TRANSPRESSIONAL DEFORMATION IN TACONIC SLATES AND ITS RELATION TO BASEMENT ARCHITECTURE

JEAN M. CRESPI
Center for Integrative Geosciences, University of Connecticut, Storrs, Connecticut 06269

H. RAY UNDERWOOD
GeoDesign, Inc., 984 Southford Rd., Middlebury, Connecticut 06762

INTRODUCTION

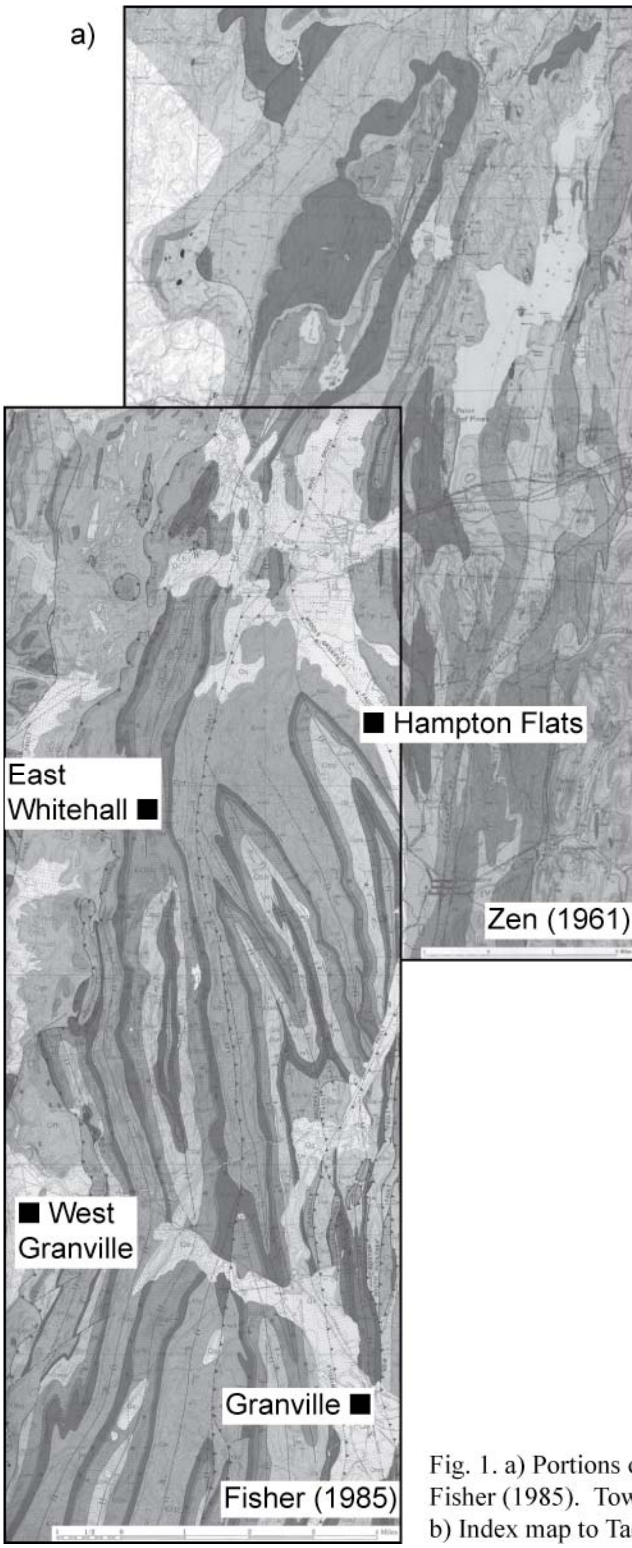
The Taconic allochthon is a north-northeast-trending tectonostratigraphic unit in westernmost New England and easternmost New York State. The allochthon, which consists of Neoproterozoic rift clastics, Cambro-Ordovician slope-rise deposits, and Ordovician flysch, was emplaced during the Middle to Late Ordovician Taconic orogeny (Rowley and Kidd 1981, Stanley and Ratcliffe 1985, Karabinos et al. 1998). The strata were folded and cleaved during orogenesis. In the northern Giddings Brook thrust sheet, the penetrative deformation, low-grade metamorphism, and dominantly fine-grained nature of the strata resulted in the formation of slate that has been extensively quarried (Dale 1899).

