Trip B-4

THE CHAMPLAIN THRUST AND RELATED FEATURES NEAR MIDDLEBURY, VERMONT

by

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This field trip will review preliminary results from investigations of the Champlain thrust, Middlebury synclinorium, and Green Mountain anticlinorium near the latitude of Middlebury by senior geology majors at Middlebury College. During the past seven years 20 senior theses have been completed; seven of these provide a nearly continuous geologic map of the Champlain thrust belt between Vergennes and Route 125 west of Middlebury at a scale of 500 feet to the inch. Other theses have included regional and local gravity studies, geologic mapping of critical localities in the Middlebury synclinorium and Green Mountain anticlinorium, petrologic studies of greenstone and ultramafic bodies east of the anticlinorium, sedimentological studies of lower Paleozoic rocks, and mapping and petrologic studies of Mesozoic igneous rocks. These efforts have built upon earlier studies in west-central Vermont by Cady (1945), Welby (1961), Osberg (1952), and the unfortunately unpublished work of Crosby (1963). Although the field trip will concentrate on the Champlain thrust west of Middlebury (Figure 1), the regional tectonic setting of the thrust is briefly discussed here as background for participants.

TECTONIC SETTING

At the latitude of Middlebury four distinct tectonic provinces are from west to east: the Adirondack massif, the Lake Champlain lowland, the Middlebury synclinorium bounded on its west side by the Champlain thrust belt, and the Green Mountain anticlinorium. The tectonic significance of the Champlain thrust must be sought in the nature of these provinces and their boundaries.

In the Lake Champlain lowland (Welby, 1961) a relatively undeformed 5,000 foot sequence of Upper Cambrian through Middle Ordovician clastic and mainly carbonate shelf assemblage rocks rest with profound unconformity on a crystalline Precambrian basement (Figure 2). The Precambrian is extensively exposed in the Adirondack massif. The boundary between the Adirondacks and the lowland is a complex of fault blocks, down-faulted to the east, and structural relief on the Precambrian basement is at least 5,000 feet.

To the east of the Champlain lowland an Eocambrian to Middle Ordovician clastic and mainly carbonate shelf assemblage nearly 10,000 feet thick presumably rests on Precambrian basement (Figure

