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Rotated Garnets and Tectonism in Southeast Vermont

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Trip 7

ROTATED GARNETS AND TECTONISM IN SOUTHEAST VERMONT

by

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Conventional structural and stratigraphic data (fig. 1--based primarily on Doll et al., 1961) and their topological implications suggest that during the late Paleozoic two large, recumbent, isoclinal, sigmoid folds in Paleozoic, metamorphosed, stratified rocks of southeast Vermont (Table 1) predated the mantled gneiss domes with which they are associated. One of these folds involved units stratigraphically and structurally beneath the Siluro-Devonian calcareous and non-calcareous schists of the Waits River formation. The other, involving Siluro-Devonian units structurally above but of otherwise undemonstrated stratigraphic relationship to the same unit, is exposed in culminations associated with seven domes. The approximate axial parallelism of these folds and the opposite rotations of their short limbs suggest that these folds resulted from westward extrusion of rocks in between.

Using methods described elsewhere (Rosenfeld, 1970), regional study of spirally arranged inclusions in garnets and rotations determined therefrom confirms the early presence within the Waits River formation of a surface, quasi-parallel to the bounding strata now exposed to the east and west, across which the rotational senses possessed mirror symmetry (Rosenfeld, 1968). After graphical correction for effects resulting from rise of the gneiss domes, the rotational axes of the garnets parallel those of the giant recumbent folds; and the rotational senses of the garnets are those to be expected from flexure slip folds having the observed rotations of their short limbs (fig. 2; Rosenfeld, 1968, p. 193).

In further accord with the westward extrusion are:

(1) pebbles and former phenocrysts in the eastern part of the area extremely elongated in the direction of extrusion; also a prominent mineral lineation in the same direction (observable on Putney Mountain-Windmill Mountain Ridge; Rosenfeld, 1968, p. 197-199);

(2) boudinage in the eastern part of the area with fractures quasi-parallel to the corrected rotational axes of the garnets; these give way to the west to compressional folding of the same orientation (observable in central Vermont just east of the Green Mountains);

(3) an angular divergence in a westerly direction of about 10 degrees between the Standing Pond formation on one side of the Waits