Nearly thirty years ago, Rowley et al. (1979) led a field trip for the New York State Geological Association through part of the slate belt in the northern Giddings Brook thrust sheet. The mapping presented in that field guide and the bedrock geologic map of the Glens Falls-Whitehall region compiled by Fisher (1985) show that the folds and slaty cleavage in the section of the Giddings Brook thrust sheet between Granville/West Granville and Hampton Flats/East Whitehall are not parallel to the overall trend of the Taconic allochthon (Fig. 1). Although the allochthon trends north-northeast, the folds and slaty cleavage in this area trend north-northwest. The primary goal of this field trip is to examine evidence supporting the hypothesis that the strata in this area underwent transpressional deformation. The field trip (Fig. 2) will begin in the classic area mapped by Zen (1961) to the north of Hampton Flats where the folds and slaty cleavage trend north-northeast. Inspection of the style of deformation of the strata to the north of Hampton Flats will provide a framework for understanding that of the strata in the area between Granville/West Granville and Hampton Flats/East Whitehall. Continuation of the field trip to the south to examine the area of anomalously north-northwest-trending folds and slaty cleavage will include stops that permit discussion of not only transpression but also the magnitude of tectonic volume change in slate, which remains a controversial topic.

STRUCTURAL DOMAINS

The northern Giddings Brook thrust sheet is divided into two structural domains on the basis of the (1) trend of the regional-scale D_2 folds (F_2), (2) strike of slaty cleavage (S_2), (3) dip of slaty cleavage (S_2), (4) rake of the mineral lineation (L_2), (5) state of strain, (6) strain symmetry, and (7) magnitude of finite strain. The last three characteristics refer only to the strain related to S_2 formation and are determined primarily from strain fringes around pyrite framboids and subspherical carbonaceous material. S_2 was superposed on the F_2 folds during the final stages of fold development and is approximately axial planar to the folds. Thus, the characteristics used to define the structural domains reflect only a portion of the deformation history undergone by the strata. D_2, however, is the main deformation event in the northern Giddings Brook thrust sheet, and S_2 is the dominant cleavage in the strata.

Domain 1 lies to the north of Hampton Flats, and domain 2 lies between Granville/West Granville and Hampton Flats/East Whitehall. Exposures that display characteristics of both domains 1 and 2 also exist, and these define a minor structural domain referred to as domain 1/2. Domain 1/2 lies on the eastern edge of domain 2 and is not considered on this field trip.