ROUTE MAP FOR FIELD TRIP B·4

NEIGC, 1972

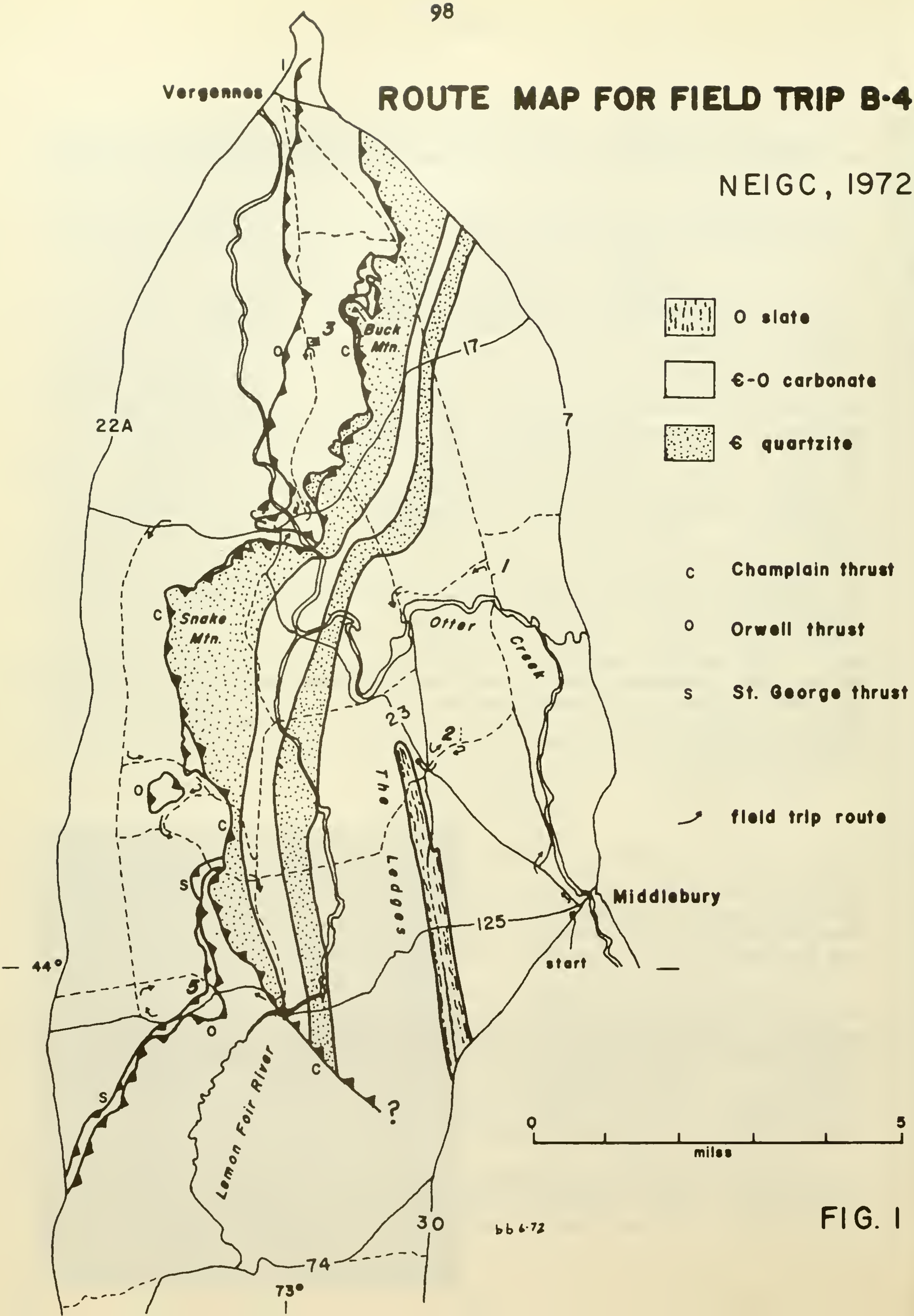

FIG. 1

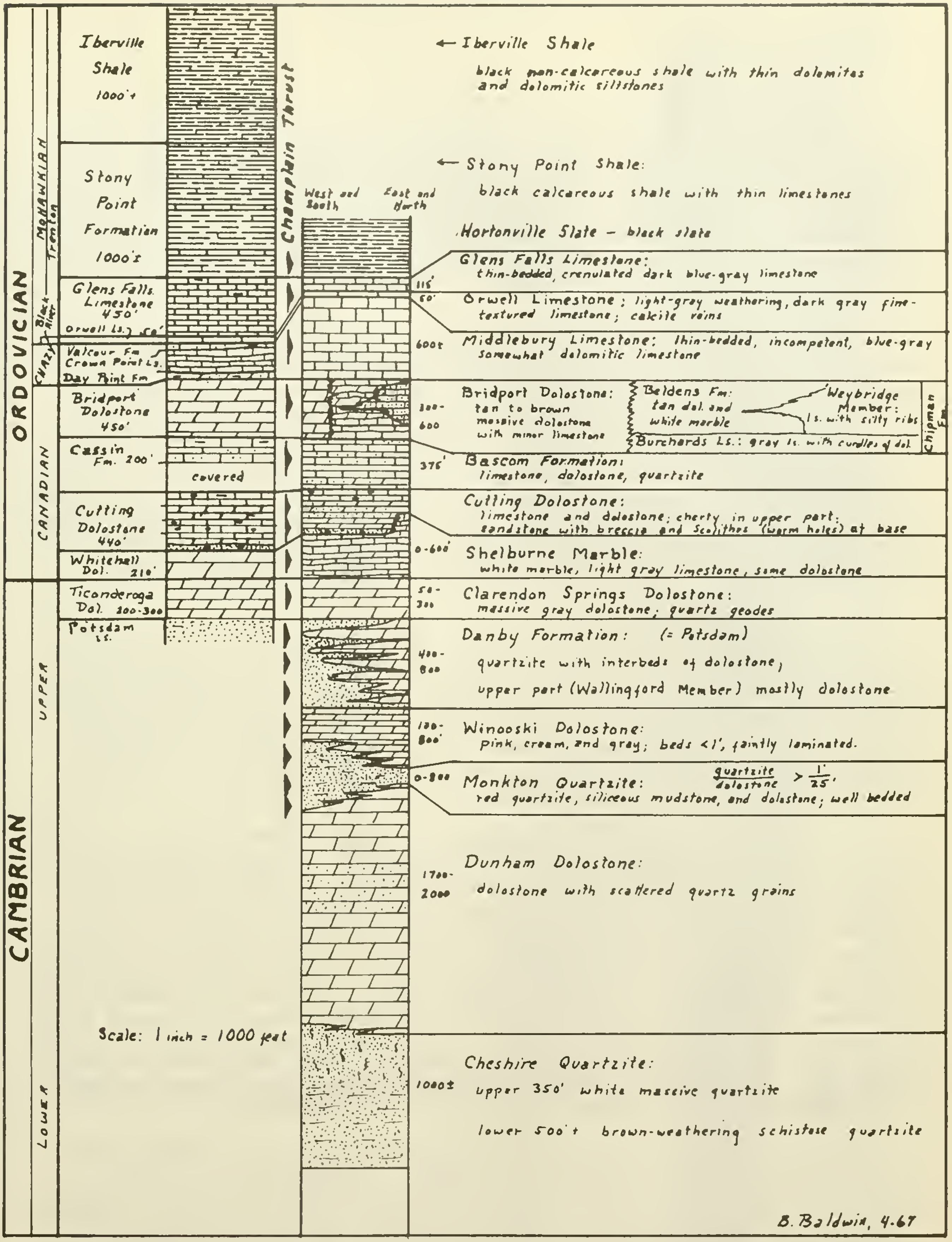

FIG. 2. Sequence of strata near Middlebury, Vt.

Compiled from Cady, 1945; Kay and Cady, 1947; Cady and Zen, 1960; Welby, 1961.

2). This sequence is rather intensely deformed into the south-plunging, westward inclined, Middlebury synclinorium (Cady, 1945). The two disparate early Paleozoic shelf assemblages of the Lake Champlain lowland and the Middlebury synclinorium (Figure 2) are separated by the Champlain thrust belt. The thrust belt is a series of east-dipping, low-angle faults which can be traced from at least southwestern Vermont and the adjacent New York northward into Canada (Cady, 1969).

The Green Mountain anticlinorium (Cady, 1945) rises sharply just east of the Middlebury synclinorium and is a west-vergent, doubly plunging, complex anticlinorium with an exposed core of Precambrian Mount Holly basement (Figure 3). Structural relief on the Precambrian unconformity between the floor of the Middlebury synclinorium and the crest of the anticlinorium is at least 3 miles, and probably as much as 6 miles, in an east-west distance of about 8 miles (Powell, 1969; Tennyson, 1970). The boundary between the synclinorium and the anticlinorium at the surface is locally marked by east-dipping thrusts, but is mainly a descending cascade of west-vergent folds (Osberg, 1952; Tennyson, 1970) termed the Green Mountain front.

The Green Mountain front is a major stratigraphic as well as tectonic boundary marking an abrupt facies change in Eocambrian to Ordovician rocks from the mainly carbonate miogeoclinal shelf assemblage on the west to "eugeoclinal" graywacke assemblage on the east. The Taconic "klippe", also of the eastern eugeoclinal facies, now lies athwart the Middlebury synclinorium on top of shelf rocks of the same age to the south of Middlebury, but has been removed by erosion northward.

