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

Prepared in cooperation with the
STATE OF VERMONT, VERMONT AGENCY OF NATURAL RESOURCES, VERMONT GEOLOGICAL SURVEY; and the
STATE OF NEW HAMPSHIRE, DEPARTMENT OF ENVIRONMENTAL SERVICES, NEW HAMPSHIRE GEOLOGICAL SURVEY

Scientific Investigations Map 3462
Sheet 2 of 2

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 Keyes 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).

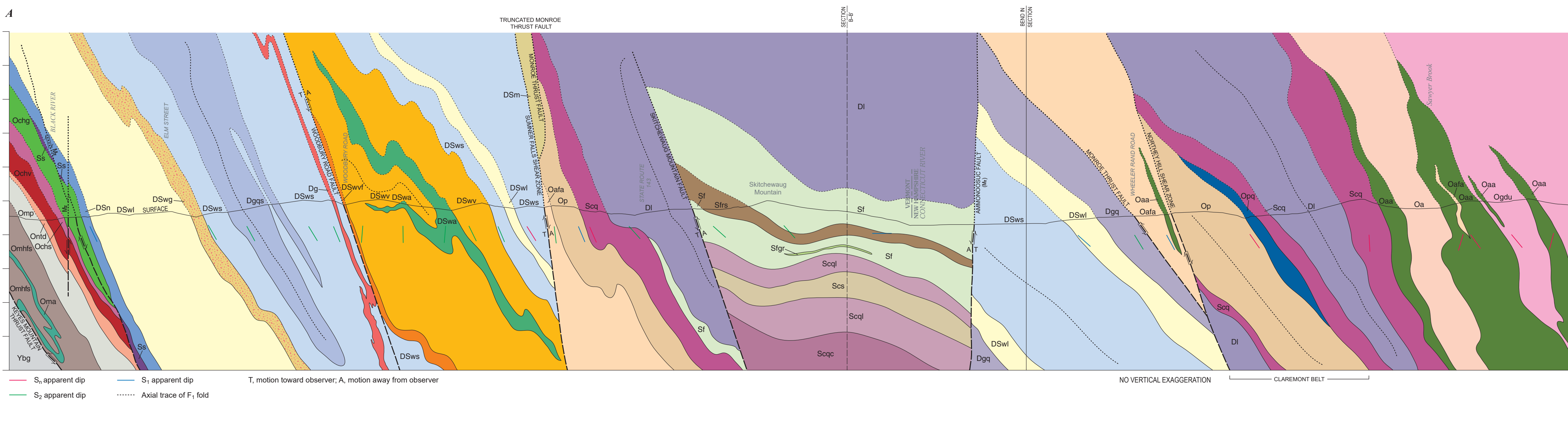
The oldest foliation in the Silurian and Devonian rocks of the CVT and NHS is a layer-parallel Acadian schistosity (S_1) that contains rarely observed Acadian isoclinal folds (F_1). These folds are the nappe-stage folds of Thompson and others (1968). The overturned, and subsequently truncated, fold-nappe 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