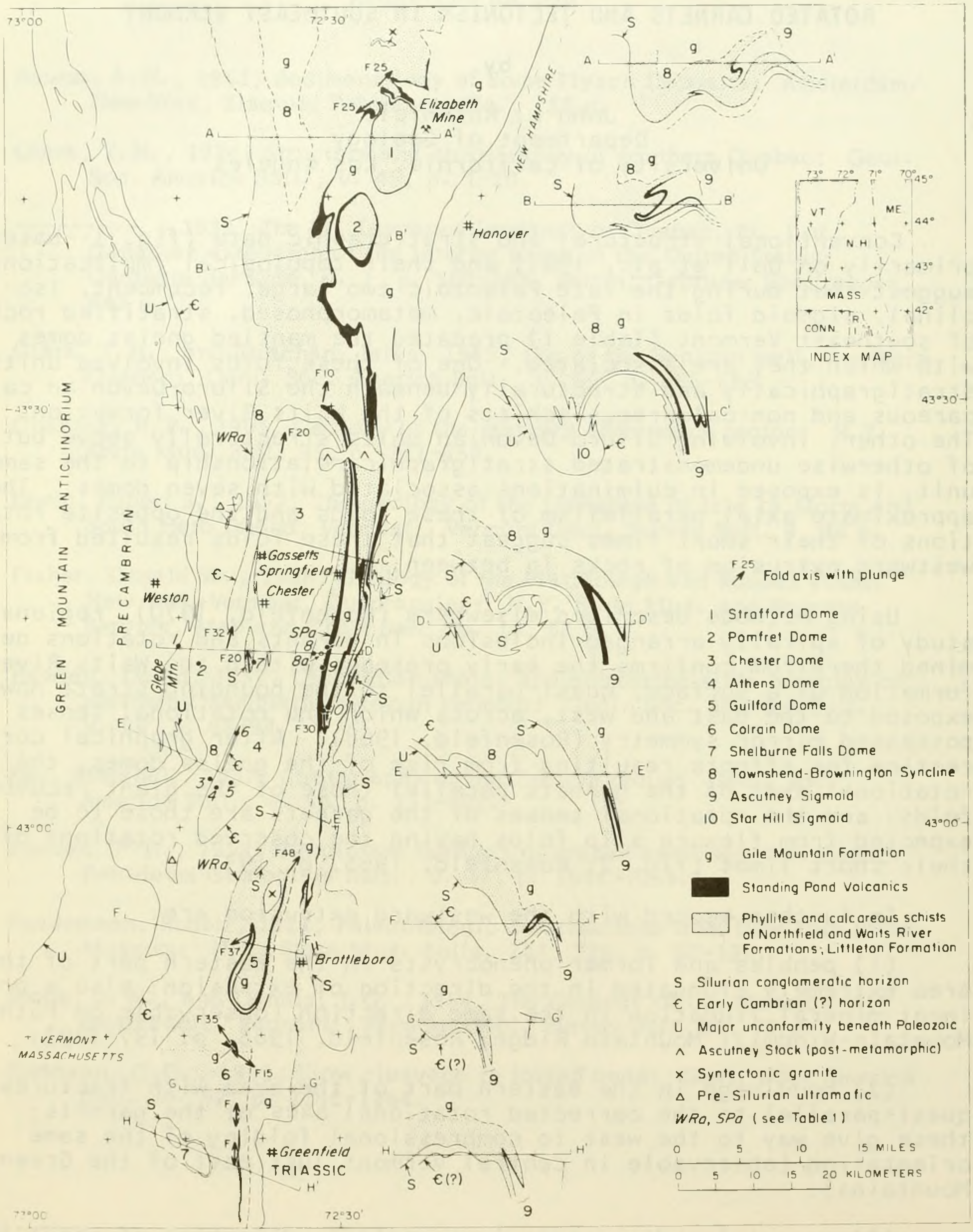

Fig. 1 - Field trip stops italicized

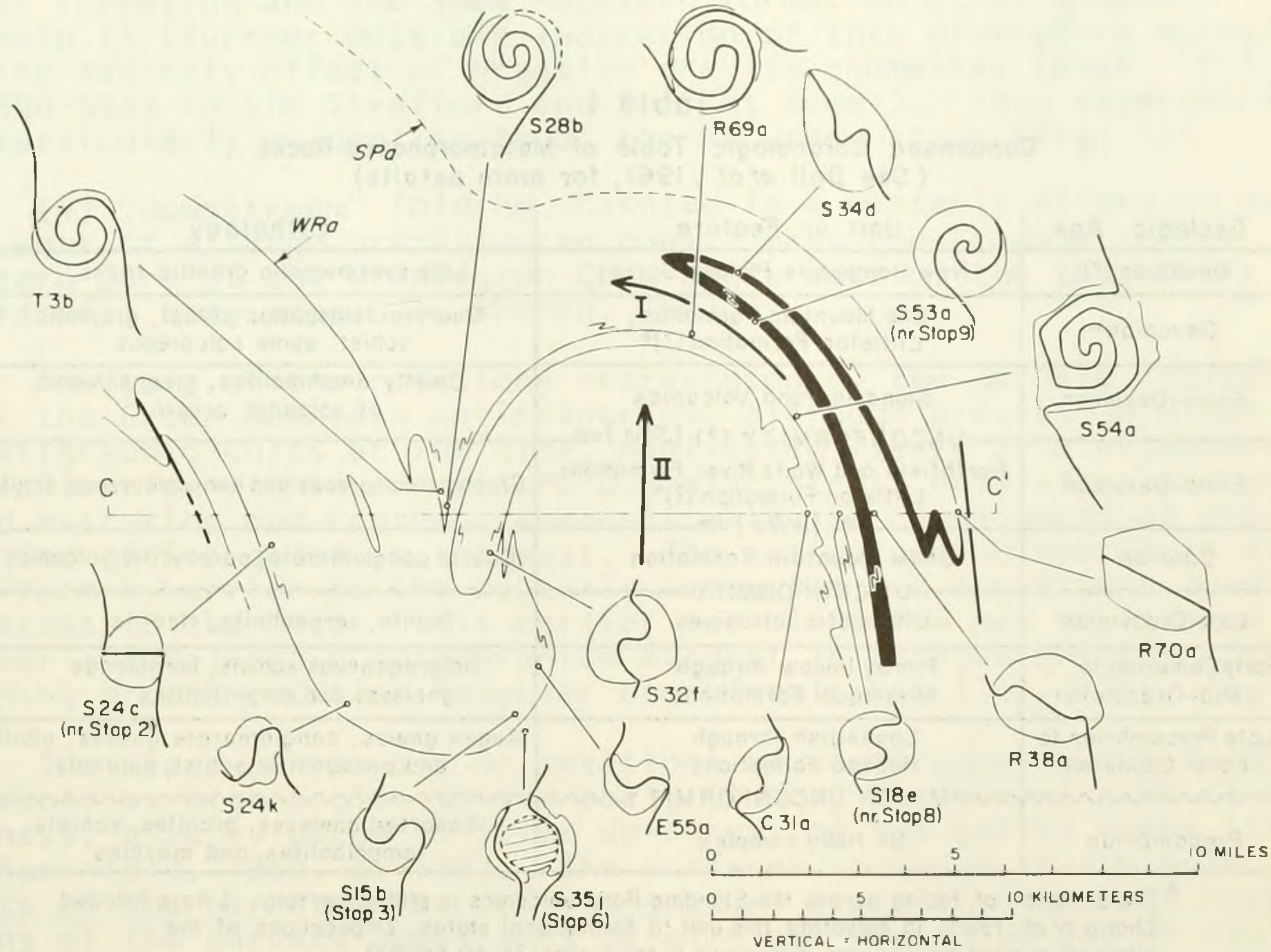
S28b
R69a
SPa
S34d
WRa
T3b
I
S53a
(nr Stop9)
S54a
II
C
C'
S24c
(nr Stop 2)
S32f
R70a
R38a
S24k
S18e
(nr Stop8)
C31a
E55a
S15b
(Stop 3)
S35
(Stop 6)
0
5
10 MILES
0
5
10 KILOMETERS
VERTICAL = HORIZONTAL