With the exception, presumably, of the Chester dome, no bona fide "Yankee" Precambrian cratonic basement is known east of the Green Mountain anticlinorium. Significantly a belt of serpentinized dunites (Beyer, 1972) and meta-greenstones (Crocker, 1972; Doolan and others, in preparation) lie just east of the anticlinorium embedded in meta-graywackes of the early Paleozoic "eugeoclinal" assemblage. These rocks certainly mark a most significant tectonic boundary. It would appear, thus, the entire lower Paleozoic North American continental margin assemblage is exposed in a belt now less than 50 miles wide. Putting it another way, in the context of current plate tectonic theory, once one takes a single step east of the Green Mountain anticlinorium everything to the Bay of Maine is of suspect geo-political allegiance.

An unconformity of late Middle Ordovician age seen at one place or another in most of the region, including the Taconic "klippe", separates the apparently west-derived shelf and "eugeoclinal" assemblage from an apparently east-derived detrital-shale assemblage. The critical overlying rocks are the Hortonville Formation in the Middlebury synclinorium, the Pawlet Formation in the Taconic "klippe" (Zen, 1962), and the Moretown Formation east

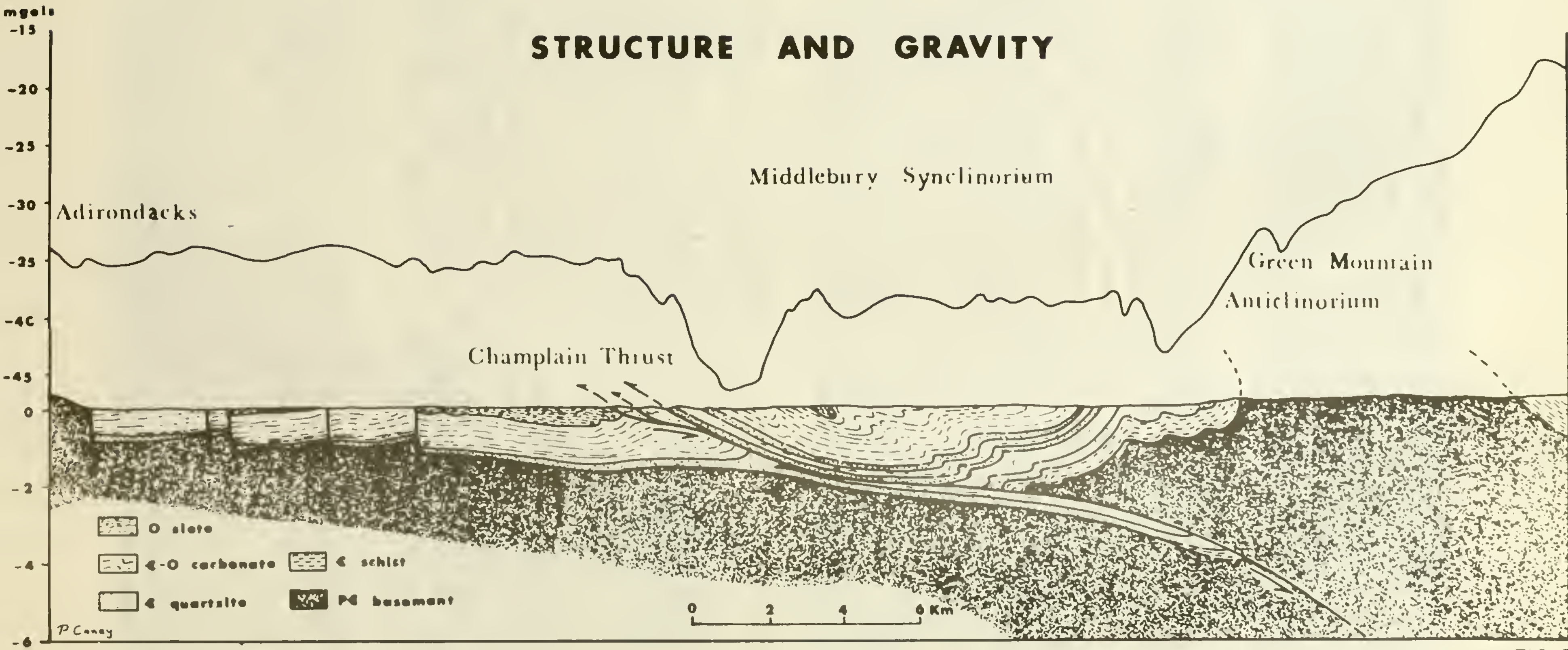
STRUCTURE AND GRAVITY
mgals
-15
-20
-25
-30
-35
-40
-45
0
-2
-4
-6
Km
Adirondacks
Middlebury Synclinorium
Green Mountain Anticlinorium
Champlain Thrust
O slate
Є-O carbonate
Є quartzite
Є schist
PЄ basement
0 2 4 6 Km
P Coney

FIG. 3

of the Green Mountain anticlinorium. Silurian-Devonian detrital rocks mask all prior tectonic relationships east of the Moretown Formation to the Ordovician Oliverian volcanic arc along the Vermont-New Hampshire border (Rodgers, 1970), the presumed source of the detrital-shale flood. Very preliminary studies by Sedgwick (1972) suggest the Moretown Formation has a distinctly different heavy mineral assemblage compared to all older west-derived shelf and "eugeoclinal" rocks sampled to date.

