## U.S. Department of the Interior U.S. Geological Survey

DISCUSSION The bedrock geology of the 7.5- by 15-minute Springfield quadrangle consists of highly deformed and metamorphosed Mesoproterozoic through Devonian

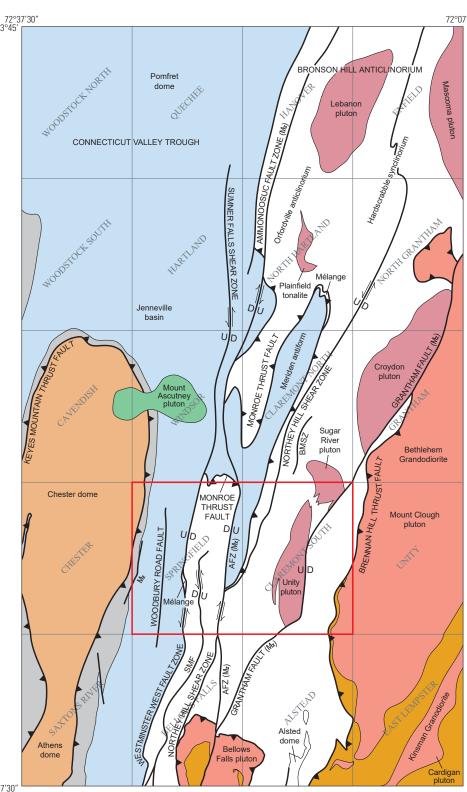
metasedimentary and meta-igneous rocks that are intruded by dikes of the Mesozoic White Mountain Igneous Suite. In the west, Mesoproterozoic gneisses of the Mount Holly Complex are the oldest rocks and form the eastern side of the Chester dome (Ratcliffe and others, 2011). The Moretown slice structurally overlies the Chester dome along the Keves Mountain thrust fault (Ratcliffe, 2000a, b; Ratcliffe and others, 2011); the fault represents the ancient Ordovician suture (Red Indian line) between crustal blocks with Laurentian versus Ganderian affinity (Macdonald and others, 2014; Valley and others, 2015; Valley and others, 2020). The allochthonous Cambrian through Ordovician Moretown slice includes the Moretown and Cram Hill Formations and the North River Igneous Suite. Silurian and Devonian metasedimentary and metavolcanic rocks of the Connecticut Valley trough (CVT) unconformably overlie the Moretown slice. The easternmost extent of the CVT in New Hampshire is exposed in a belt of rocks south of the Claremont Airport, which is contiguous with the Meriden antiform in the North Hartland quadrangle to the north (Walsh, 2016) (fig. 1). Ordovician to Silurian and Devonian metasedimentary and metaigneous rocks of the New Hampshire sequence (NHS) (Billings, 1937, 1956; White and Jahns, 1950; Ratcliffe and others, 2011; Rankin and others, 2013) structurally overlie the CVT along the Monroe thrust fault. The oldest part of the New Hampshire sequence was built on Ganderian crust (Rankin and others, 2013) and consists of Ordovician metamorphosed volcanic, plutonic, and sedimentary rocks of the Bronson Hill arc including the Ammonoosuc Volcanics, the Partridge Formation, and the Oliverian Plutonic Suite. The Ammonoosuc Volcanics are the base of the exposed section in the map area. The Bronson Hill arc rocks may be partly correlative with rocks of the Shelburne Falls arc found in the Moretown slice (Valley and others, 2015). The Bronson Hill arc rocks are exposed in fault-bounded structural belts, including the Monroe thrust sheet, the Claremont belt, the Sugar River and Unity domes, and the footwall of the Brennan Hill thrust fault. Collectively, these belts form the regional Orfordville anticlinorium and the western part of the broader Bronson Hill anticlinorium in western New Hampshire (fig. 1). Silurian to Devonian metasedimentary rocks of the Clough Quartzite, and Fitch and Littleton Formations unconformably overlie the Bronson Hill arc rocks. These rocks are crosscut by Devonian granitic and pegmatitic dikes and sills of the New Hampshire Plutonic Suite including the 399±3 Ma (mega-annum) Bethlehem Granodiorite (Merschat and others, 2015). At least six post-tectonic Cretaceous mafic dikes occur in the map area. The dikes are more numerous in the adjacent Mount Ascutney quadrangle where they show a similar preferred northeast trend (fig. 3 of this report; Walsh and others, 2020). Table 1 summarizes the results of uranium-lead (U-Pb) zircon geochronology from samples collected in the map area. STRUCTURAL GEOLOGY The oldest structure in the Springfield quadrangle is a relict gneissosity in the