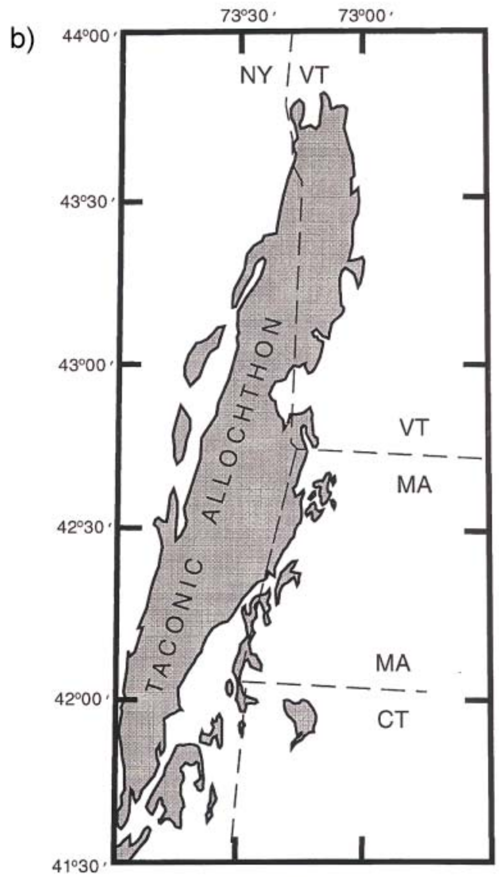


Fig. 1. a) Portions of bedrock geologic maps of Zen (1961) and Fisher (1985). Towns referred to in text indicated by squares. b) Index map to Taconic allochthon.