The Champlain and related thrusts and the folds in the Middlebury synclinorium involve rocks as young as late Middle Ordovician. The east side of the Green Mountain anticlinorium is often argued to involve Silurian-Devonian rocks as well (Cady, 1968). If all these major structures have any genetic relationship to one another, as is generally assumed, much deformation is as young as Acadian (Middle Devonian) at least. The emplacement of the Taconic "klippe" is well documented as Taconic (Middle Ordovician) and numerous ductile folds and minor structures beneath and adjacent to the "klippe" in synclinorium rocks are correlated with this emplacement (Crosby, 1963). All these "Taconic" structures, including the "klippe" (Crosby, 1963; Johnson, 1970) are redeformed by younger more "brittle" deformation thought to be Acadian (Crosby, 1963). The Middlebury region, then, has suffered at least two deformations. To what extent these phases were discrete events or a single continuum is yet to be resolved.

THE CHAMPLAIN AND RELATED THRUSTS

General Statement. The Champlain and related faults form a belt of east-dipping, low-angle thrusts which separate the Middlebury synclinorium on the east from the Lake Champlain lowland to the west. The belt of thrusts brings up resistant rocks, such as Cambrian Monkton Formation quartzite, which have produced a line of hills and ridges. Snake and Buck Mountains are the prominent ridges at the latitude of Middlebury. The system of faults forms a tightly packed series of slices exposed in a belt seldom more than 2 miles wide. The Champlain thrust is the most easterly of the faults while the other faults lie just west of, and structurally below, the Champlain thrust. For regional stratigraphic detail the reader is referred to Cady (1945) and Welby (1961), and to Figure 2.

Champlain Thrust. The Champlain thrust (Stop 3) enters the area at the north end of Buck Mountain and extends southward for at least 15 miles to Route 125 west of Middlebury. The fault can be easily traced northward into Canada, but its fate south of Route 125 is still in question (Stop 5). Cady (1945) and the Centennial Geologic Map of Vermont (Doll and others, 1961) terminate it in the very poorly exposed south-plunging anticline just west of Cornwall several miles south of Route 125. Over almost the entire trace west of Middlebury, Cambrian Monkton Formation is thrust over highly deformed Ordovician carbonate and shale.

The thrust plane lies within several hundred feet of the base of the Monkton Formation and only at the south end of Buck Mountain (Cady, 1945; Welby, 1961; Egan, 1968) does it bite lower into several tens of feet of Dunham Dolostone. The Monkton Formation on the upper plate generally dips gently eastward into the Middlebury synclinorium forming a prominent dip slope on the east sides of Buck and Snake Mountains. Near the fault trace, however, local imbrications and folds are evident in Monkton Formation layers. The fault plane is only rarely exposed, but at several points on Buck and Snake Mountains dips between 7 and 25 degrees eastward are seen.

The trace of the fault wanders in topography and has right en echelon offsets from the north end of Buck Mountain south to Snake Mountain. South of the summit of Snake Mountain it trends southward then angles southeasterly until lost beneath glacial cover south of Route 125. The en echelon offsets result in a series of salients and re-entrants. Structure contouring on the fault surface (Westervelt, 1967), gravity studies and geologic mapping (Davidson, 1970) suggest the salients are shallow downwarps and the re-entrants are mainly up-warps. Thus, the marked offsets are apparently primarily due to topographic expression of undulations in the fault plane rather than numerous cross-faults as shown on earlier maps (Welby, 1961; Doll and others, 1961). The southern "termination" near Route 125, where the trace angles southeastward, is marked by a southward structural plunge of the Monkton Formation before it and the fault trace are buried by glacial cover. If the fault continues southward it must climb up-section to place higher units on the sole. If the fault indeed terminates near Cornwall then the plunge of the Monkton is probably due to rapid decrease in dip separation into the anticlinal core (Smith, 1972).

Stratigraphic separation on the fault reaches nearly 5,000 feet. If the shallow dips of the fault surface are projected eastward beneath the Middlebury synclinorium, and reasonable reconstructions of geometry are made on the upper and lower plate, the dip separation is well over 10,000 feet. Depending on how far the Monkton Formation extended westward from its present exposures along the fault trace, the dip separation could be much more. If the fault terminates west of Cornwall this dip separation must decrease rapidly to zero, but where last seen Monkton Formation must lie over at least Bridport Formation giving a stratigraphic separation of about 3,000 feet.

Related Thrusts West of the Champlain Thrust. The lower plate of the Champlain thrust is made up of a series of thrust slices from north of Buck Mountain to its apparent termination near Route 125. South of Route 125 the lower thrusts angle to the southwest away from the last seen southeasterly trend of the Champlain thrust.

Rocks within the slices are generally intensely deformed into tight west-vergent folds.

At the south, near Route 125 (Stop 5), two thrusts are identified. The most westerly is the St. George thrust (Cashman, P., 1972; Cashman, S., 1972; Lyman, 1972) followed eastward by the Orwell thrust (Cady, 1945; Welby, 1961). The St. George thrust generally places Glens Falls Formation over Middle Ordovician shales whereas the Orwell thrust generally places Bridport Formation over Glens Falls Formation. Mapping at the north and south ends of Snake Mountain suggests the thrusts become younger from west to east since the St. George thrust is truncated by the Orwell thrust and the Champlain thrust truncates both the Orwell and St. George thrusts (Cashman, P., 1972; Cashman, P. and others, 1972; Cashman, S., 1972; Lyman, 1972). Dips on the fault planes of the two older thrusts vary. Of the two the St. George thrust often appears the steeper, and in several places it must exceed 30°E. Dips on the Orwell thrust are horizontal at the Crane School "klippe", or salient (Cashman, S., 1972), but elsewhere may be close to 10°E. At the south end of Snake Mountain both thrusts are truncated by the Champlain thrust placing Monkton Formation directly on Middle Ordovician shale north of the truncation. The Orwell thrust reappears from beneath the Champlain thrust on the north side of Snake Mountain and has been mapped northward to Buck Mountain. At Buck Mountain, particularly in the re-entrant north of the main summit, several small thrust slices lie between the Orwell and Champlain thrusts superimposing Bridport and Crown Point Formations in imbricate slices (Westervelt, 1967).