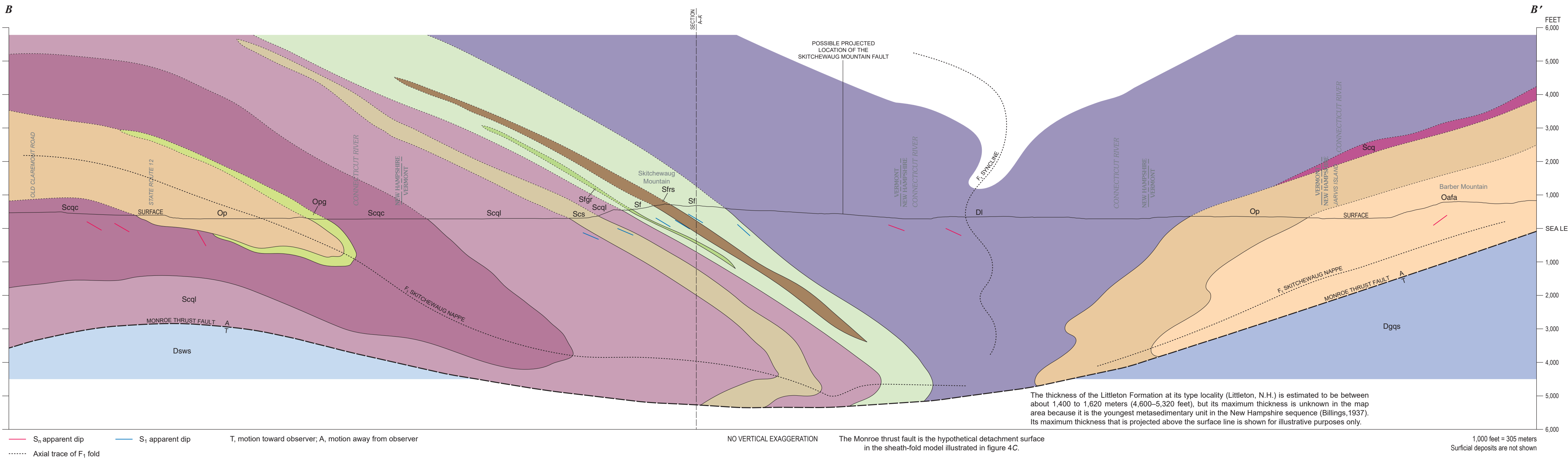
mainly quartz, calcite, and dolomite, occur as vein-filling material in the cleavage planes. This youngest generation of cleavage shows variable orientations, but includes two dominant trends that strike north-northeast and west-northwest and dip sub-vertically, which is sub-parallel to the regional 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.

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_1 nappe-stage event that pre-dated lower-amphibolite-facies peak metamorphism. The onset of doming occurred during F_2 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_2 structures by D_3 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_1 folds and faults as well as peak-metamorphic 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 $^{40}Ar/^{39}Ar$ 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