Mesoproterozoic Mount Holly Complex in the Chester dome. At or near the contact with the cover rocks, the Mesoproterozoic gneissosity is parallel to a penetrative foliation that is a second-generation foliation in the pre-Silurian cover rocks. This second generation foliation is axial planar to abundant isoclinal and reclined folds of both the gneissosity in the Mount Holly Complex and the schistosity in the younger pre-Silurian rocks. This fabric is interpreted to be a relict Taconic foliation; perhaps related to movement along the Keyes Mountain thrust fault. A younger, and almost certainly, Acadian foliation is also found sub-parallel to this older Taconic foliation in the pre-Silurian rocks. In contrast to the rocks in the Moretown slice, there is no clear evidence in the remainder of the map area for an Ordovician deformational fabric in the exposed pre-Silurian rocks in the Bronson Hill arc. Documented Ordovician deformation is scarce in the Ammonoosuc Volcanics in New Hampshire (Rankin and others, 2013). This observation, coupled with regional evidence for widespread Ordovician deformation in the Albee Formation beneath the Ammonoosuc Volcanics (Rankin and others. 2013). implies that the Ammonoosuc Volcanics may post-date regional deformation that is related to the Penobscottian or Taconic orogenic episodes (Boone and others. 1989; Rankin and others, 2013). The oldest foliation in the Silurian and Devonian rocks of the CVT and NHS is a layer-parallel Acadian schistosity  $(S_1)$  that contains rarely observed Acadian isoclinal folds  $(F_1)$ . These folds are the nappe-stage folds of Thompson and others (1968). The overturned, and subsequently truncated, fold-nappe on Skitchewaug Mountain is the type locality (Thompson, 1954; Thompson and others, 2012) for the fold-nappe theory of Thompson and others (1968). This theory was later modified to include thrust faults (Robinson and others, 1991), and the major structures which floor the early Acadian folds are shown on this map as the Monroe fault (Ratcliffe and others, 2011; Walsh, 2016) and the Brennan Hill thrust (Robinson and others, 1991). Transport along these early faults was generally southeast to northwest (fig. 4) as indicated by the orientation of abundant lineations that include highly stretched pebbles and sub-parallel fold axes. The sub-parallel