Although stratigraphic separations on the older thrusts are understandably less than those found on the Champlain thrust, dip separation on the Orwell thrust could be equally as large as that calculated for the Champlain thrust. In reality the soles of all these thrusts probably converge at depth beneath the Middlebury synclinorium.

Folds and Minor Structures. Most folds found directly below the Champlain thrust (Stop 3) are tight flexural-flow or passive folds usually inclined or overturned in westerly directions. A well developed axial surface "crenulation" or "fracture" cleavage is common, particularly in Crown Point limestones (Stop 3). Directly above the Orwell thrust, particularly in Bridport dolostones and limestones, fold patterns are more complex (Stop 4). Trends of folds are generally northward, but locally axial traces sweep into more latitudinal trends. In many places the folded bedding, particularly just above the Orwell thrust, is truncated by thrusting and the folds seem to have developed before as well as during faulting. At no place, however, has the axial surface crenulation cleavage of the folds below the Champlain thrust been found to be deformed by any penetrative later cleavage. On the other hand, numerous overturned to recumbent folds with variable trends are found in Ordovician shales below the thrust belt. Some of these have a well developed axial surface cleavage, but one large fold on the west face of Snake Mountain where the Champlain thrust lies directly on the shale, has a north-trending cleavage unrelated to fold geometry (Lyman, 1972). Crosby (1963) reports evidence of two deformations south of Route 125 in Bridport Formation on the upper plate of the Orwell thrust. In general, however, evidence for two "distinct" deformations so characteristic of the Middlebury synclinorium to the east of the thrust belt is not so obvious in and west of the thrust belt.

GRAVITY DATA

About 500 gravity stations have been made in the vicinity of Middlebury. The results thus far are very preliminary. Two east-west profiles by Powell (1969; Powell and Coney, 1969) between the Adirondack Mountains and the east flank of the Green Mountain anticlinorium show a sharp, asymmetrical westward, gravity high of nearly 50 milligals over the anticlinorium relative to a broad low over the Middlebury synclinorium and Lake Champlain lowland (Figure 3). There is also a slight gravity high over the Adirondacks. The absolute Bouguer anomaly over the Green Mountains is only about -15 milligals which is anomalously high for continental regions. These results are similar to those of Diment (1968) and Bean (1953). It would appear that the structural relief displayed on the Precambrian unconformity from the floor of the synclinorium to the crest of the anticlinorium also affects the entire crust bringing dense material to high levels beneath the anticlinorium.

More detailed studies adjacent to the Champlain thrust by Smith (1972) show a distinct south-trending trough-like gravity low of about 8 to 15 milligals just east of the trace of the Champlain thrust east of Snake Mountain. The trough appears to turn southwesterly at the south end of Snake Mountain migrating to a similar position just east of the Orwell thrust. It thus crosses the southeasterly projection of the last outcrops of the Champlain thrust at nearly 90°.

Davidson(1970) carried out gravity studies and geologic mapping in the offset of the Champlain thrust between Buck and Snake Mountains (Stop 4) where an east-west cross fault was mapped by Welby (1961) and shown on the state geologic map (Doll and others, 1961). Welby estimated the down to the south displacement on this cross fault at about 2,000 feet to explain the westward offset of the Champlain thrust from Buck to Snake Mountain. Considering the trace of the Orwell thrust less than 100 feet of dip separation on such a fault can be generated. Gravity contours trend northerly west of the thrust traces between Snake Mountain and Addison and northwesterly east of the thrust traces between Buck and Snake Mountain. These trends, combined with results from numerous computer-generated gravity models, and the structural data, suggest the cross-fault is unnecessary.

REGIONAL ASPECTS

If the dip separation on the Champlain thrust belt is 10,000 to 20,000 feet or more it becomes difficult to get rid of this displacement without driving the master sole thrust of the system into and beneath the Green Mountain anticlinorium offsetting the Precambrian basement (Figure 3) (Powell, 1969; Tennyson, 1970). Judging from structure sections drawn across northern Vermont (Doll and others, 1961) and at the latitude of Brandon (Crosby, 1963) south of Middlebury others reach similar conclusions. Several efforts to determine if the Champlain thrust system re-appears out of the eastern flank of the synclinorium, passing in the air over the anticlinorium, have resulted in no evidence to support such an option. This suggests the Champlain thrust belt, the Middlebury synclinorium, and the Green Mountain anticlinorium are inescapably linked in a strongly west-vergent tectonic system which drove the western cratonic foreland beneath the Champlain thrust belt and the west-vergent synclinorium-anticlinorium couple. Silurian-Devonian rocks seem to be involved in some way east of the anticlinorium. Thus, the massive eastward underthrusting and resultant couple, which based on gravity data must have involved the entire crust, are presumably in part at least "Acadian".

At James Pasture (Stop 2) and elsewhere in the Middlebury synclinorium (Crosby, 1963; Soule, 1967) there is ample evidence of a northwest-trending early "ductile" deformation which produced recumbent flow-folds with penetrative axial surface "mineral" cleavage. These structures are clearly deformed by later north-trending folds and cleavage (Stop 2), generally of a more "brittle" aspect. A similar fabric is found in schists on the Green Mountain anticlinorium (Tennyson, 1970). The later deformation appears to produce some, but not all, of the main map pattern of the synclinorium and anticlinorium. If the axial surface cleavage in folds found below the Champlain thrust is the same as the "late" cleavage it often resembles in the synclinorium (which has not been proved), it would appear the thrust belt developed sequentially west to east during and after most of the folding on both sides of the belt. Most workers conclude the early deformation was Taconic and relate it to emplacement of the Taconic "klippe". The later deformation is related to the Acadian and linked to the Champlain thrust and much of the gross geometry of the synclinorium-anticlinorium couple. Nothing in studies made thus far at Middlebury College refutes this general interpretation, but on the other hand neither does it prove it. Much remains to be done.