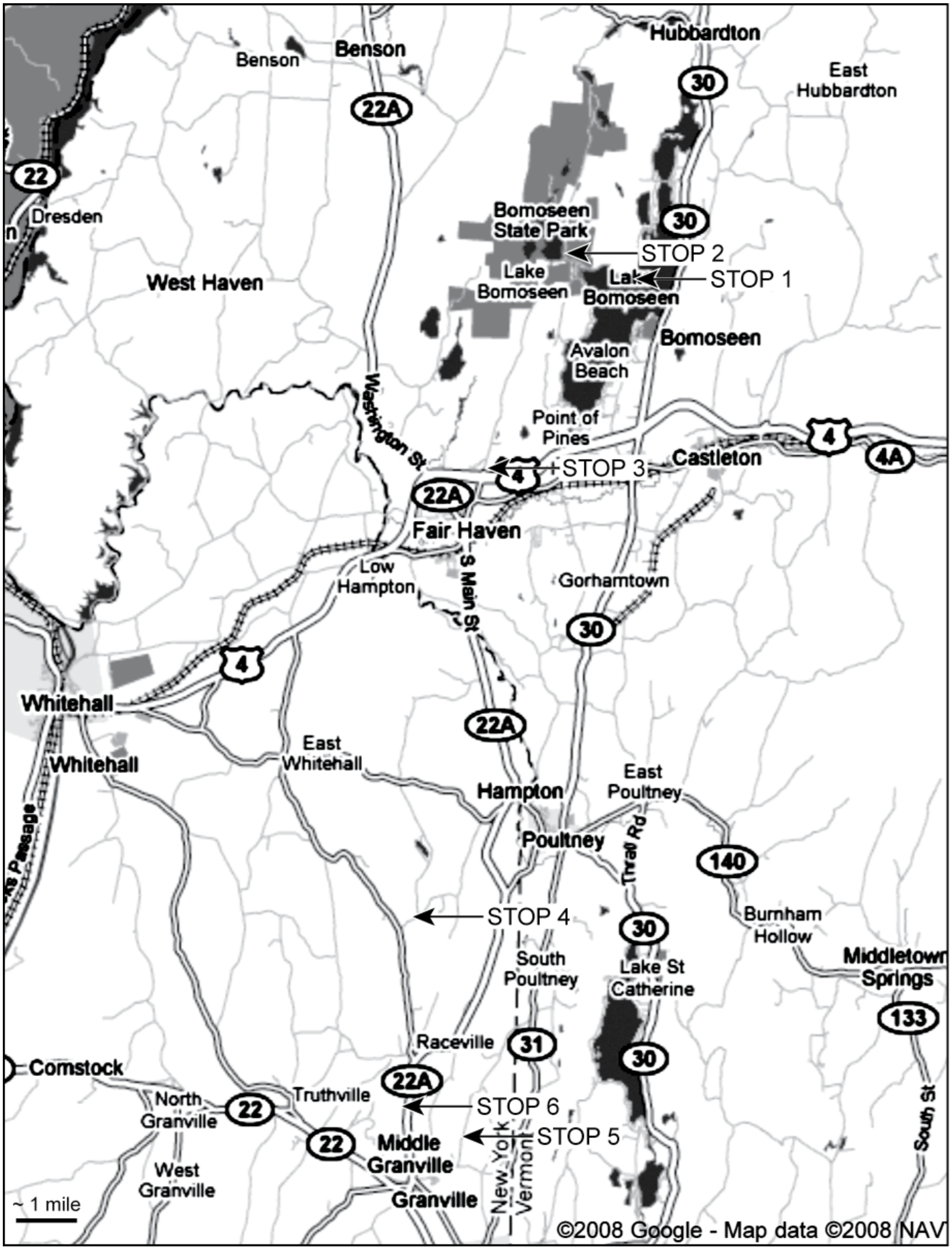


Fig. 2. Road map of area traversed during field trip. Stop locations shown by arrows.

Domain 1

Domain 1 is characterized by north-northeast-trending F_2 folds. The mean strike of S_2 is also north-northeast, and the mean dip is about 30°E. The mean trend of L_2 is east-southeast such that the rake of L_2 on S_2 is about 90°. Fibers in strain fringes are curved in thin sections oriented perpendicular to S_2 and parallel to L_2. The sense of curvature is consistently clockwise when the thin sections are viewed to the north-northeast and the fibers are traced toward the core object. This indicates top-to-the-west-northwest non-coaxial flow, which is consistent with the west-northwest vergence of the F_2 folds. In thin sections oriented parallel to S_2, the trace of the fibers in the strain fringes is straight and parallel to L_2. This evidence for plane strain in combination with the curved shape of the fibers in S_2-perpendicular and L_2-parallel thin sections gives a monoclinic symmetry for the strain related to S_2 formation. The strain magnitude is quantified using the length of the fibers in the strain fringes. Fibers were measured and $1 + e_1$ was determined for five sites. Site means for $1 + e_1$ range from 2.1 to 2.4, and the mean value for $1 + e_1$ for the five sites is 2.3. For additional information on domain 1, see Chan (1998).

Domain 2

Domain 2 is characterized by north-northwest-trending F_2 folds. Some folds can be traced continuously to the north and south of domain 2 where the fold axis changes trend from north-northwest to north-northeast. Both the strike and the dip of S_2 differ from that observed in domain 1. The mean strike of S_2 is north-northwest, and the mean dip is about 45°E. L_2 also differs in orientation, the mean trend being southeast. The change in orientations of S_2 and L_2 results in a rake of L_2 on S_2 of about 50° from the south-southeast. Like domain 1, fibers in strain fringes in S_2-perpendicular and L_2-parallel thin sections are curved and the sense of curvature is consistently clockwise when the thin sections are viewed to the north-northeast and the fibers are traced toward the core object. In S_2-parallel thin sections, the long axis of the strain fringes is parallel to L_2. At some sites, the strain fringes bracket the core object and show no evidence of fiber growth perpendicular to the long axis of the strain fringes. At other sites, the strain fringes completely surround the core object, and the fibers display radial growth. The former morphology indicates plane strain and the latter flattening strain. In addition, at several sites the fibers are curved in S_2-parallel thin sections. The sense of curvature is consistently clockwise when the thin sections are viewed down into the ground and the fibers are traced toward the core object. The fibers at these sites, therefore, are curved in three dimensions, indicating triclinic strain symmetry, and the sense of shear has thrust and left-lateral components. The strain magnitude was determined for seventeen sites from measurements of fiber length. Site means for $1 + e_1$ range from 1.2 to 1.65, and the mean value for $1 + e_1$ for the seventeen sites is 1.4. Site means for $1 + e_2$ range from 1.0 to 1.3, and the mean value for $1 + e_2$ for the seventeen sites is 1.05. If only the seven sites displaying flattening strain are considered, the mean value for $1 + e_2$ is 1.1. For additional information on domain 2, see Underwood (2006).