Fig. 2

Table 1

Condensed Chronologic Table of Metamorphosed Rocks
(See Doll *et al.* , 1961, for more details)

Geologic Age	Unit or Feature	Lithology
Devonian (?)	New Hampshire Plutonic Series	Late synkinematic granitic rocks
Devonian*	Gile Mountain Formation, Littleton Formation (?)*	Quartzo-feldspathic schist, graphitic schist, some calcareous
Siluro-Devonian	Standing Pond Volcanics	Chiefly amphibolites, greenschists of volcanic origin
	UNCONFORMITY (?) (*SPa*)	
Siluro-Devonian	Northfield and Waits River Formations, Littleton Formation (?)* (*WRa*)	Graphitic calcareous and non-calcareous schist
Silurian	Shaw Mountain Formation	Quartz conglomerate, porphyritic volcanics
	UNCONFORMITY	
Late Ordovician	Ultramafic intrusives	Dunite, serpentinite, steatite
Early Cambrian to Mid-Ordovician	Pinney Hollow through Missisquoi Formations	Heterogeneous schists, hornblende gneisses and amphibolites
Late Precambrian to Early Cambrian	Cavendish through Hoosac Formations	Augen gneiss, conglomerate gneiss, albitic and paragonitic schist, dolomite
	MAJOR UNCONFORMITY	
Precambrian	Mt Holly complex	Assorted gneisses, granites, schists, amphibolites, and marbles

* The direction of facing across the Standing Pond Volcanics is still uncertain. I have followed Chang *et al.*, 1965, in elevating this unit to formational status. Implications of the alternative possibilities are discussed in their paper (p. 40, 56-62).

River formation and the Shaw Mountain formation stratigraphically beneath it (further possible indication of this divergence appears in the easterly offset of negative gravity anomalies (Bean, 1953, p. 528-533) in the Strafford and Pomfret domes). This divergence is particularly evident south of the Ascutney stock (fig. 1);

(4) "downstream" folding oriented in a westerly direction to the west of a large pre-Silurian dunite mass (observable in the eastern part of the Wilmington Quadrangle west of the East Dover ultramafic body mapped by Skehan, 1961).