Finally, a most interesting problem is what happens to about 4,000 feet of Cambrian stratigraphy exposed in the Middlebury synclinorium which is missing in the Lake Champlain lowland. The thrust belt appears to separate the two stratigraphies, and the thrust belt itself may have been controlled by the westward on-lap and thinning indicated by the facies change. Perhaps the initial thrust rode up a basement step on the base of one or another of the massive quartzite or dolostone struts breaking upward and out as the layers end to the west. On-going and future work will hopefully clarify this and many other interesting problems.

ACKNOWLEDGEMENTS

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ROAD LOG B-4

Note: Exercise caution while driving on narrow, dirt, country roads, and at blind, busy intersections. Parking space at Stops is generally limited. Park off road and do not block farm entrances or gates. Road Log starts from parking lot east of Middlebury College Science Center.

Miles

0.0 Leave Science Center parking area heading north, turn left onto Franklin Street which turns quickly north toward Route 125.

0.1 Stop. Turn right onto Route 125.

0.2 Turn left onto Weybridge Street.

1.0 Turn right following signs to Morgan Horse Farm. Chipman Hill at 1 o'clock. Chipman Hill rises 400 feet above the surrounding terrain and exposes no bedrock anywhere on its slopes. Gravity work over the feature suggests it is entirely of unconsolidated material, thus a glacial deposit, presumably a kame or drumlin.

1.4 Bear left. Road to right crosses Pulp Mill covered bridge.

1.8 Otter Creek on right.

2.7 Morgan Horse Farm on right.

3.3 Road intersection. Continue straight.

4.4 Descend into valley of Otter Creek.

4.6 On skyline at 3 o'clock, axis of Green Mountain anticlinorium.

4.9 Cross iron bridge over Otter Creek at Weybridge-New Haven town line. Power dam on left at Huntington Falls.

5.3 Stop 1: Folds in Middlebury synclinorium. Park along right side of road near power pole. Cross fence and descend across small ravine. Proceed up low rise to east to pasture and low hill about 1,000 feet east of road. Exposed on the hill, and in adjacent woods is a series of north-trending westward inclined folds with a well developed north-trending axial surface cleavage in limestones and dolostones of the Chipman Formation. Several prominent dolostone layers and the distinctive banded Weybridge Member enable the fold geometry to be clearly seen. These structures are interpreted by Crosby (1963) as late structures related to the gross geometry of the Middlebury synclinorium and probably Acadian in age.

5.3 Return to car, continue north up hill.

5.4 Turn sharp left at intersection.

6.0 Snake Mountain ridge at 12 o'clock on skyline.

6.2 Descend into valley of Otter Creek. Profile of Buck Mountain at 3 o'clock on skyline.

6.9 Turn sharp left at road intersection.

7.2 Turn left at intersection. Proceed across twin-bridges below Weybridge power dam and bear right. Continue south through Weybridge Village.

9.1 Weybridge Elementary School on left; cemetery on right.

9.3 Stop at yield sign. Then bear left onto Route 23 for 50 yards, turn left onto gravel road just past church on left.

9.9 Stop 2: Two deformations. Park at road intersection just before large white barn with two silos. Enter gate to pasture on northwest side of intersection. Please close gate after entering pasture. Proceed northwest across pasture toward low wooded ridge. No hammers, please.

This pasture, which lies in the core of the Middlebury synclinorium, was mapped by plane table by Crosby (1963) and has since been mapped hundreds of times by students from Middlebury College and numerous other institutions in New England. It is certainly one of the finest displays of multiple deformation geometry and fabric available for instructional use, and is probably one of the key areas for interpretation of the tectonic evolution of the Middlebury synclinorium.

Exposed in the pasture are a number of very subtle northwest-trending recumbent folds with a distinct axial surface mineral cleavage. The geometry of these folds is outlined by the contact between the base of the Middlebury Formation grey marbles and the top of the Beldens Formation dolostones and marbles. A thin grey slate just above the base of the Middlebury is a most useful marker. These folds and related cleavage are clearly deformed by a north-trending set of small folds and a prominent axial surface "crenulation" cleavage. The assumption is that the late folds in this pasture are the same generation as the folds seen at stop 1. The early folds here are interpreted as "Taconic".

9.9 Return to cars, turn around and retrace route to Route 23.

10.4 Stop. Turn right onto Route 23, bear to left of cemetery.

10.8 At 9 o'clock, valley of Lemon Fair River. Beyond wide valley is the dip slope on Monkton Formation off the east side of Snake Mountain. The Champlain thrust lies just on other side of skyline ridge dipping eastward beneath the Middlebury synclinorium.

11.1 Profile of Buck Mountain at 12 o'clock on skyline.

11.5 Slow for sharp turn to left in road.

13.4 Bridge over Lemon Fair River at confluence with Otter Creek on right.

14.5 First of many outcrops of Monkton Formation red quartzites and shales at base of dip slope of Snake Mountain.

15.1 Stop. Turn right onto Route 17.

15.4 Bridge across Otter Creek. Prepare for dangerous left turn on blind hill dead ahead.

15.6 Slow by white barn on right, then turn left off Route 17 onto road leading north, just before red brick farmhouse on northeast side of intersection.

16.7 Buck Mountain at 12 o'clock. The Champlain thrust lies just below the cliffs west of summit placing Monkton quartzites over Ordovician limestones and shales. The gentle east slope is a dip slope on Monkton Formation.