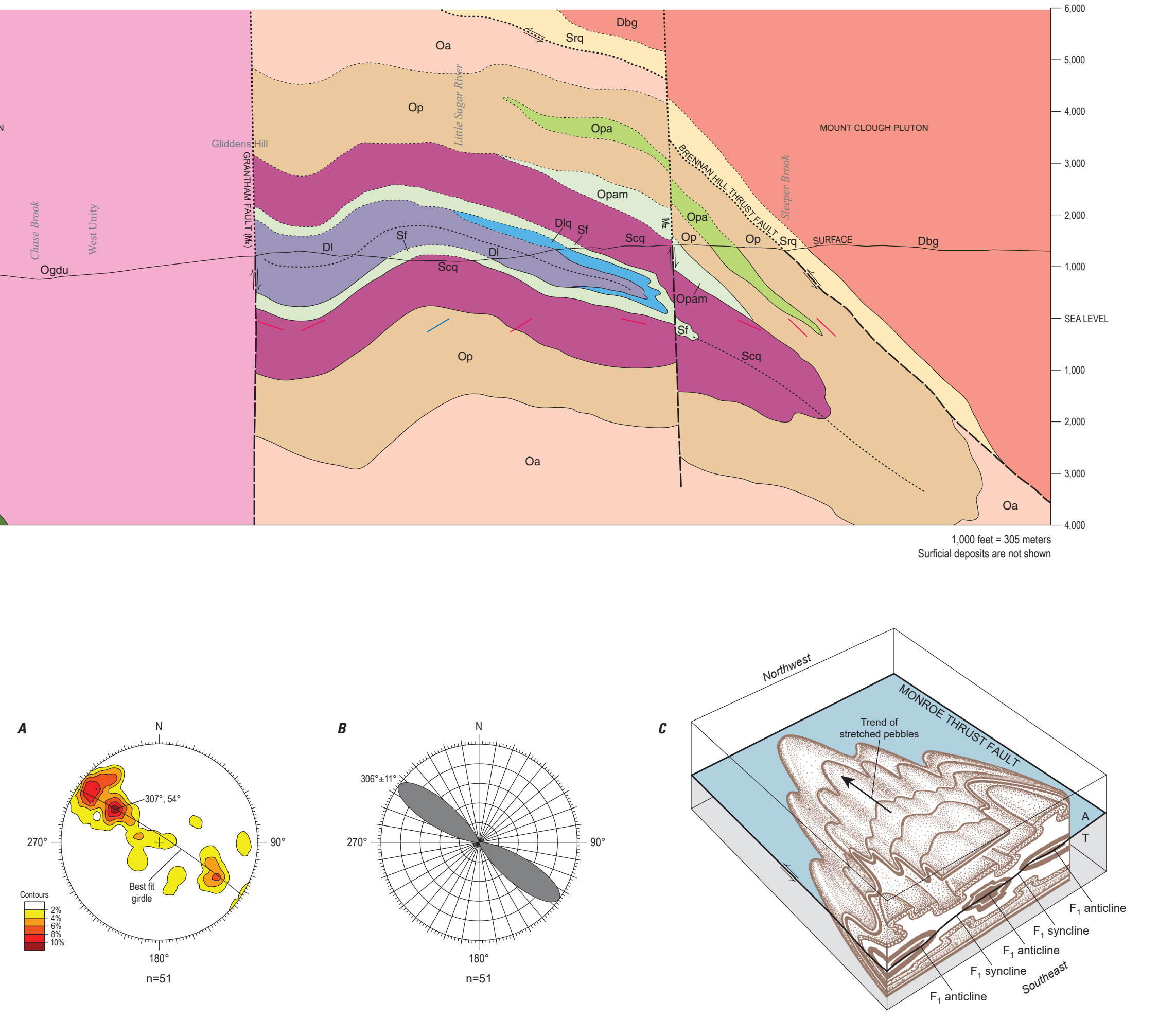


Figure 4. Diagram showing the D_1 sheath-fold model and stereonet and rose diagram results for the structural orientation of stretched-pebble lineations in the Springfield 7.5- x 15-minute quadrangle. ***A***, Stereonet shows contoured poles to stretched-pebble lineations in the Springfield 7.5- x 15-minute quadrangle with the principal-peak trend measured at 307° and the plunge measured at 54°; most of the data comes from the area around Skitchewaug Mountain. The girdle in the contoured lineations is due to subsequent D_2 through D_4 deformation. ***B***, Rose diagram showing the same principal peak as in ***A*** with the trend measured at 306°±11°; the number of structural measurements (n=51) in the dataset is indicated at the bottom of each diagram. ***C***, Schematic block diagram illustrating the D_1 sheath-fold model (modified from Alsop and Holdsworth, 1999; p. 1,345; https://doi.org/10.1016/S0191-8141(99)00099-1. The block diagram shows culminating F_1 anticlines and F_1 synclines in a sheath-fold geometry. A hypothetical detachment surface (Monroe thrust fault, blue plane) illustrates an interpretation shown on cross section *B–B′*. The observations are consistent with a sheath-fold model for D_1 structures in the upper plate of the Monroe thrust fault in the map area. In combination with the unconformity at the base of the Littleton Formation (Elbert and others, 1988), the model is one explanation for the apparent lack of stratigraphic symmetry between culminating F_1 anticlines at Skitchewaug Mountain and Barber Mountain due to the extreme attenuation between opposing folds. An alternative hypothesis that is difficult to test due to the lack of exposure, involves significant displacement along the Skitchewaug Mountain fault, which may project into the line of cross-section *B–B′*. Evidence for high-strain during D_1 deformation comes from mylonitic fabric along the Monroe thrust fault, isoclinal and locally rootless F_1 folds, rare observations of sheath-fold geometry (especially in limestone or marble), and region-wide elongation of stretched quartz pebbles and cobbles (especially in the Clough Quartzite) (Billings, 1937; Thompson and others, 1968; Rumble 1969; Kohn and others, 1992). The trend of stretched-pebble lineations is regionally northwest-southeast, which is considered the D_1 (or nappe-stage) transport direction (Rumble, 1969), and the trend is locally modified by D_2 deformation (Kohn and others, 1992). The stereonet (***A***) and rose diagram (***B***) were plotted using the Structural Data Integrated System Analyser (DAISY 3, version 5.08-9) software by Salvini and others (1999) and Salvini (2016). Arrows on the detachment surface (Monroe thrust fault) indicate direction of movement. Permission to use the block diagram (***C***) was obtained from Elsevier at https://www.sciencedirect.com/science/journal/01918141. Abbreviations: A, away from observer; T, toward observer.

