample 16PR05A exhibited S-C′ shear fabric with a top-to-the-east sense of movement (Fig. 4F).

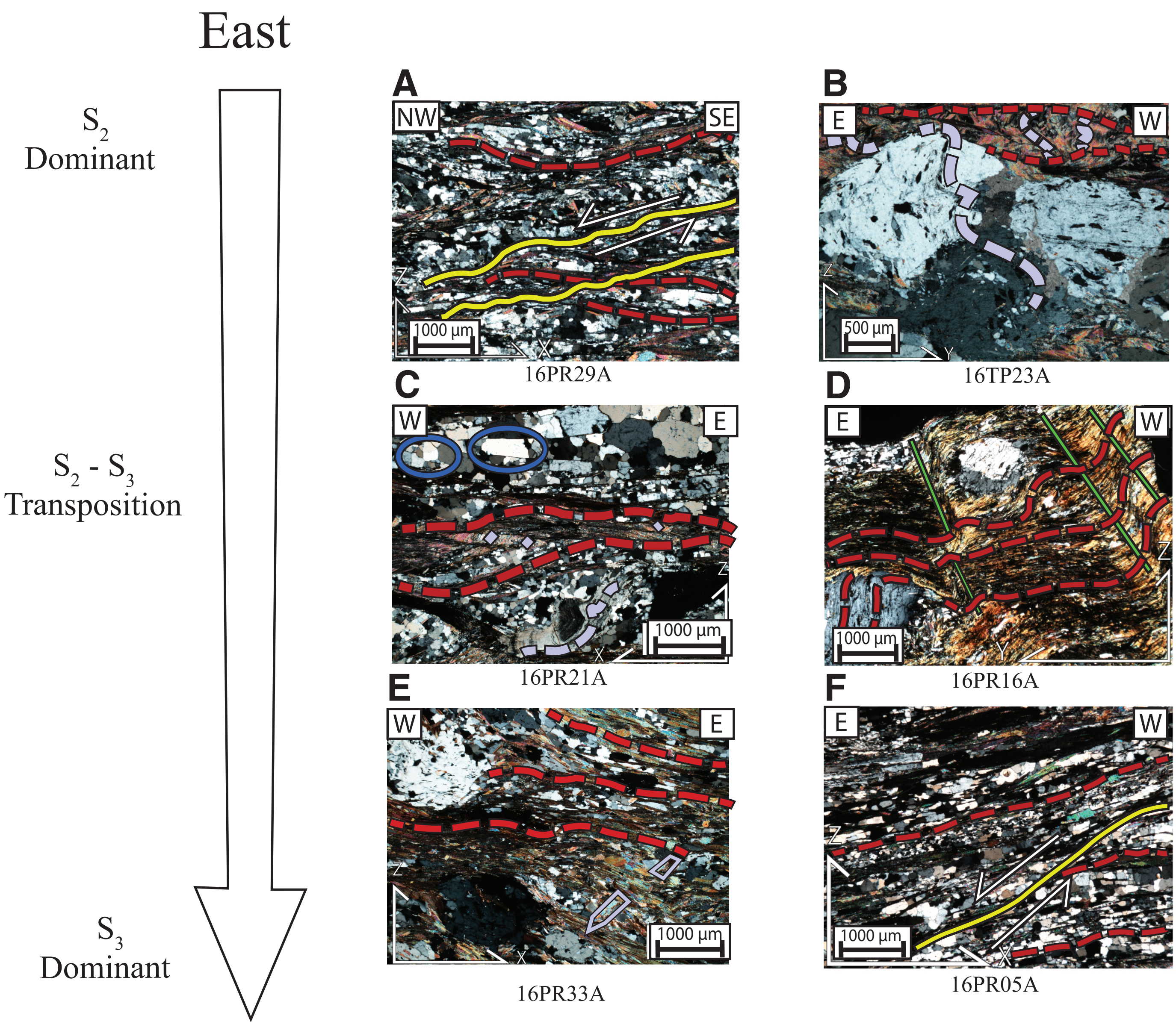

Figure 4. Thin section photomicrographs of samples (A) 16PR29A, (B) 16TP23A, (C) 16PR21A, (D) 16PR16A, (E) 16PR33A, and (F) 16PR05A aligned with progression west across the Prospect Rock fault footwall. The dominant foliation (S_n) for each photomicrograph is defined as dashed red lines, and truncated foliations (S_{n-1}) are denoted in gray outlines (mica domains) or gray dashed lines (foliation traces). Crenulation hinges of the dominant foliation (S_{n+1}) are indicated in green. Sense of motion is denoted as solid yellow lines with white arrows indicating relative movement. Blue circles denote polygonal quartz grains.