18.3 Stop 3: Champlain Thrust. Park at cemetery. Walk east along north side of cemetery fence to east end of cemetery. Cross fence and enter juniper woodland and pasture and proceed northeastward toward summit of Buck Mountain. The best route to the summit is up the northwest ridge on skyline through grove of large hemlock trees. The walk to the summit first crosses outcrops of Orwell limestone on the west flank of an overturned syncline. Glens Falls Formation, largely covered, is in the core. A minor thrust fault places Middlebury Formation limestones over the east flank of the fold. East of the thrust the Middlebury limestones are caught in a tight overturned anticline with a well developed axial surface fracture cleavage. An overturned syncline follows to the east with a core of Glens Falls Formation. The axis of the fold is just above the base of the steep slope rising to the summit at about the 550-foot contour line. Continuing up the steep slope outcrops of Orwell appear followed quickly by Middlebury limestone, all here overturned to the west. Directly above the Middlebury limestone are outcrops of Monkton quartzites and dolostones, followed above and to the summit by red Monkton quartzites. The Champlain thrust lies between overturned Middlebury limestone and right side up Monkton quartzite. The trace of the thrust is exposed to the south at the foot of the quartzite cliffs. Excellent panoramic view from the summit: Snake Mountain to the southwest, the Lake Champlain Lowland and the Adirondack Mountains to the west. Retrace route to cemetery and cars.

18.3 Turn around and return to Route 17.

18.4 Profile of Snake Mountain at 1 o'clock. Champlain thrust lies at base of steep cliffs and slopes just below skyline and dips about 7° east.

20.9 Slow for right turn onto Route 17.

21.3 Continue straight on Route 17 past junction from left of Route 23.

21.5 Stop 4: Orwell Thrust. Park along north side of road near gate into pasture on right. Walk west along road to outcrops of Bridport dolostones on right. Just beyond to west is a large roadcut in Ordovician Stony Point shale. The Orwell thrust lies between the two exposures placing Bridport over Stony Point. If one enters woods and ascends hill north of road the fault trace can be followed to the summit of the hill in a pasture where Bridport caps the west face of the hill over shale. Good exposures of Bridport Formation in pasture. Looking south-southwest across road and valley to Snake Mountain from summit of hill the Orwell thrust lies several feet into woods at edge of hillside pasture. The Champlain thrust lies just above it descending from summit of Snake Mountain far to west. The Champlain thrust truncates the Orwell thrust several hundred yards to west and Monkton quartzite lies directly on shale from here to the west face of Snake Mountain. Note similar elevation of thrust traces north and south of road suggesting minor, if any, cross faulting. Return to cars.

21.5 Continue west on Route 17.

23.0 At 9 o'clock the Champlain thrust is exposed at base of quartzite cliffs near skyline ridge. Several caves which have formed in weak shale below the resistant quartzite provide excellent exposures of the overhanging fault plane and minor structures in shale below.

23.3 Turn left off Route 17 onto gravel road leading south along west face of Snake Mountain.

26.6 Turn left (east) on gravel road.

27.1 At 3 o'clock, Crane School hill half a mile to south is either a klippe or tongue-like salient of the Orwell thrust placing Bridport and Crown Point Formations over Ordovician shales. At 10 o'clock, just to left of saddle on Snake Mountain ridge on skyline the Orwell and St. George thrusts are truncated by the Champlain thrust.

28.0 Turn right at intersection. Orwell thrust "klippe" straight ahead.

28.5 At 3 o'clock cliffs of folded Bridport Formation in woods just above Orwell thrust.

28.8 Beehives on left. On right, lower slopes in pasture expose Ordovician shales below Orwell thrust.

29.0 Slow for road junction. Turn left.

29.2 Iberville shale exposed on knolls and hills surrounding farms.

29.6 At about 10 o'clock Champlain thrust lies at foot of prominent cliffs of Monkton quartzite at edge of farmland.

29.7 Culvert across small creek. From this point to pass over Snake Mountain at 30.2 the route crosses all three thrusts.

29.9 Road crosses Champlain thrust. Monkton Formation is exposed in small road cuts and in quarry at right on upper plate.

30.2 Pass over Snake Mountain. Shift to lower gear for steep, winding descent.

30.6 Crossroads. Turn right (south).

30.8 Winooski Formation exposed in cliffs on east side of road.

31.9 First of many dip slope outcrops of Monkton Formation.

32.4 Stop. Intersection with Route 125. Cemetery on right. Turn right. Around this intersection are the last and southernmost exposures of the Monkton Formation and the Champlain thrust which presumably angle southeasterly beneath glacial cover.

32.8 At 3 o'clock cliff of well-bedded Monkton quartzites. At 12 o'clock, and extending south, low hills are in Bridport and Crown Point Formations on upper plate of Orwell thrust here heading southwest.

33.3 Continue on blacktop past dirt road to right. From here to 34.0 road passes complex relationships involving Orwell and St. George thrusts. At 33.5 road cuts on right expose Glens Falls Formation on upper plate of St. George thrust which angles nearly east-west up the brow of hill to north. On left at 33.9 outcrops of Bridport Formation on upper plate of Orwell thrust.

34.5 Turn right (north) off Route 125 onto narrow blacktop.

35.0 Intersection. Turn right. Good panorama of Snake Mountain to northeast.

35.8 Stop 5: St. George Thrust. Park in larger quarry in Ordovician shales on right. Brief stop to examine the St. George thrust and minor structures in lower plate, and to view problem of the southern termination of the Champlain thrust. From quarry ascend into woods and then pasture to top of hill. Glens Falls Formation outcrops on north side of hill on upper plate of St. George thrust. From top of hill cliffs of Monkton Formation to east can be seen plunging southeastward into Lemon Fair valley. Champlain thrust is at foot of cliffs and hills. The thrust is lost from here southeastward beneath extensive glacial cover. Follow trace of St. George thrust east-northeast down hill to stream and dirt road. Both Orwell and St. George thrusts continue north of road on west face of long south-plunging ridge in woods. Turn left on dirt road and return to cars.