DISCUSSION

The orientation of structural elements and the strain are relatively homogeneous within each structural domain. In domain 1, the approximately down-dip L_2 is internally consistent with the evidence for plane strain and monoclinic strain symmetry. S_2 is interpreted as having formed within a thrust-sense shear zone. In domain 2, the moderately raking L_2 and the evidence for flattening strain and triclinic strain symmetry are consistent with the predictions of models of transpression in which the shear zone is inclined rather than vertical (Sanderson and Marchini 1984, Jones et al. 2004). S_2 is interpreted as having formed within a shear zone characterized by left-lateral and thrust components of motion.

A straightforward interpretation of these observations and inferences is that the bulk shortening direction was similarly oriented for both domains 1 and 2 during S_2 formation and the orientation of the shear zone differed. The two-dimensional character of the deformation in domain 1 indicates that the strike of the shear zone is north-northeast, i.e., parallel to the strike of S_2. In domain 2, the strike of the shear zone is more difficult to determine. For a bulk shortening direction parallel to the trend of L_2 in domain 1, a shear zone striking northwest will behave as an oblique ramp and have components of left-lateral and thrust motion. A northwest-striking oblique ramp is consistent with the geologic history of the region. Rankin (1976) and

Thomas (1977, 2006) have shown how the overall architecture of the Appalachians was influenced by the Neoproterozoic rift system that developed during the initial stages of opening of the Iapetus Ocean. Northwest-striking transfer zones are an important element of the rift system.

Paleogeographic reconstructions place the Neoproterozoic rift system outboard of the Mesoproterozoic basement massifs in the Appalachians. Although the Taconic allochthon lies to the west of the Mesoproterozoic Green Mountain and Berkshire massifs, the strata composing the allochthon were deposited on the slope and rise of the Iapetus Ocean to the east of the massifs and transported across the massifs during the Taconic orogeny (Stanley and Ratcliffe 1985, Bradley 1989). Basement heterogeneities can cause stress concentrations that affect the deformation of the overlying strata (Schedl and Wiltschko 1987, Wissing et al. 2003). Thus, reactivation of an Iapetan transfer zone as an oblique ramp during emplacement of the Taconic allochthon is a reasonable working hypothesis to explain the characteristics of domain 2.

REFERENCES CITED

Bradley, D.C., 1989, Taconic plate kinematics as revealed by foredeep stratigraphy, Appalachian orogen: Tectonics, v. 8, p. 1037-1049.

Chan, Y.C., 1998, Kinematic and geochronologic constraints on the structural development of the northern Taconic allochthon in western New England, U.S.A. [Ph.D. thesis]: Storrs, University of Connecticut, 117 p.

Dale, T.N., 1899, The slate belt of eastern New York and western Vermont: U.S. Geological Survey, 19th Annual Report, pt. 3, p. 153-300.

Fisher, D.W., 1985, Bedrock geology of the Glens Falls-Whitehall region, New York: New York State Museum, Map and Chart Series No. 35, scale 1:48,000, 1 sheet.

Goldstein, A., Knight, J., and Kimball, K., 1998, Deformed graptolites, finite strain, and volume loss during cleavage formation in rocks of the Taconic slate belt, New York and Vermont, U.S.A.: Journal of Structural Geology, v. 20, p. 1769-1782.

Jones, R.R., Holdsworth, R.E., Clegg, P., McCaffrey, K., and Tavarnelli, E., 2004, Inclined transpression: Journal of Structural Geology, v. 26, p. 1531-1548.

Karabinos, P., Samson, S.D., Hepburn, J.C., and Stoll, H.M., 1998, Taconian orogeny in the New England Appalachians: Collision between Laurentia and the Shelburne Falls arc: Geology, v. 26, p. 215-218.

Rankin, D.W., 1976, Appalachian salients and recesses: Late Precambrian continental breakup and the opening of the Iapetus Ocean: Journal of Geophysical Research, v. 81, p. 5605-5619.

Rowley, D.B., and Kidd, W.S.F., 1981, Stratigraphic relationships and detrital composition of the medial Ordovician flysch of western New England: Implications for the tectonic evolution of the Taconic orogeny: Journal of Geology, v. 89, p. 199-218.