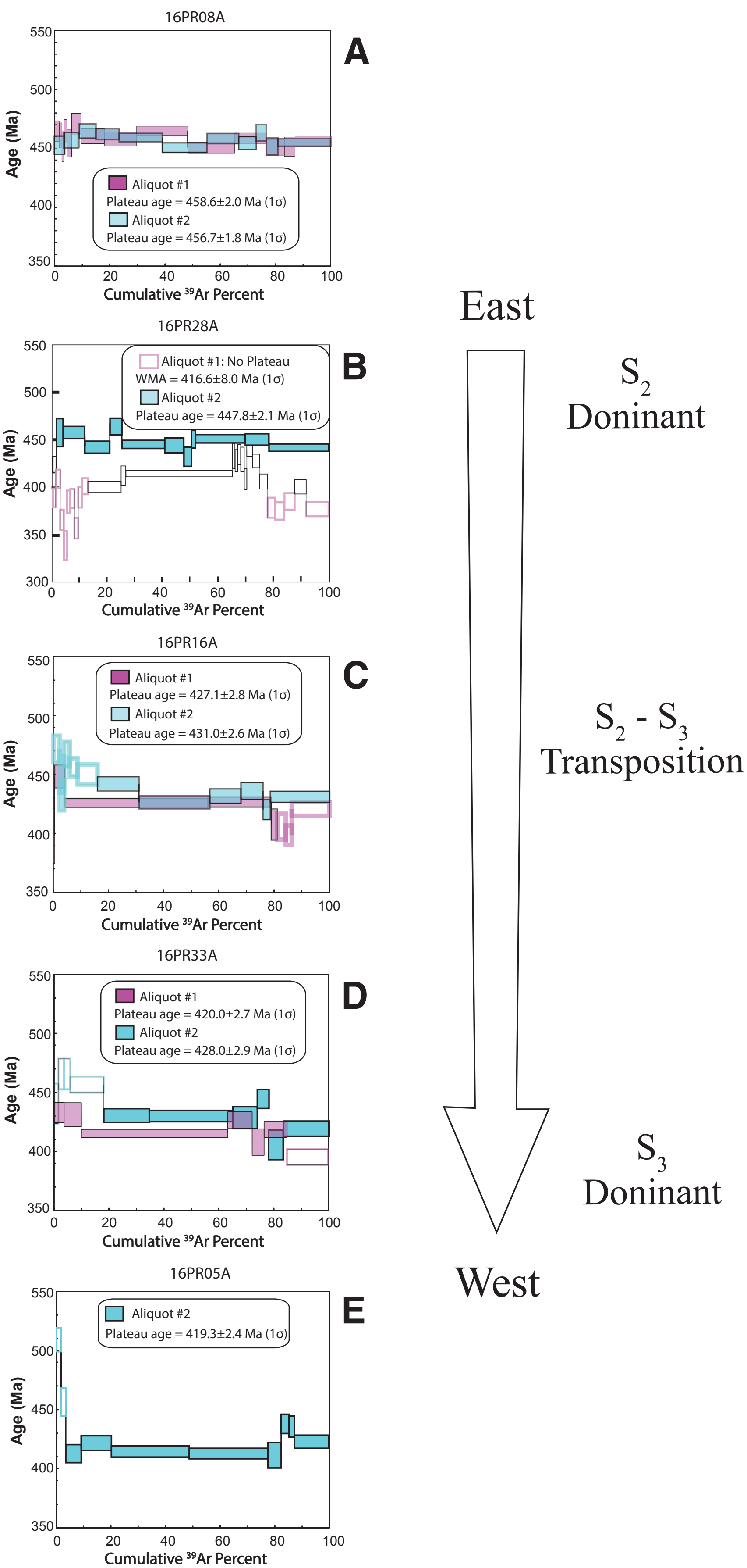

Figure 5. Apparent $^{40}Ar/^{39}Ar$ age spectra of muscovite from samples (A) 16PR08A, (B) 16PR28A, (C) 16PR16A, (D) 16PR33A, and (E) 16PR05A, aligned to show changes moving from east to west. Box heights, weighted mean averages, and quoted errors are reported at the 1σ level. Shaded boxes define reported plateau ages, and outlined colored boxes were excluded from plateau calculations. Black boxes define steps utilized to calculate the weighted mean average (WMA). A single muscovite grain was analyzed per aliquot, except for 16PR28A (two grains for aliquot 2).

$^{40}Ar/^{39}Ar$ Dating

Detailed methods, complete $^{40}Ar/^{39}Ar$ data tables, and apparent age spectra for all samples are provided in the Supplemental Material. The $^{40}Ar/^{39}Ar$ ages from across the Prospect Rock fault footwall showed progressively younger ages for more westerly samples, and ages fell into three categories: ca. 459–448 Ma, ca. 432–427 Ma, and ca. 420 Ma (Fig. 2). Plateau ages between 458.6 ± 2.0 Ma (1σ) and 447.5 ± 2.0 Ma were found in samples east of the Green Mountain anticlinorium axis (Figs. 2, 5A, and 5B). With the exception of sample 16PR28A, apparent age spectra from these samples yielded generally concordant plateau ages from multiple aliquots of the same sample. Based on the dominance of S_2 foliations and lack of S_3 foliation development, we interpreted the strong ca. 458 Ma signal to best constrain the timing of S_2 formation.