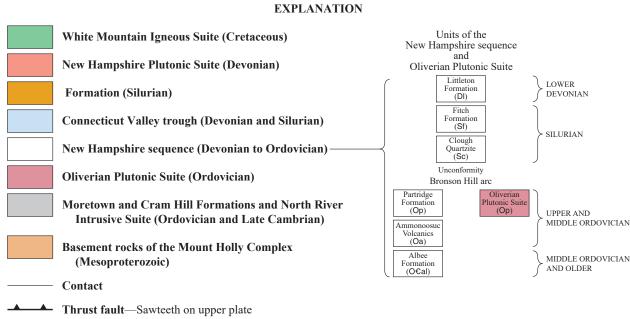
mineral lineations and fold axes indicate very high strain, and this combined with map patterns suggests the Acadian  $F_1$  "nappe-stage" folds likely developed as sheath folds at this time (fig. 4). Significant tectonic mélange is present along the base of the Monroe fault in the area around Chestnut Hill. Only in the hinge regions of these early  $F_1$  folds, or in areas where bedding is massive (such as on the exposed upright limb at Skitchewaug Mountain) is it possible to see bedding that is not parallel to a foliation. Both the CVT and NHS rocks contain this first-generation (Acadian  $S_1$ ) schistosity. The  $S_1$  foliation developed prior to peak metamorphism that reached as high as staurolite and sillimanite grade (this study; Spear and others, 2008; McAleer and others, 2017). The second-generation planar fabric ( $S_2$  foliation) in all the Silurian and Devonian rocks varies from a non-penetrative cleavage to a penetrative schistosity.  $F_2$  folds associated with the second generation planar fabric  $S_2$  foliation vary from open to isoclinal with generally consistent gentle plunges to both the north and south, but locally the plunges are quite steep, especially in shear zones. Acadian  $S_1$ and S<sub>2</sub> are the most dominant, or visibly conspicuous, planar fabrics east of the Moretown slice. Locally, these two planar fabrics are parallel and it is difficult to discern one from the other. In such places where only a single penetrative schistosity is observed, and no crosscutting relative age relationships can be discerned, a dominant foliation symbol is used on the map  $(S_p)$ . The Acadian  $S_1$  schistosity and younger  $S_2$  foliation are deformed by a minimum of two younger cleavages ( $S_3$  and  $S_4$ ). The next youngest generation of planar features include broad to open folds  $(F_3)$  with both gentle and steep fold hinges and associated millimeter- to centimeter (cm)-spaced crenulation cleavage  $(S_3)$ . The  $F_3$  and  $S_3$  structures have many different orientations, although they most commonly strike northeast and dip either vertically or steeply northwest, and locally exhibit sinistral sense of rotation (fig. 3). They are, in part, related to the last stages of doming, and the older  $S_1$  schistosity and  $S_2$  foliation are deformed by them. It is not certain whether these younger "dome-related"  $F_3$  and  $S_3$  structures are entirely coeval across the map; the  $S_1$  schistosity is interpreted as Acadian, the  $S_2$  foliation is interpreted as Acadian to Alleghanian, and the  $S_3$  cleavage is interpreted as Neo-Acadian, Alleghanian, or younger. Late-stage F<sub>3</sub> folds locally show a left-lateral sense of rotation and are probably related to late dome-stage Alleghanian deformation or motion along lower-greenschist-facies regional faults at around 300 Ma (McWilliams and others, 2013) or between 310 and 280 Ma (McAleer and others, 2017). The S<sub>3</sub> cleavage and associated F<sub>3</sub> axial surfaces show a preferred northeast strike and moderate northwest dip (fig. 3). The  $S_3$  cleavage locally exhibits fracture-parting and is thus included in the brittle fabric analysis

The youngest cleavage  $(S_4)$  in the area is a 1-cm- to 30-cm-spaced crenulation cleavage that locally occurs as parallel sets of kink bands or low-amplitude,

long-wavelength folds with variable fold hinge orientations. Secondary minerals,



8 MILES 12 KILOMETERS 0 6



**Post-peak metamorphic fault**—Arrows indicate relative motion; U, upthrown side; D, downthrown side. Mz, Mesozoio

Partridge Formation, gray granofels member (Opg)

Cram Hill Formation, felsic volcanic rock (Ochv)

Unity pluton (Oadu)

SP-2485

CS-3009

SP450

Figure 1. Simplified tectonic map and index to 7.5-minute quadrangles (gray text). Modified from Lyons and others (1997), Ratcliffe and others (2011), and Walsh (2016). The area of this report is outlined in red. The Albee Formation is not exposed in the map area. Abbreviations: AFZ, Ammonoosuc fault zone; BMSZ, Bald Mountain shear zone (McAleer and others, 2017); SMF, Skitchewaug Mountain fault.

Table 1. Summary of reported U-Pb zircon ages from rocks in the Springfield 7.5- x 15-minute quadrangle [Abbreviations: LA-ICP-MS, laser ablation inductively coupled plasma mass spectrometry; Ma, mega-annum (million years before present); MDA, maximum depositional age for detrital zircons; SHRIMP, sensitive high-resolution ion microprobe; TIMS, thermal ionization mass spectrometry; U-Pb, uranium-lead] Map unit and rock type Age (Ma) Method Sample number CS-3025 399±3 SHRIMP Bethlehem Granodiorite (Dab) Merschat and others (2015) VT/Sp1-85 Waits River Formation, felsic volcanic member (DSwvf) 423±4 TIMS Aleinikoff and Karabinos (1990); Hueber and others (1990

MDA 452 LA-ICP-MS Walsh and others (2017)

446±6 SHRIMP Valley and others (2020)