35.8 Continue east along dirt road.

36.3 Stop. Blind intersection with busy Route 125. Turn left (east) on Route 125.

37.3 Slow down for sharp left turn on Route 125 after bridge over Lemon Fair River.

38.3 Straight ahead are The Ledges, a prominent north-trending cliff exposing Bascom through Middlebury carbonates on west flank of Middlebury synclinorium.

38.7 Slow for left bend and winding ascent of The Ledges.

39.8 Slow for right bend in road at ridge crest.

40.0 Slow for hidden crossroad. Hortonville shales in core of Middlebury synclinorium exposed in small roadcuts and outcrops.

41.8 Blinker light at edge of Middlebury College campus.

42.0 Turn right opposite Catholic Church onto Franklin Street and Middlebury College Science Center. End of trip.

REFERENCES CITED

Bean, R. J., 1953, Relation of gravity anomalies to the geology of central Vermont and New Hampshire: Geol. Soc. America Bull., v. 64, p. 509-538.

Beyer, B. J., 1972, Petrology and origin of ultramafic bodies in Vermont (abs.): Vermont Acad. Arts and Sci., 7th Intercoll. Student Symp., April; also unpubl. senior thesis, Middlebury Coll.

Cady, W. M., 1945, Stratigraphy and structure of west-central Vermont: Geol. Soc. America Bull., v. 56, p. 515-558.

_____, 1968, Tectonic setting and mechanism of the Taconic slide: Amer. Jour. Sci., v. 266, p. 563-578.

_____, 1969, Regional tectonic synthesis of northwestern New England and adjacent Quebec: Geol. Soc. America Mem. 120, 181 p.

Cashman, P. H., 1972, Structural geology of southern Snake Mountain, Addison County, Vermont: unpubl. senior thesis, Middlebury Coll.

_____, Cashman, S. M., and Lyman, T. J., 1972, Structural analysis of the Champlain thrust at Snake Mountain, Addison County, Vermont (abs.): Vermont Acad. Arts and Sci., 7th Intercoll. Student Symp., April.

Cashman, S. M., 1972, Structural geology of the Crane School salient and central Snake Mountain, Addison County, Vermont: unpubl. senior thesis, Middlebury Coll.

Crocker, D. E., 1972, Petrologic and tectonic analysis of the orthogeoclinal greenstones in Washington County, Vermont (abs.): Vermont Acad. Arts and Sci., 7th Intercoll. Student Symp., April, also unpubl. senior thesis, Middlebury Coll.

Crosby, G. W., 1963, Structural evolution of the Middlebury synclinorium, west-central Vermont: unpubl. Ph.D. dissertation, Columbia Univ., 136 p.

Davidson, Gail, 1970, A new interpretation of Champlain thrust structure near Snake Mountain (abs.): Vermont Acad. Arts and Sci., 5th Intercoll. Student Symp., April, also unpubl. senior thesis, Middlebury Coll.

Diment, W. H., 1968, Gravity anomalies in northwestern New England, in: Zen, E-an, White, W. S., Hadley, J. B., and Thompson, J. B., Jr., editors, Studies of Appalachian geology, northern and maritime (Billings vol.): New York, Wiley-Interscience, p. 399-413.

Doll, C. G., Cady, W. M., Thompson, J. B., Jr., and Billings, M. P., 1961, Centennial geologic map of Vermont: Vermont Geol. Survey.

Egan, R. T., 1968, Structural geology of south of Buck Mountain, Addison County, Vermont: unpubl. senior thesis, Middlebury Coll.

Johnson, A. H., 1970, Structural and geochemical data from the Sunset slice of the Taconic klippe near Orwell, Vermont (abs.): Vermont Acad. Arts and Sci., 5th Intercoll. Student Symp., April, also unpubl. senior thesis, Middlebury Coll.

Lyman, Tracy, 1972, Structural analysis of the Champlain thrust at north Snake Mountain, Addison County, Vermont: unpubl. senior thesis, Middlebury Coll.

Osberg, P. H., 1952, The Green Mountain anticlinorium in the vicinity of Rochester and East Middlebury, Vermont: Vermont Geol. Survey Bull. 5, 127 p.

Powell, R. E., 1969, Structural and gravity profiles of the Champlain Valley, Champlain thrust, and Green Mountain front, west-central Vermont: unpubl. senior thesis, Middlebury Coll.

_____, and Coney, P. J., 1969, Structural and gravity profiles of the Champlain Valley, Champlain thrust, and Green Mountain front, west-central Vermont: New York State Geol. Assoc. Guidebook to Field Excursions, 41st Ann. Mtg., p. 148.

Rodgers, John, 1970, The tectonics of the Appalachians: New York, Wiley-Interscience, 271 p.

Sedgwick, G. B., 1972, An analysis of the heavy mineral distribution in central Vermont: unpubl. senior thesis, Middlebury Coll.

Smith, P. L., 1972, Gravity studies in the vicinity of Cornwall, Vermont: unpubl. senior thesis, Middlebury Coll.

Soule, J. M., 1967, Structural geology of a portion of the north end of the Middlebury synclinorium, Weybridge, Addison County, Vermont: unpubl. senior thesis, Middlebury Coll.

Tennyson, Marilyn, 1970, Regional tectonics of west-central Vermont: unpubl. senior thesis, Middlebury Coll.

Welby, C. W., 1961, Bedrock geology of the central Champlain Valley of Vermont: Vermont Geol. Survey Bull. 14, 296 p.

Westervelt, Thomas, 1967, A structural analysis of the Champlain thrust at Buck Mountain, Addison County, Vermont: unpubl. senior thesis, Middlebury Coll.

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