Along both sides of the axial trace of the Green Mountain anticlinorium, apparent age spectra ranged between 432.0 ± 2.1 Ma and 427.1 ± 2.6 Ma (Figs. 2 and 5C), dating S_2 foliations. Steps from these apparent age spectra displayed a larger range of ages, where non-plateau-included steps exhibited ages that fell within ranges associated with Taconic and Salinic orogenic cycles (Fig. 5C). The westernmost samples proximal to the Honey Hollow fault (16PR05A, 16PR33A) yielded plateau ages of 419.30 ± 2.4 Ma, 420.0 ± 2.7 Ma, and 428.7 ± 2.9 Ma (Figs. 5D and 5E). Age spectra were mostly consistent when plateaus were achieved (i.e., lower dispersion), suggesting reliable dating of the dominant S_3 foliation.

DISCUSSION

Implications for the Prospect Rock Fault and the Green Mountain Anticlinorium

The ages of the easternmost samples are consistent with $^{40}Ar/^{39}Ar$ ages (white mica) and U-Pb (titanite) dating results from Aiken (2018), which constrained the formation of the Taconic S_2 foliation in rocks of the Hazens Notch Formation in the high- to ultrahigh-pressure Tillotson Peak Complex during exhumation through blueschist–greenschist-facies conditions ca. 471–456 Ma (see Table 1). Laird et al.'s (1984) reported age (468 ± 6.4 Ma) for glaucophane from blueschist of the Tillotson Peak Complex falls within this range.

We interpret ages from samples near the Green Mountain anticlinorium hinge zone to represent mixed ages due to incomplete resetting of micas that grew during S_2 development and underwent deformation/partial recrystallization during S_3 development (see trends depicted in Figs. 4 and 5). Composite S_2/S_3 foliations have been documented in the area by Kim et al. (1999), although S_3 in their scheme was assigned to the Acadian orogenic cycle (S_4 in southern Quebec). Conservatively, these plateau ages place minimum age constraints on the formation of S_2 and maximum age constraints on the timing of formation of S_3.