Rowley, D.B., Kidd, W.S.F., and Delano, L.L., 1979, Detailed stratigraphic and structural features of the Giddings Brook slice of the Taconic allochthon in the Granville area, *in* Friedman, G.M., ed., Field Trip Guide for the 51st Annual Meeting of the New York State Geological Association and 71st Annual Meeting of the New England Intercollegiate Geological Conference: Rensselaer Polytechnic Institute, Troy, New York, p. 186-242.

Sanderson, D.J., and Marchini, W.R.D., 1984, Transpression: Journal of Structural Geology, v. 6, p. 449-458.

Schedl, A., and Wiltschko, D.V., 1987, Possible effects of pre-existing basement topography on thrust fault ramping: Journal of Structural Geology, v. 9, p. 1029-1037.

Stanley, R.S., and Ratcliffe, N.M., 1985, Tectonic synthesis of the Taconian orogeny in western New England: Geological Society of America Bulletin, v. 96, p. 1227-1250.

Thomas, W.A., 1977, Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: American Journal of Science, v. 277, p. 1233-1278.

Thomas, W.A., 2006, Tectonic inheritance at a continental margin: GSA Today, v. 16, p. 4-11.

Underwood, H.R., 2006, Analysis and interpretation of structural measurements and kinematic data for a section of the Giddings Brook thrust sheet of the Taconic allochthon near Middle Granville, New York [M.S. thesis]: Storrs, University of Connecticut, 69 p.

Wissing, S.B., Ellis, S., and Pfiffner, O.A., 2003, Numerical models of Alpine-type cover nappes: Tectonophysics, v. 367, p. 145-172.

Zen, E-an, 1961, Stratigraphy and structure at the north end of the Taconic Range in west-central Vermont: Geological Society of America Bulletin, v. 72, p. 293-338.

ROAD LOG

Miles from last point	Total miles	
0.0	0.0	Meet in the parking lot of the Shaw's supermarket in Fair Haven, Vermont. The supermarket is on the west side of VT 22A 0.25 miles south of US 4. If traveling to Fair Haven along US 4, take Exit 2 and go south along VT 22A to find the supermarket. Be aware that a Shaw's supermarket search using Google Maps and MapQuest may result in directions to a location north of US 4. Leave parking lot and proceed south on VT 22A.
0.1	0.1	Turn left onto Fourth St.
0.6	0.7	Turn left onto Dutton Ave. Dutton Ave. may be labeled Dutch Ave. on Google Maps and MapQuest maps.
0.3	1.0	Cross over US 4.
0.2	1.2	Continue straight on Scotch Hill Rd.
3.9	5.1	At Y in road, stay to the right.
0.2	5.3	Turn left onto Cedar Mountain Rd. at entrance to Bomoseen State Park. Cedar Mountain Rd. is a one-lane, dead-end, gravel road.
1.3	6.6	STOP 1 Park at entrance to abandoned quarry. Do not block driveway to house. Walk north along the path into the quarry. A path leads off to the right from the main path into the quarry. Continue along the main path and climb up slate pile on the east side to view quarry walls.

This is a well-known exposure of the Cedar Mountain syncline. The strata belong to the Cambrian Mettawee (Middle Granville) Slate Formation. The main cleavage in the strata is the slaty cleavage (S_2), which is axial planar to the fold. The west wall of the quarry exposes both a profile view of the fold and a folded S_0 plane with a well-expressed S_0-S_2 intersection lineation parallel to the fold axis. A crenulation cleavage (S_3) is also present and is readily observed in blocks in the pile of waste slate.

The quarry lies in the transition region between Taconic rocks to the west, in which S_2 is the dominant cleavage and S_3 is either absent or only weakly developed, and Taconic rocks to the east, in which S_3 is the dominant cleavage. Because S_3 pervades the strata in the quarry, the exposure is not mapped as part of domain 1. Structural orientations, however, are consistent with this domain. Both the north-northeast trend of the fold axis and the shallow, approximately 25E dip of S_2 are characteristic of domain 1.