483±3 SHRIMP Aleinikoff and others (2011)

includes two dominant trends that strike north-northeast and west-northwest and dip sub-vertically, which is sub-parallel to the regional joint trends and brittle faults (fig. 3). The kinks bands and cleavage locally exhibit fracture-parting and are thus included in the brittle fabric analysis (fig. 3). The  $S_4$  cleavage and the outcrop-scale and map-scale brittle faults in the area, the latter of which generally strike north-south and dip sub-vertically (fig. 3), are related to Mesozoic extension (Hatch, 1988). In the Hartland and North Hartland quadrangles to the north, the kink bands are spatially associated with the Ammonoosuc fault (Walsh, 2016), but sufficient data were not observed in this map area to demonstrate spatial correlation between kink bands and brittle faults. The youngest deformation is characterized by Mesozoic brittle faulting, kink bands, motion along the Ammonoosuc and Grantham faults and smaller unnamed faults, and subsequent jointing. Locally, fault surfaces with slickensides suggest brittle reactivation of the dominant foliation surfaces as well as reactivation of many ductile faults including the Keyes Mountain and Skitchewaug Mountain faults, and faults of the Sumner Falls shear zone and Northey Hill shear zone.

SEA LEVEL

4.000

SEA LEVEL -

2,000

mainly quartz, calcite, and dolomite, occur as vein-filling material in the cleavage planes. This youngest generation of cleavage shows variable orientations, but

METAMORPHISM AND TECTONIC HISTORY Rocks of the Mount Holly Complex in the core of the Chester dome may have reached hornblende-granulite-facies metamorphic conditions during the Mesoproterozoic Grenville Orogen (Rivers, 2012), but direct evidence of Grenville granulite-facies metamorphism is lacking (Ratcliffe, 2000a, b). The basement rocks subsequently experienced staurolite-kyanite-zone (lower-amphibolite-facies) metamorphism during the Ordovician Taconic and Devonian Acadian metamorphic events. Paleozoic metamorphism reached amphibolite-facies conditions in the Mount Holly Complex, the Moretown slice, the eastern part of the NHS, and the western part of the CVT, but never exceeded greenschist-facies conditions in parts of the central CVT and NHS during the Acadian orogeny. No relict-Taconic metamorphic mineral assemblages are recognized in the pre-Silurian rocks, perhaps due to the thoroughness of recrystallization associated with the Acadian metamorphic overprint. The Monroe thrust fault carried the NHS rocks over the CVT during an early-Acadian F<sub>1</sub> nappe-stage event that pre-dated lower-amphibolite-facies peak metamorphism. The onset of doming occurred during F<sub>2</sub> folding and deformed the Monroe thrust sheet, folded earlier isograds, and created the Meriden antiform and related dome structures (fig. 1). Doming continued, suggested by the deformation of D<sub>2</sub> structures by D<sub>3</sub> structures. Lower-greenschist-facies (Alleghanian) faults and shear zones such as the Northey Hill, Westminster West (fig. 1), Sumner Falls, and Skitchewaug Mountain fault, truncated F<sub>1</sub> folds and faults as well as peakmetamorphic isograds, and are defined by zones of pervasive retrogression. These faults experienced a protracted history and played a major role in creating the metamorphic discontinuity that is documented across the Connecticut River Valley, indicated by amphibole and muscovite  ${}^{40}\text{Ar}/{}^{39}\text{Ar}$  ages of ~380 and ~330 Ma in Vermont, and ~330 and ~270 Ma in New Hampshire (Harrison and others, 1989; McWilliams and others, 2013; McAleer and others, 2014, 2015, 2017; Walsh and others, 2017). Additionally, in the vicinity of the Bald Mountain shear zone in the adjacent Mt. Ascutney quadrangle (McAleer and others 2017; Walsh and others, 2020),  ${}^{40}$ Ar/ ${}^{39}$ Ar data from muscovite record a mixture of cooling ages of ~300 Ma and crystallization ages of ~245 Ma. The younger ages are recorded by muscovite that defines the shear-zone fabric and pseudomorphically replaces staurolite. These younger ages (~300 and ~245 Ma) extend the period of ductile deformation and down-to-the-east normal extension that occurred in the area and lasted into the Triassic (McAleer and others, 2014, 2015, 2017). Taken together, the relative- and absolute-age constraints suggest that peak metamorphic conditions developed during the Acadian orogeny and that retrograde greenschist-facies metamorphism occurred during the Alleghanian orogeny. Spear and others (2008) document monazite ages that range from ~430 to 290 Ma. This wide range of ages suggests monazite growth or recrystallization occurred during both the Acadian and Alleghanian orogenies. The recognition that peak metamorphic assemblages are truncated along major faults associated with lower-greenschist-facies fabrics led Spear and others (2008) to propose a major Alleghanian fault along their "western New Hampshire boundary thrust" or the informally named "chicken yard line" (Trzcienski and others, 1992); the fault is now mapped as the Westminster West fault zone (fig. 1) (Armstrong, 1997; Armstrong and others, 1997; Ratcliffe and others, 2011; McWilliams and others, 2013). This fault zone is now recognized as continuous with the Sumner Falls shear zone (this study; Walsh, 2016; Walsh and others, 2020). Other mapped faults including the Woodbury Road and Skitchewaug Mountain faults, as well as those located in the Bald Mountain shear zone (fig. 1) and Northey Hill shear zone, share a similar history (this study; McAleer and others, 2017). Apatite fission track data indicate that the brittle Ammonoosuc fault was active prior to about 100 Ma and experienced little to no reactivation in the Cretaceous, but other regionally significant older, ductile shear zones (such as the Northey Hill shear zone) experienced Late Cretaceous (~80 Ma) brittle reactivation (Roden-Tice and others, 2009). Additional apatite fission-track data suggest some Cretaceous activity on regional brittle faults (for example, the Grantham fault) may have extended into the Paleocene (Schnalzer and others, 2015). The sense of displacement along faults shown on sheets 1 and 2 is provided where known, but