Age spectra between ca. 429 Ma and 419 Ma are consistent with the timing of the Salinic orogenic cycle. The $^{40}Ar/^{39}Ar$ ages (glaucophane and white mica) from within the Tillotson Peak Complex as described in Aiken (2018), associated with the formation of D_4 fold structures, detail a similar age range (ca. 435–405 Ma) to our western samples (Table 1). These samples display a single S_3-associated dominant fabric, with S_2 implied by truncated mica grains/domains. Microstructures of westernmost samples are consistent with dynamic recrystallization (see Table 2; Table S3 [see footnote 1]) and can be linked to deformation associated with the Honey Hollow fault's overall eastward sense of movement. Cumulatively, this may support the model of Thompson and Thompson (2003) outlining overall westward movement of the Prospect Rock fault with local eastward reactivation.

Late Silurian–Early Devonian Ages within Vermont

The $^{40}Ar/^{39}Ar$ ages proximal to the Honey Hollow fault share a common ca. 420 Ma age signal with $^{40}Ar/^{39}Ar$ age spectra from samples from the Hinesburg and Rattlesnake thrusts (Fig. 1). While these are considered to be Taconic thrust faults (Ratcliffe et al., 2011), to date, neither has yielded radiometric Taconic ages (Sutter et al., 1985; Webb et al., 2019; Kim et al., 2019). Rather, a $^{40}Ar/^{39}Ar$ apparent age spectrum from an ultramylonite sampled in the hanging wall immediately above the Hinesburg thrust showed a strong age gradient from low- to high-temperature steps with a maximum age of ca. 420 Ma. These data suggest the partial resetting of a Silurian top-to-the-northwest shear fabric (Kim et al., 2014, 2019). In samples from the Rattlesnake thrust (Webb et al., 2019), plateau and weighted mean ages of white mica range from ca. 419 to 409 Ma, and they are interpreted to reflect top-to-the-west thrusting. The ca. 420 Ma signal is thus present along the western front of the Green Mountains in both northern and southern Vermont (Fig. 1).

Regional Correlations

To aid in placing our data into broader regional context, Figure 6 shows a compilation of age constraints for key rock units and events from the Taconic orogeny though the Devonian Acadian orogeny in southern Quebec and Vermont (see Table 1 for structural correlations). Overall, plateau ages from $^{40}Ar/^{39}Ar$ step heating from the Prospect Rock fault footwall are correlative to ages from $^{40}Ar/^{39}Ar$ studies in the Quebec Appalachian regions of Canada, where evidence for the Salinic orogeny is well preserved (Table 1; Castonguay et al., 2001, 2007, 2012; Tremblay and Pinet, 2016). Plateau ages from the eastern limb of the Green Mountain anticlinorium in this study, interpreted to date D_2 deformation, are the same age to slightly younger than D_2 age constraints for the Taconic orogeny in southern Quebec (S. Quebec D_2 in Fig. 6). Plateau ages associated with the central and western sides of the Green Mountain anticlinorium in this study, interpreted to date D_3, overlap with Salinic D_3 ages in southern Quebec, including S_3 mica-based $^{40}Ar/^{39}Ar$ ages throughout the Notre-Dame Mountains anticlinorium, which record overprinting (NDA-SMA D_3 in Fig. 6). These strikingly similar ages of