In addition to the fold and cleavages, reduction spots are a highlight of the exposure. The green spots can be ellipsoidal or irregular in shape. Reduction bands subparallel to S_0 are also present.

		Turn around and retrace route along Cedar Mountain Rd.
1.2	7.8	Turn right at stop sign.
0.1	7.9	At Y in road, stay to the left.
0.1	8.0	STOP 2 Park temporarily in grassy area along side of road. Obtain permission from homeowner to park in the parking area of one of the houses. The outcrop is the large cliff face just to the east of Glen Lake.

This exposure of the Scotch Hill syncline is a frequent stop on field trips to the northern Taconic allochthon. Please do not hammer on the outcrop face and be on guard for poison ivy.

The folded strata belong to the Ordovician Poultney Formation. The exposure is mapped as part of domain 1 on the basis of the orientations of the fold axis and S_2. Detailed information on the S_2-related strain is not available because strain fringes have not been sampled. The north-northeast trend of the fold axis is shown by the S_0-S_2 intersection lineation, which is best observed on west-facing, vertical S_0 surfaces on the short limb of the fold. The mean orientation of S_2 is 025, 25E.

Two sets of veins can be observed on the outcrop face. Veins in one set intersect S_0 at an angle to the S_0-S_2 intersection lineation, and veins in the other set intersect S_0 parallel to the S_0-S_2 intersection lineation. Cross-cutting relations are visible on both limbs of the fold and show that veins in the latter set are younger. These veins, which are coaxial with the fold, are interpreted to have formed in response to flexural folding. On the short limb of the fold, they display Z shapes. The vein asymmetry is not as clear on the long limb of the fold, but there is a very wide vein that displays an S shape. To observe this vein, go around the small shed and climb to the base of the exposure behind the shed. The top half of the vein is visible in the main outcrop face, and the bottom half is visible in the continuation of the exposure in front of the main outcrop face. Despite being pre-folding, veins in the older set lie in nearly the same orientation on the long and short limbs of the fold. This is interpreted to be a result of rigid rotation of S_0 combined with shearing within layering in opposite senses on the two limbs during flexural folding.

		Continue south along West Castleton Rd./Scotch Hill Rd.
3.9	11.9	STOP 3
		Park along side of road.
		There is an outcrop on the west side of the road. More illustrative outcrops are present to the east along either side of the Exit 3 off ramp from US 4.

These exposures of the Cambrian Browns Pond Formation lie on the long limb of the Scotch Hill syncline. Data obtained from strain fringes have been used in combination with the orientation of outcrop-scale structural elements to place the exposures in domain 1.

Features observable in the exposures include calcite veins, which form two main sets. The veins that strike approximately north-south are more easily observed in the outcrops along the exit ramp, and the veins that strike approximately east-west are more easily observed in the outcrop along the road. Veins in both sets are deformed and are inferred to predate S_2 formation. The thickness and orientation of the veins in the north-south striking set differ depending on whether the vein lies in limestone or slate. In relatively coherent beds of limestone, the veins are thick and about perpendicular to S_0. In slate, the veins are thin and lie at a low angle to S_2 as a result of rotation during S_2 formation. Boudinage is visible in many of the veins in the slate layers. In contrast, veins in the east-west striking set are folded.

		Continue south along Scotch Hill Rd./Dutton Ave./Main St.
1.0	12.9	LUNCH STOP
		Park in parking space adjacent to the town green of Fair Haven, Vermont.
		Continue south along Main St.
0.3	13.2	Continue straight onto VT 22A over railroad tracks. Do not turn right onto VT 4A.
1.6	14.8	Cross into New York State.
3.1	17.9	Turn right onto CR 18.
2.1	20.0	Turn left onto Hills Pond Rd. Hills Pond Rd. is a one-lane, gravel road.
1.0	21.0	Hills Pond Rd. becomes paved.
1.5	22.5	Turn right onto South Rd.
0.1	22.6	STOP 4
		Park along side of road.
		The outcrop is on the north side of the road directly opposite a driveway.