given the protracted history described above, the faults may be reactivated with

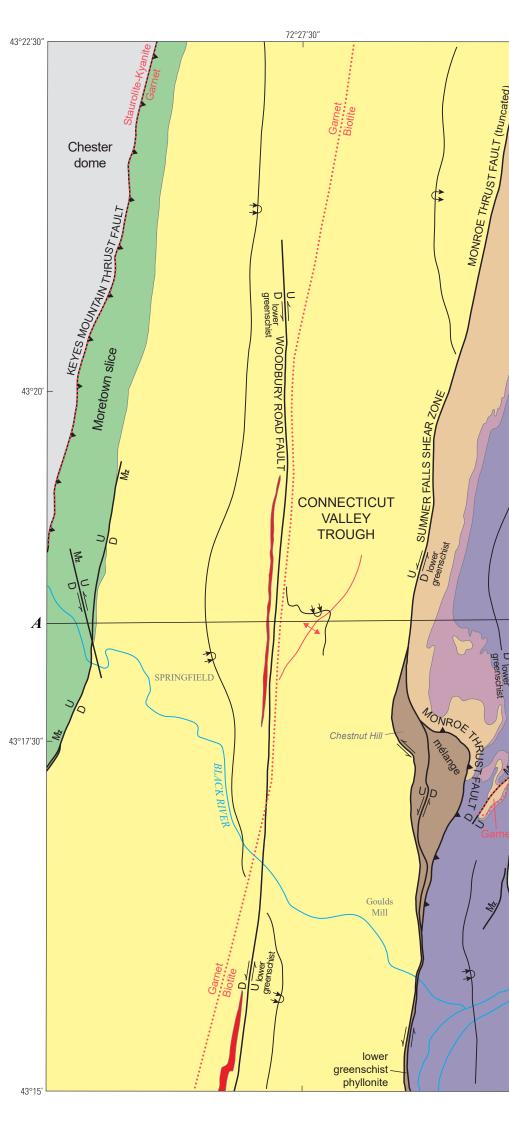
varying senses of motion. Recent 1:24,000-scale geologic mapping and supporting

research in the Connecticut Valley from Lebanon, New Hampshire, to Bellows

Falls, Vermont, provides new evidence for the tectonic evolution of the valley and

demonstrates that it is the locus of complex faulting throughout its Phanerozoic

history (Walsh and others, 2017).