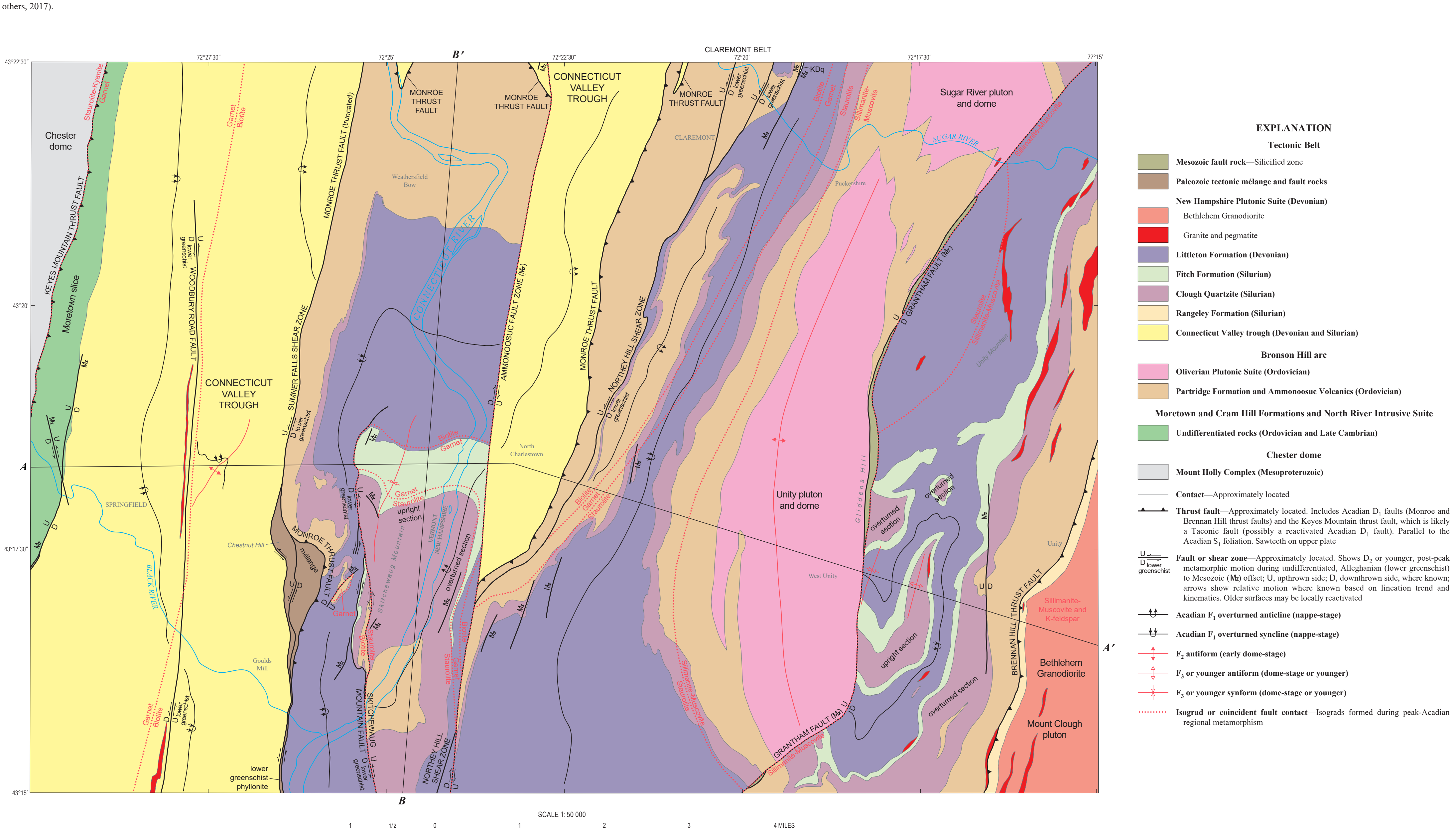


Figure 2. Tectonic map showing the major structural features of the Springfield 7.5- x 15-minute quadrangle. The map is characterized by fault-block domains that truncate and deform stratigraphy, Acadian F_1 folds, and metamorphic isograds. Retrograde lower-greenschist high-strain zones occur in the Connecticut River Valley along the Sumner Falls shear zone, the Woodbury Road fault, the Skitchewaug Mountain fault, and the Northey Hill shear zone. The Sumners 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 called the “chicken yard line” or “western New Hampshire boundary thrust” by Spear and others (2008). KDq, Cretaceous to Devonian quartz veins.