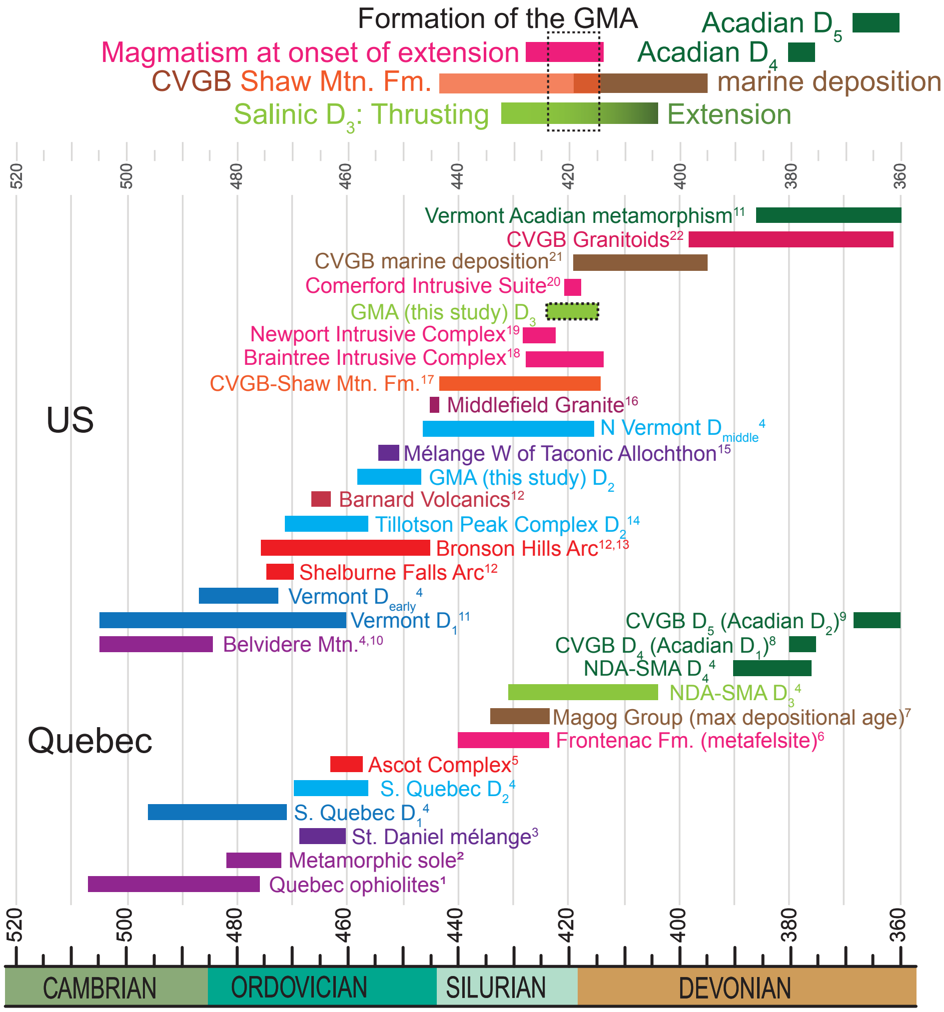

Figure 6. Time line depicting duration of tectonic events in the northern Appalachians, including Vermont and Quebec. Colors are as follows: purples—ophiolites and mélanges; blues—Taconic deformation and metamorphism; red—arc magmatism; oranges and browns—sedimentary rocks of the Connecticut Valley–Gaspé Basin (CVGB); lime green—Salinic (D_3) deformation; dark green—Acadian deformation and metamorphism. NDA-SMA—Notre-Dame Mountains and Sutton Mountains anticlinoria. Summary bars across the top of the figure highlight the formation of the Green Mountain anticlinorium (GMA) in the temporal context of events tied to the Salinic and Acadian orogenies. Ranges shown either are from primary publications that report dates or in a few cases refer to papers that summarize the literature. For ages reported by primary papers, bars reflect errors at the 2σ level. If the paper did not indicate sigma level, bars reflect error(s) as reported. Footnotes for references are as follows: 1—David and Marquis (1994), Dunning et al. (1986), Whitehead et al. (1995, 1996, 2000), Tremblay et al. (2011); 2—Whitehead et al. (1995), Tremblay et al. (2011); 3—Schroetter et al. (2006), Tremblay et al. (2011); 4—Castonguay et al. (2012) and references therein; 5—David and Marquis (1994); 6—Dorais et al. (2017); 7—Perrot et al. (2017); 8—Tremblay et al. (2000); 9—Perrot (2019); 10—Laird et al. (1993); 11—Laird et al. (1984, 1993); 12—Karabinos et al. (2017) and references therein; 13—Valley et al. (2020); 14—Aiken (2018); 15—Jacobi and Mitchell (2018); 16—Macdonald et al. (2014); 17—Aleinikoff and Karabinos (1990), see Walsh et al. (2010) for discussion of fossil age control; 18, 19—Aleinikoff et al. (2011); 20—Rankin et al. (2007); 21—McWilliams et al. (2010), Perrot et al. (2018), Karabinos and Crowley (2019); 22—Aleinikoff et al. (2011).