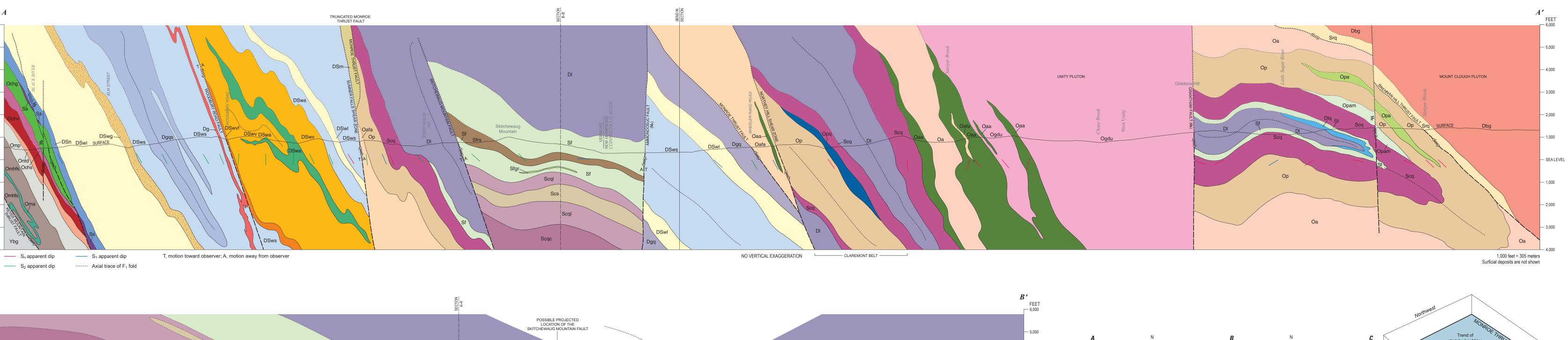
called the "chicken yard line" or "western New Hampshire boundary thrust" by Spear and others (2008). KDq, Cretaceous to Devonian quartz veins. This research builds upon a preliminary map covering the Vermont part of the area by Walsh and others (1996a, b). Previous mapping in the area included several sketch maps, simplified regional maps, and field-trip guidebook maps (Richardson, 1931; Ratté, 1952; Thompson, 1954; Rosenfeld, 1968; Thompson and others, 1968; Boxwell and Laird, 1987; Thompson and others, 1990; Trzcienski and others, 1992; Thompson and others, 1993; Armstrong and others, 1997; Thompson and others, 2012). Prior to this study, no detailed published maps existed for the New Hampshire part of the area; the geology was mapped only at statewide scale (Billings, 1956; Lyons and others, 1997). This report consists of sheets 1 and 2 as well as an online geographic information system (GIS) database that includes contacts of bedrock geologic units, faults, outcrops, and structural geologic information. Sheet 1 of this report includes the geologic map, description of map units, correlation of map units, explanation of map symbols, and an index to geologic mapping. Sheet 2 of this report includes a discussion, two cross sections, two tectonic maps (figs. 1 and 2), a summary of

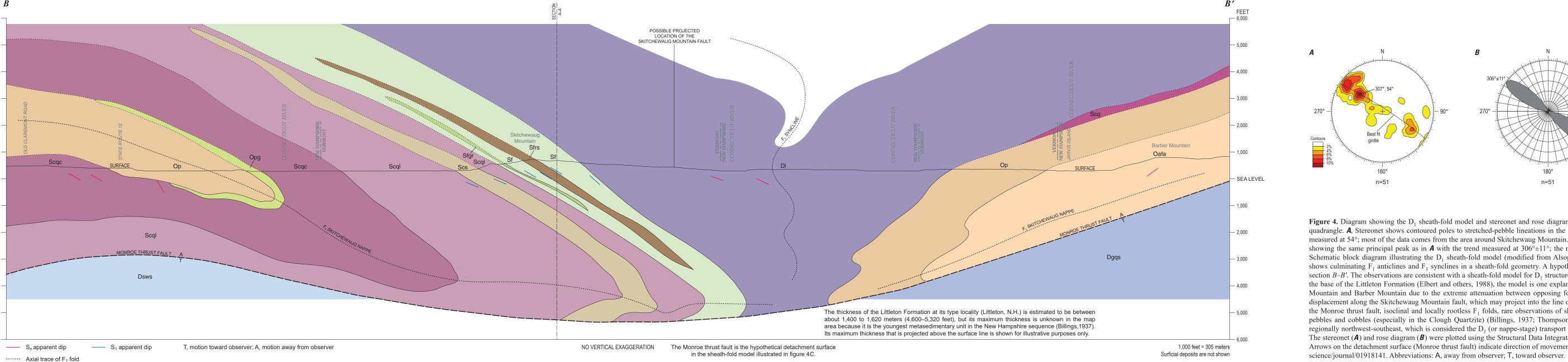
and 4).