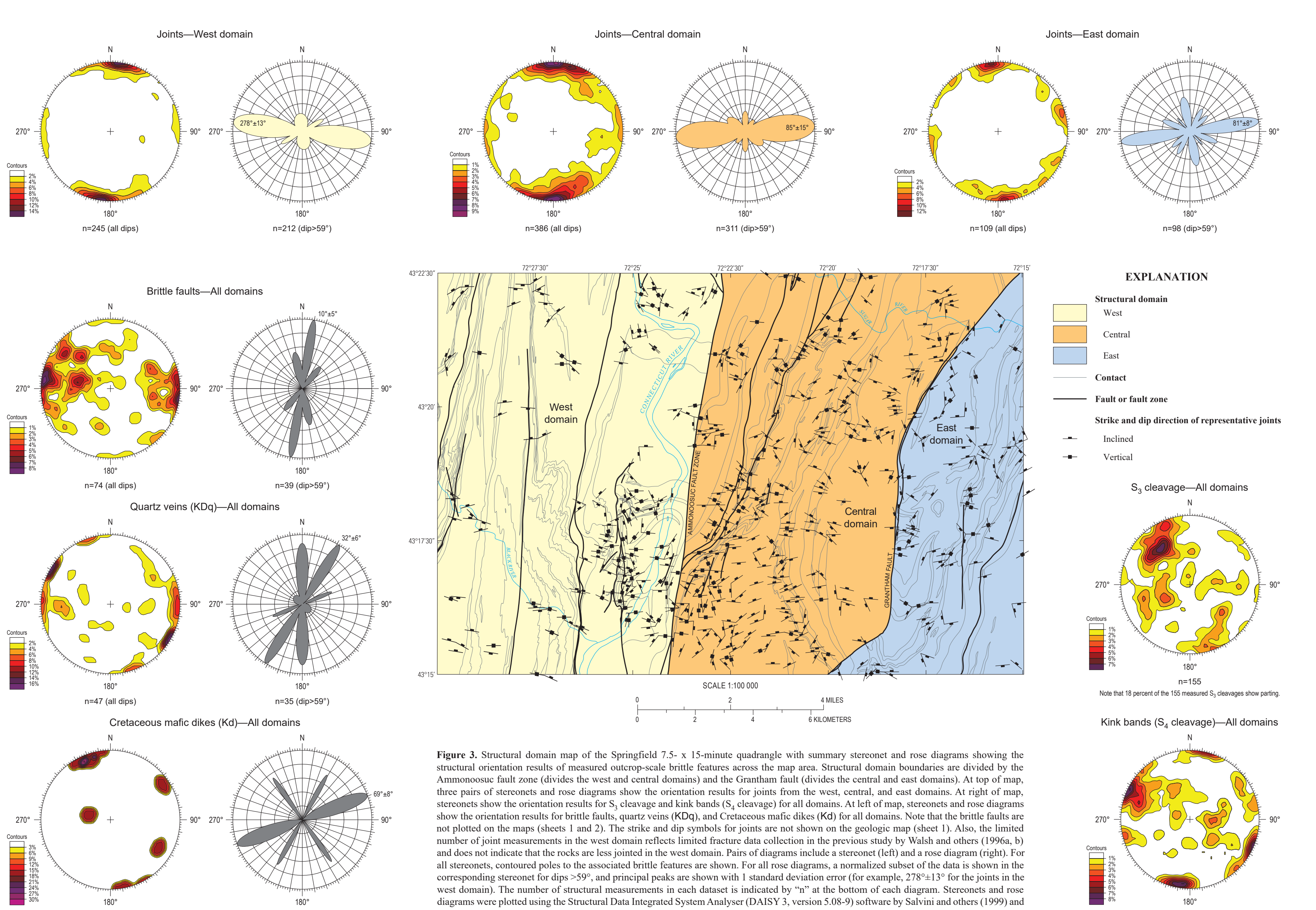


Figure 3. Structural domain map of the Springfield 7.5- x 15-minute quadrangle with summary stereonet and rose diagrams showing the structural orientation results of measured outcrop-scale brittle features across the map area. Structural domain boundaries are divided by the Ammonoosuc fault zone (divides the west and central domains) and the Grantham fault (divides the central and east domains). At top of map, three pairs of stereonets and rose diagrams show the orientation results for joints from the west, central, and east domains. At right of map, stereonets show the orientation results for S_3 cleavage and kink bands (S_4 cleavage) for all domains. At left of map, stereonets and rose diagrams show the orientation results for brittle faults, quartz veins (KDq), and Cretaceous mafic dikes (Kd) for all domains. Note that the brittle faults are not plotted on the maps (sheets 1 and 2). The strike and dip symbols for joints are not shown on the geologic map (sheet 1). Also, the limited number of joint measurements in the west domain reflects limited fracture data collection in the previous study by Walsh and others (1996a, b) and does not indicate that the rocks are less jointed in the west domain. Pairs of diagrams include a stereonet (left) and a rose diagram (right). For all stereonets, contoured poles to the associated brittle features are shown. For all rose diagrams, a normalized subset of the data is shown in the corresponding stereonet for dips >59°, and principal peaks are shown with 1 standard deviation error (for example, 278°±13° 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 Salvini (2016). Consult the geographic information systems (GIS) database for the complete dataset.

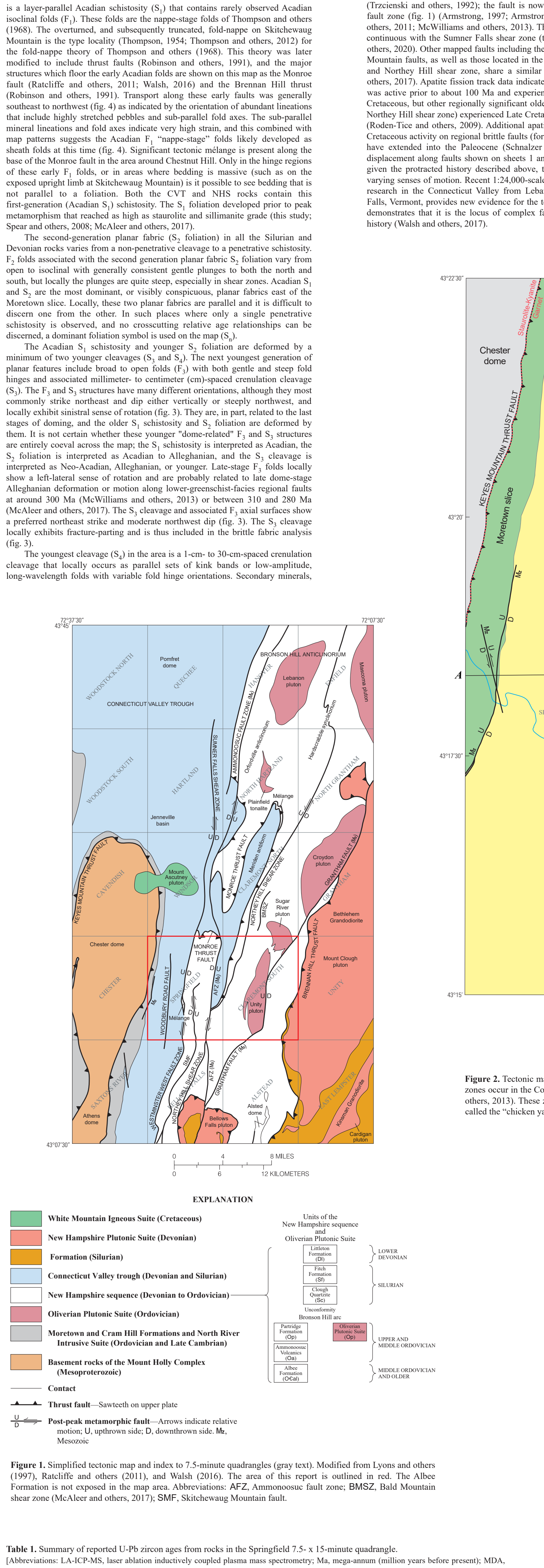


Figure 1. Simplified tectonic map and index to 7.5-minute quadrangles (gray text). Modified from Lyons and others (1997), Ratcliffe and others (2011), and Walsh (2016). The area of this report is outlined in red. The Albee Formation is not exposed in the map area. Abbreviations: AFZ, Ammonoosuc fault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

Sample number	Map unit and rock type	Age (Ma)	Method	References
CS–3025	Bethlehem Granodiorite (Dgb)	399±3	SHRIMP	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)
SP–2485	Partridge Formation, gray granofels member (Opg)	MDA 452	LA-ICP-MS	Walsh and others (2017)
CS–3009	Unity pluton (Ogdu)	446±6	SHRIMP	Valley and others (2020)
SP450	Cram Hill Formation, felsic volcanic rock (Ochv)	483±3	SHRIMP	Aleinikoff and others (2011)