Analysis of the rotations represented by the garnets indicates that the Green Mountain anticlinorium, although present in older stratigraphic units at the time, manifested itself as a rejuvenated anticlinorium within the Siluro-Devonian strata only after the westward extrusion and contemporaneously with the development of the mantled gneiss domes to the east. The anticlinorium therefore did not form a barrier to the westerly extrusion and consequent loading of areas to the west. This earlier anticlinorium may be related to an earlier Paleozoic metamorphism evident in rotated garnets containing growth-rotation "angular unconformities" (loc. S35j, fig. 2).

The shear senses and orientations of conspicuous minor folds, commonly at high angles to the early (inner) rotational axes of the garnets, give evidence of later up-thrust of the gneiss domes (fig. 2; Rosenfeld, 1968, p. 193). The surfaces included in the outer parts of the garnets also reflect gradual transition to late rotations of the garnets about axes parallel to the folds and of similar rotational senses. The high angle between the early and late rotational axes of the garnets, both of which must have paralleled the schistosity at their respective times of growth, permits apportionment of the rotation. On the east limb of the Chester Dome, garnets at one locality show 625° rotation for the early stage of deformation and 105° for the late stage.

Interpretation of the proximate mechanism of diastrophism for the early and major diastrophic event depends primarily upon knowledge of the as yet unknown age relationship of the units bounding the Waits River formation on the east. If these units should prove older than the Waits River formation, the indicated westward transport of material may be ascribed to flexure-slip folding of the westward-opening lower half of a giant, initially recumbent, sigmoid fold whose upper half is nowhere exposed in eastern Vermont. If the same units should prove younger than the Waits River formation, the transport may be ascribed to westward intrastratal extrusion of the relatively dense Waits River formation, possibly down a gently inclined slope tilted toward the west. It is thus of great importance to resolve this ambiguity by development of procedures for resolving the above stratigraphic uncertainty.

Road Log for Trip 7

Road log begins on Route 11, just west of the summit of the pass over the east range of the Green Mountains, 0.5 miles southwest of North Windham, Vermont, about 200 feet west of the west boundary of the Saxtons River Quadrangle. <u>This excursion is basically a "no hammer" trip</u>, although collecting at Stop 3 is all right. I'd like to enlist the assistance of all participants in helping to preserve the highly visible minor structural features so that future geologists will be able to see them in their field context. May these features avoid the "tragedy of the commons!" Names of units and major structural features referred to below are largely from Doll *et al*., 1961, and Rosenfeld, 1968. A perusal of these references before undertaking this excursion will be helpful.

<u>Mileage</u>

0.0 <u>STOP 1. Angular unconformity between the overlying prograde metamorphosed conglomerates of the Tyson formation and the underlying retrograde metamorphic rocks and pegmatites of the Precambrian Mount Holly complex</u>. This unconformity is significant for this trip because it demonstrates the direction of stratigraphic "tops." Proceed easterly on Route 11 through the Hoosac formation.

0.6 North Windham. Turn right onto Rt. 121.

0.8 Northernmost exposures of Turkey Mountain member (amphibolite) of Hoosac formation outcrop in draw to west. Continue through schists of Pinney Hollow formation.

2.2 Near crest are exposures of Chester amphibolite member of Pinney Hollow formation. Strong down-dip lineation of pale green amphiboles. Continue through Ottauquechee and Stowe formations.

2.6 <u>STOP 2. First rotated garnet locality in outcrop at northwest corner of intersection</u>. Garnets in schist of Stowe formation show small counterclockwise rotation after growth about nearly horizontal axes when viewed in a northerly direction (<u>the direction of view used subsequently unless otherwise stated</u>). Proceed southerly from Rt. 121 on Windham Road past outcrops of Stowe formation and rusty shales of the Whetstone Hill member of the Missisquoi formation.