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VALLEY Sugar River pluton MONROE TROUGH / THRUS' and dome THRUST FAULT FAUL Unity pluton and dome Bethlehe Granodiorit Mount Clough SCALE 1:50 000 5 KILOMETERS 

Figure 2. Tectonic map showing the major structural features of the Springfield 7.5- x 15-minute quadrangle. The map is characterized by fault-block domains that truncate and deform stratigraphy, Acadian F<sub>1</sub> folds, and metamorphic isograds. Retrograde lower-greenschist high-strain zones occur in the Connecticut River Valley along the Summer Falls shear zone, the Woodbury Road fault, the Skitchewaug Mountain fault, and the Northey Hill shear zone. The Summers Falls shear zone is a splay of the Westminster West fault zone (Armstrong, 1997; McWilliams and others, 2013). These zones show evidence for both ductile and locally brittle deformation during the protracted Acadian and Alleghanian orogenic events. Major Mesozoic brittle faults include the Ammonoosuc and Grantham faults. Note that the Sumner Falls shear zone is informally

reported U-Pb zircon ages (table 1), and measured outcrop-scale strike and dip results from structural features with summary stereonets and rose diagrams (figs. 3

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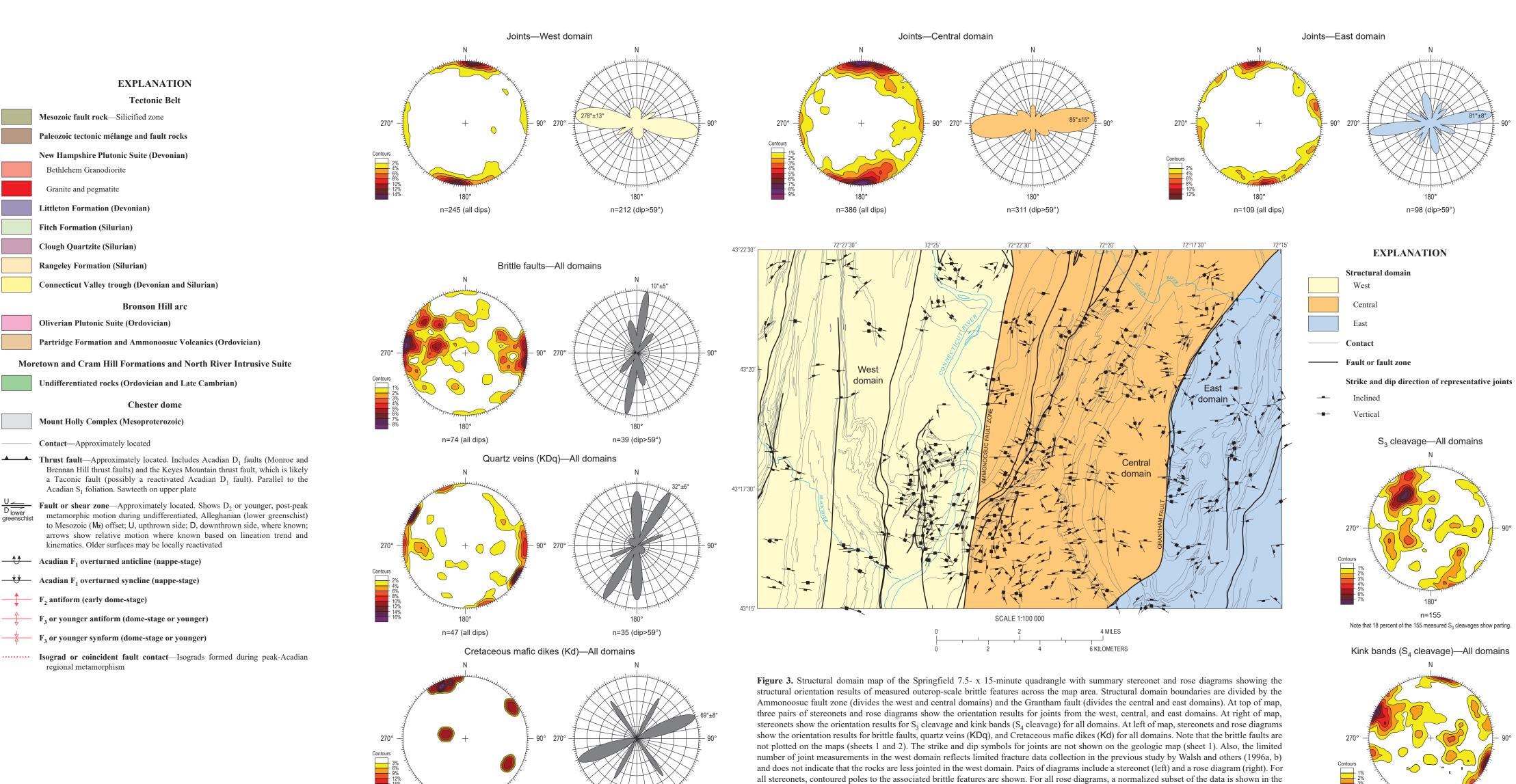
by mafic magmas based on Sr and O isotopic and major element relationships:

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Bedrock Geologic Map of the Springfield 7.5- x 15-Minute Quadrangle, Windsor County, Vermont, and Sullivan County, New Hampshire



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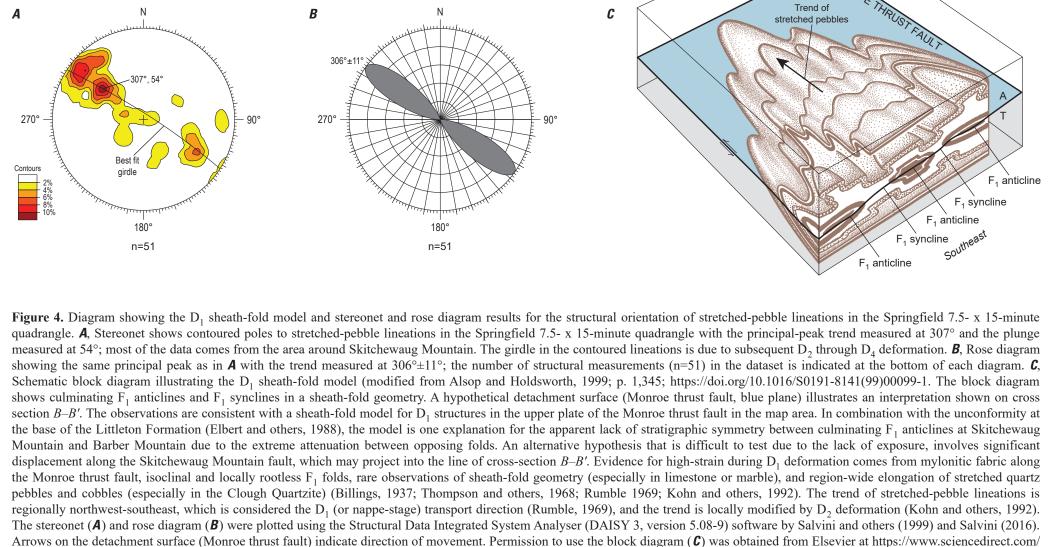
Cube area, New Hampshire: Cambridge, Mass., Harvard University, Ph.D

n=5 (dip>59°)

n=6 (all dips)

dissertation, 120 p.

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corresponding stereonet for dips  $>59^\circ$ , and principal peaks are shown with 1 standard deviation error (for example,  $278^\circ \pm 13^\circ$  for the joints in the west domain). The number of structural measurements in each dataset is indicated by "n" at the bottom of each diagram. Stereonets and rose diagrams were plotted using the Structural Data Integrated System Analyser (DAISY 3, version 5.08-9) software by Salvini and others (1999) and

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