This is a small exposure of the Cambrian Mettawee (Middle Granville) Slate Formation within domain 2. The outcrop lies on the long limb of a north-northwest-trending anticline. The Cambrian Browns Pond

Formation is exposed to the north of the road and yields strain fringes that are curved in S_2-parallel thin sections. This is one of three locations in domain 2 where evidence for triclinic strain symmetry has been found. The strain fringes also record flattening strain.

This stop is in the heart of domain 2, and the overall north-northwest-trending structural grain of domain 2 can be easily seen on Google Earth images of the area directly north of this stop. Although the images have not been analyzed in detail, the prominent lineaments are probably the Browns Pond Formation and sandstone layers in the Hatch Hill Formation.

		Continue west along South Rd.
0.3	22.9	Turn left onto CR 21.
2.3	25.2	Turn left onto NY 22A.
0.1	25.3	Cross over Mettawee River.
0.6	25.9	Veer right onto Raceville Rd.
0.1	26.0	Turn left onto Butler Rd. Butler Rd. is not marked.
0.1	26.1	Turn right onto Cross Rd. Cross Rd. is a gravel road.
0.9	27.0	Turn right onto New Boston Rd.
0.6	27.6	Continue straight onto Stoddard Rd.
1.0	28.6	STOP 5
		Park along side of road.
		One outcrop is on the east side of the road opposite the drained beaver pond, and the other is on the island in the drained beaver pond. The latter outcrop can be accessed using an ATV track at the south end of the pond.

Exposures along this road lie in the core of a syncline in domain 2 and provide excellent examples of deformed graptolites. The short limb of the fold is exposed in the outcrop along the road, and the core is exposed on the island in the drained beaver pond. The graptolite-bearing strata belong to the Ordovician Mount Merino Formation. The graptolites appear as white “films” on S_0 surfaces because during S_2 formation strain fringes developed adjacent to the periderm, which also fractured and infilled with fibrous material. At high magnification, chocolate-tablet structure can be seen in the periderm of graptolites from the exposure along the road. This contradicts evidence for prolate strain from measurements of the thecal spacing of the graptolites (Goldstein et al. 1998). The thecal spacing, which indicates large volume loss, is inferred to record the total strain undergone by the strata since deposition. Estimates of volume change using markers that record only the strain related to S_2 formation support approximately constant-volume deformation.

		Continue south along Stoddard Rd.
0.5	29.1	Turn right at T intersection onto Fox Rd./Depot St. Fox Rd. is not marked.
0.8	29.9	Turn right onto Main St. Main St. is CR 24.
0.1	30.0	Turn right onto NY 22A.
1.2	31.2	STOP 6
		Park in small parking area on the east side of NY 22A.
		The outcrop is directly opposite the parking area.

This road cut exposes the Ordovician Poultney Formation. The outcrop lies on the long limb of a north-northwest-trending anticline in domain 2, and the strain fringes indicate triclinic strain symmetry and flattening strain.

The outcrop provides good examples of clastic dikes and sills (?), which formed before lithification, and brittle faults, which formed after S_2 formation. The clastic dikes lie at a high angle to S_0 and S_2 and are folded. Some of the sandstone layers may be clastic sills. The distance between two relatively thick sandstone layers, for example, changes, indicating that they are not parallel to S_0. In addition, some sandstone layers do not show evidence for internal layering. The brittle faults are generally steeply dipping, and the direction and sense of slip along the faults are well shown by slickenfibers and steps. Normal and strike-slip motions are observed. Post-S_2 faults with similar kinematics have been mapped in other exposures in domain 2.