4.0 Windham Center. From here almost to South Windham, the road lies within the banded rusty-weathering graphitic schists of the Ottauquechee formation. Rise in metamorphic grade is most evident in the field in the transition from pale green amphibolites to dark green to black amphibolites. Near Windham Center we cross the oligoclase isograd, northwest of which plagioclase more calcic than nearly pure albite is not found, regardless of bulk composition of the rock. This isograd is related to a miscibility gap within the plagioclase feldspar series.

7.6 South Windham. Chester amphibolite.

8.0 Jamaica-Townshend town line. Enter the typical green garnet-magnetite-chlorite-sericite schist comprising the main part of the Pinney Hollow formation and through which the road passes for the next 2.0 miles.

10.0 Turkey Mountain member appears on ridge to west. From here to West Townshend we pass from the Pinney Hollow formation into the characteristic albite schists of the Hoosac formation.

10.7 West Townshend, ancestral home of the Tafts of Ohio. Turn left onto Rt. 30 and proceed southerly through a tectonically compressed section from Hoosac to the base of the Missisquoi formation.

11.1 Base of Missisquoi formation. Continue in typical "pinstripe" quartzofeldspathic schists of Moretown member of Missisquoi formation.

11.6 Roadcuts on west side of highway show eastward dipping beds of "pinstripe" in Moretown with a prominent boudinage fracture of horizontal orientation. Continue in highly contorted schists and amphibolites of the Moretown across the axis of the Townshend-Brownington syncline onto the west limb of the Athens (pronounced Aythens) dome.

12.8 Thin amphibolites in smooth outcrops of Moretown on the left exhibit boudinage.

13.1 Park cars in parking area on right at Townshend Flood Control Dam. STOP 3 is in the roadcut on the northeast side of the highway opposite the dam. Rotated garnets showing counterclockwise rotation on the west limb of the Athens dome. Note the relative consistency of the shear sense indicated by the rotated garnets in contrast to that of the drag folds. The origin of this contrast has been discussed elsewhere (Rosenfeld, 1970, p. 92). Garnets observed here are believed to have grown and rotated before development of the Athens dome during the lateral extrusion toward the west. The relict "oligoclase isograd" may be observed in the form of coexistent albite, oligoclase, and clinozoisite encapsulated in garnets at this locality (Rosenfeld, 1970, p. 90-91), even though the staurolite isograd is only a few tens of feet to the east. Note the large boudinage fractures in amphibolites here. Proceed southeasterly on Rt. 30 through a compressed but apparently complete section from the Moretown to the Hoosac formation.

13.5 Scott Covered Bridge on right. Amphibolite in what is believed to be Hoosac formation on left. If these rocks correlate with the main band of the Hoosac to the west, they are of a distinctly more banded and gneissic facies. Just beyond the bridge on the left are some very nice secondary drag folds on a large fold, incompletely exposed in the outcrop.

13.8 STOP 4. Conglomerate gneiss of Tyson formation (?) on west in contact with Bull Hill gneiss member of Cavendish formation. The Bull Hill gneiss characteristically has coarse microcline augen and is of granitic composition. However, it is also a rather widespread stratigraphic unit on the

Chester and Athens domes. It is therefore possible that the Bull Hill gneiss represents a metamorphosed stack of rhyolitic volcanics. In the southern part of the Athens dome, it has not been possible to delineate accurately the boundary between the Bull Hill gneiss and what are believed to be older but lithologically similar Precambrian granitic augen and flaser gneisses in the core of the dome. Note counterclockwise drag folds in gneiss, believed to be a result of upthrusting of the gneissic core of the dome. Proceed easterly on Rt. 30 through broad zone of granitic gneisses to

15.0 Townshend. Turn left off Rt. 30 onto Rt. 35 and proceed northerly.

15.4 STOP 5. Outcrops lie across the field to the west and consist of magnetite-bearing granite flaser gneiss, believed to have been the relatively low-density "plunger" accounting for the buoyant upward thrust of the Athens dome. Continue north on Rt. 35 through heterogeneous gneisses, some rusty weathering and containing coarse graphite flakes rather like the Washington gneiss described by Emerson in the Berkshires.