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

Armstrong, T.R., Walsh, G.J., and Spear, F.S., 1997, A transect across the Connecticut valley sequence in east-central Vermont, Trip A–6, *in* Grover, T.W., Mango, H.N., and Hasenohr, E.J., eds., New England Intercollegiate Geological Conference, 89th Annual Meeting, Killington-Pico region, Vt., Sept. 19–21, 1997, Guidebook to field trips in Vermont and adjacent New Hampshire and New York: Castleton, Vt., Castleton State College, p. A6–1 to A6–56.

Elbert, D.C., Harris, A.G., and Denkler, K.E., 1988, Earliest Devonian conodonts from marbles of the Fitch Formation, Bernardston nappe, north-central Massachusetts: American Journal of Science, v. 288, no. 7, p. 684–700. [Also available at https://doi.org/10.2475/ajs.288.7.684.]

Hatch, N.L., Jr., 1988, New evidence for faulting along the "Monroe Line", eastern Vermont and westernmost New Hampshire: American Journal of Science, v. 288, no. 1, p. 1–18. [Also available at https://doi.org/10.2475/ajs.288.1.1.]

McAleer, R.J., Kunk, M.J., Merschat, A.J., Walsh, G.J., Valley, P.M., Kunk, M.J., and Wintsch, R.P., 2017, Alleghanian deformation and recrystallization in the Connecticut Valley of VT and NH [abs.]: Geological Society of America Abstracts with Programs, v. 49, no. 2. [Also available at https://doi.org/10.1130/abs/2017NE-290077.]

Ratcliffe, N.M., 1995b, Digital bedrock geologic map of the Chester quadrangle, Vermont: U.S. Geological Survey Open-File Report 95–576–A, 2 pls., scale 1:24,000.

Ratcliffe, N.M., 2000a, Bedrock geologic map of the Cavendish quadrangle, Windsor County, Vermont: U.S. Geological Survey Geologic Quadrangle Map GQ–1773, 1 pl., scale 1:24,000, 19-p. pamphlet. [Also available at https://pubs.er.usgs.gov/publication/gq1773.]

Rosenfeld, J.L., 1968, Garnet rotations due to the major Paleozoic deformations in southeast Vermont, *in* Zen, E-A, White, W.S., Hadley, J.B., and Thompson, J.B., Jr., eds., Studies of Appalachian geology, northern and maritime: Wiley-Interscience Publishers, New York, p. 185–202.

Rumble, D., III, 1969, Stratigraphic, structural, and petrologic studies in the Mt. Cube area, New Hampshire: Cambridge, Mass., Harvard University, Ph.D dissertation, 120 p.

Salvini, F., Billi, A., and Wise, D.U., 1999, Strike-slip fault-propagation cleavage in carbonate rocks—The Mattinata fault zone, Southern Apennines, Italy: Journal of Structural Geology, v. 21, no. 12, p. 1731–1749. [Also available at https://doi.org/10.1016/S0191-8141(99)00120-0.]

Salvini, F., 2016, DAISY 3—The Structural Data Integrated System Analyser (version 5.08-9): Rome, Italy, Roma Tre University, Department of Geological Sciences, software available at http://host.uniroma3.it/progetti/fralab/Downloads/Programs/.

Valley, P.M., Walsh, G.J., and McAleer, R.J., 2015, New U-Pb zircon ages from the Bronson Hill arc, west-central New Hampshire [abs.]: Geological Society of America Abstracts with Programs, v. 47, no. 3, p. 41. [Also available at https://gsa.confex.com/gsa/2015NE/webprogram/Paper252722.html.]

Valley, P.M., Walsh, G.J., Merschat, A.J., and McAleer, R.J., 2020, Geochronology of the Oliverian Plutonic Suite and the Ammonoosuc Volcanics in the Bronson Hill arc—Western New Hampshire, USA: Geosphere, v. 16, no. 1, p. 229–257. [Also available at https://doi.org/10.1130/GES02170.1.]

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

By

Gregory J. Walsh,[1] Peter M. Valley,[1] Thomas R. Armstrong,[2] Nicholas M. Ratcliffe,[3] Arthur J. Merschat,[1] and Beau J. Gentry[4]

2020