deformation may link the formation and deformation of the Green Mountain anticlinorium to tectonic models for the Taconic and Salinic orogenic cycles in southern Quebec (see Tremblay and Pinet, 2016).

While the ca. 420 Ma ages from our study are interpreted to reflect the formation of the Green Mountain anticlinorium via thrusting, the timing for the formation of the Green Mountain anticlinorium (Fig. 6) overlaps with regional age constraints on the onset of extension and the formation of the Connecticut Valley–Gaspé Basin (Rankin et al., 2007; Dorais et al., 2017). We note, however, that this timing also overlaps with the development of the Acadian orogenic front to the east in Maine and Quebec (see isochrons in Bradley et al., 2000). Interestingly, the ages of Acadian isochrons that project toward the axis of the Green Mountain anticlinorium are notably absent from our data, as are penetrative fabrics associated with Devonian Acadian deformation (D_4 and D_5). Younger Acadian deformational ages are expected in southern Quebec and New England than in Newfoundland, as diachronous deformation along strike of the orogen has been demonstrated between Quebec and New England (Tremblay and Pinet, 2016, and references therein).

CONCLUSIONS

The $^{40}Ar/^{39}Ar$ data combined with microstructural analyses of samples from across the Green Mountain slice in northern Vermont suggest the occurrence of at least two episodes of deformation. The dominant foliations identified through petrographic analysis can be linked to plateaus ages of samples, resulting in the recognition of two foliations (S_2, S_3) that represent distinct orogenic events. S_2 formed during Taconic motion on the Prospect Rock fault (458.6 ± 2.0 Ma to 447.5 ± 2.0 Ma). S_3 is inferred to have formed by east-directed back thrusting along the Honey Hollow fault (420.0 ± 2.7 Ma to 419.3 ± 2.4 Ma), matching the analogous Sutton fault in southern Quebec (Castonguay et al., 2007). Samples with intermediate ages (432.0 ± 2.1 Ma to 427.1 ± 2.6 Ma) are associated with a crenulation cleavage and represent progressive formation of the Green Mountain anticlinorium and overprinting of S_2 by S_3. Plateau ages ca. 420 Ma further link to ^{40}Ar/^{39}Ar data obtained from the Rattlesnake thrust and Hinesburg thrust (Webb et al., 2019; Kim et al., 2019), suggesting that late Silurian deformation may have been more extensive in New England than recognized previously. Significantly, the ^{40}Ar/^{39}Ar data from along the Prospect Rock fault do not exhibit ages corresponding to the Acadian orogeny, except locally in disturbed spectra, despite previous interpretations of Green Mountain anticlinorium formation during this period (Laird et al., 1984; Thompson and Thompson, 2003). Notably, the formation of the Green Mountain anticlinorium at ca. 420 Ma overlapped temporally with published constraints on the onset of extension and the formation of the Connecticut Valley–Gaspé Basin. These results highlight the need for further studies quantifying the timing of relationships between metamorphism and deformation throughout the northern Appalachians.

ACKNOWLEDGMENTS

This research was supported in part by a University of Vermont College of Arts and Sciences seed grant to Laura Webb and a Vermont Geological Society grant to Evan Tam. Dan Jones provided technical support associated with sample preparation and ^{40}Ar/^{39}Ar analyses. We thank reviewer David Foster and Editors Dawn Kellett and Nancy Riggs, as well as reviewer Ian Honsberger, for particularly constructive and critical comments that significantly improved the paper.

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Manuscript Accepted by the Society 2 November 2021
Manuscript Published Online 21 October 2022