16.9 Simpsonville.

18.4 Easy to miss intersection. Bear left off Rt. 35 onto Grafton Road.

18.6 For the next 0.2 miles, passing through a band of calc-silicate rocks, characterized by coarse graphite flakes and pyrrhotite, that strikes northeasterly through the core gneisses of the Athens dome at a large angle to the mantling strata. This discordance provides, perhaps, the best evidence to date that the core gneisses of the Athens dome lie unconformably beneath the mantling strata.

18.8 Continue through banded, contorted, biotite gneisses of the core of the Athens dome.

19.6 Top of grade. Bull Hill gneiss on dip slopes along east side of South Branch of Saxtons River to north. Valley probably owes its alignment to an easily eroded dolomite (observable at a number of localities on Rt. 35 north of Grafton) that separates albite schist of the Hoosac formation on the west from the Bull Hill gneiss.

20.3 Easy to miss turn. Turn sharply left onto single lane, steep dirt road (Acton Hill Road). Proceed through Hoosac formation.

20.6 Cross brook.

20.9 East contact of garnet-kyanite- staurolite-paragonite schist of Pinney Hollow formation in core of anticlinal portion of Ober Hill fold. Pass across Ober Hill fold.

21.6 Intersection. Let lead car turn around before entering intersection. Then, one by one, each car should turn left, then back up sufficiently far to make room for following cars to do same. Continue back down the Acton Hill Road, following lead car.

21.8 Park your car as far off the road to the right as possible. STOP 6, exhibiting garnets with angular growth unconformities, is on the ledges visible to the southwest of the road (Rosenfeld, 1968, p. 196). The rock is a garnet-staurolite-paragonite-muscovite schist. Chloritoid and staurolite exist as an armored relict assemblage in the garnet. There is no chloritoid outside the garnet. The earlier garnet probably grew during the Taconic orogeny or possibly during an earlier orogeny. Proceed back toward Townshend-Grafton Road.

22.1 On the left are some remarkably fine counterclockwise drag folds, some of which have transcurrent "slip fractures" of similar shear sense about the same axis. These fractures provide evidence of the "lateness" of these folds.

22.9 Townshend-Grafton Road. Turn left and continue north.

27.7 Grafton, a picturesque village in which some of the finer examples of old Yankee architecture have been restored and preserved by the liberal application of dollars. Turn left onto Rt. 121, passing successively through a rather complete section of units from the Hoosac formation to the rusty-weathering, graphitic schists of the middle Ordovician Cram Hill member of the Missisquoi formation.

29.9 STOP 7. Westward dipping beds of conglomeratic quartzite and interbedded garnet-muscovite schist of Silurian Shaw Mountain formation. These beds lie on the east limb of a syncline (Spring Hill syncline) whose axial surface dips to the west. This syncline is believed to be the detached (by megaboudinage) westward-opening, lower part of the Star Hill sigmoid (Figure 1, Section D-D'). It contains in its core a section of dense amphibolites that is thicker than usual within the Shaw Mountain formation. This dense mass, in the "keel" of the formerly westward opening fold, is believed to have "hinged" downward clockwise during the doming stage. Thus, the exposure at this stop is believed to be a relict of the short limb of the Star Hill sigmoid. In support of this interpretation is the sequence of rotations found in garnets within a schistose parting of Shaw Mountain quartzite a mile to the north--early clockwise, late counterclockwise. "Unrotating" the late rotation at this exposure aligns the elongate pebbles in a west-southwest orientation, the direction of lateral extrusion. Some of the quartzite at this locality contains coexistent staurolite and chloritoid, a not rare assemblage in this unit. Turn around and return to

32.1 Grafton on Rt. 121, continuing through the village across the Saxtons River and turning left onto

32.2 Rt. 35, proceeding northerly along approximately the same stratigraphic horizon that was followed south of Grafton. Bull Hill gneiss to east.

33.9 Dolomite under albite schist of Hoosac formation on left. Leaving Athens dome; entering Chester dome.

36.4 Enter Grafton Gulf.
36.9 Leave Grafton, Windham County; enter Chester, Windsor County.
37.0 Note pillar of dolomite supporting albite schist on left, dip slope of Bull Hill augen gneiss on right.
37.5 Summit of Grafton Gulf.
38.3 Leave Saxtons River Quadrangle; enter Ludlow Quadrangle.
39.5 Chester. Turn right onto Rt. 103.
40.9 Return to Saxtons River Quadrangle.
42.3 Bull Hill gneiss on east limb of Chester dome.
42.5 Enter town of Rockingham, Windham County. Crossing Hoosac formation.
42.7 Crossing from Pinney Hollow through intermediate units into Missisquoi formation.
44.3 Easy to miss intersection. Turn sharp left off Rt. 103 onto dirt road with bridge over railroad tracks.
44.4 "Vermont Beautiful" on left!
44.5 Covered bridge.
44.8 Crossing Shaw Mountain formation--not exposed near road.
44.9 STOP 8. Ledges in woods north of road. Sieve texture garnets in calcareous schists of lower Waits River formation showing early counterclockwise rotation (Event I; conspicuous) followed by late clockwise rotation (Event II; observed with difficulty). Continue easterly.
45.7 Optional STOP 8a. Main zone of calcareous schists with subordinate phyllites within Waits River formation. One of the best exposures of the Waits River formation in southern Vermont. Big sprays of zoisite. Isoclinal folding. Easily observed rotated garnets. Mafic dike with calcite phenocrysts. Turn right across bridge and railroad tracks.
46.0 Turn left onto Rt. 103.
46.2 Turn right off Rt. 103 onto Pleasant Valley Road. Passing through heterogeneous rock types of Standing Pond formation, mostly mafic volcanics.
47.1 Turn right off the Pleasant Valley Road onto single lane dirt road.
47.2 Park cars and proceed northerly across field about 1,500 feet into woods just northwest of northwest corner of field to STOP 9 at contact between garnetiferous phyllite of Waits River formation on west and coarse garnetiferous schist of the Standing Pond formation containing sprays of hornblende (fasciculitic schist or "garbenschiefer"). Large garnets show a single large clockwise rotation associated with Event I, in contrast to those at Stop 8. A photograph of a rotated garnet from this locality appears as figure 14-6 in Rosenfeld, 1968 (p. 195). Evidence of Event II at this locality appears only as gently northward plunging crinkles. For further discussion of this locality, see Rosenfeld, 1970, p. 89. Return to Pleasant Valley Road by car.
47.3 Turn right onto Pleasant Valley Road.
48.7 Septum of Waits River-like calcareous schist and phyllite in Standing Pond formation.

48.8 Exposures of banded and massive amphibolites of Standing Pond formation near eastern contact with Gile Mountain formation. Clockwise drag folds. Road continues southerly along east side of Standing Pond formation.

51.0 Intersection with Rt. 121. Continue east on Rt. 121.

51.3 Village of Saxtons River. Park cars. STOP 10. The purpose of this stop is to observe southward plunging minor folds in the Standing Pond formation along the axis of the upward closing fold (anticline) of the Ascutney sigmoid. The axis at this horizon reappears to the south on the Guilford dome near the syntectonic Black Mountain granite in Dummerston (fig. 1). Folds with counter-rotating garnets on their limbs appear along the north side of the river, 0.3 miles to the west (Rosenfeld, 1970, p. 85-86). Turn westerly on Rt. 121.

51.6 Bear right off Rt. 121 onto Pleasant Valley Road.

56.2 Turn left off the Pleasant Valley Road onto Rt. 103.

56.3 Turn right off Rt. 103 toward Brockways Mills, continuing across bridge past Stop 8a and to the right on paved road toward Springfield.

57.5 Park. Proceed westerly across north end of field past small cottage to STOP 11 at contact between garnetiferous phyllite of Waits River formation and "garbenschiefer" with large garnets. This locality is, perhaps, the best locality for seeing evidence of both Events I and II within a single rotated garnet. A stereoscopic photograph of a rotated garnet from this locality appears as figure 14-3 in Rosenfeld, 1968, p. 192. A discussion of the generation of the central surface of garnets at this locality is found in Rosenfeld, 1970, p. 40. The trip ends at this locality.

To get to Burlington, about 120 miles away, return to Rt. 103, turn left, and get onto Interstate 91 North at Interchange 6. Turn left onto Interstate 89 at White River Junction. Interstate 89 will take you to Burlington.

References for Trip 7

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