Trip B-5

ANALYSIS AND CHRONOLOGY OF STRUCTURES ALONG THE CHAMPLAIN THRUST WEST OF THE HINESBURG SYNCLINORIUM

by

Rolfe Stanley and Arthur Sarkisian
Department of Geology
University of Vermont

INTRODUCTION

The Champlain thrust has long attracted the attention of geologists. Prior to the discovery of fossils along this belt the thrust was considered an unconformity between the strongly-tilted Ordovician shales of the "Hudson River Group" and the overlying, gently-inclined dolostones and sandstones of the "Red Sandrock Formation" (Dunham, Monkton, Winooski formations of Cady, 1945). The "Red Sandrock Formation" was thought to be Silurian in age since it was lithologically similar to the Medina Sandstone of New York. Between 1847 and 1861 fossils of pre-Medina age were found in the "Red Sandrock Formation" and its equivalent "Quebec Group" in Canada. Based on this information, Hitchcock (1861, p. 340) stated that "it will be necessary to suppose the existence of a great fault, extending from Quebec through the whole of Canada and Vermont and perhaps to Alabama. Its course through Vermont would correspond very nearly to the western boundary of the red sandrock formation." Since then, although its extent has been greatly limited, its importance has not diminished.

Our understanding of the Champlain and associated thrusts is primarily the result of studies by Keith (1923, 1932), Clark (1934), Cady (1945), and Welby (1961). Current interest in earthquake research on the character, movement, chronology, and mechanics of faults requires a closer, more detailed study of such well mapped faults as the Champlain thrust.

Acknowledgements

The work of Cady (1945) and Welby (1961) along the Champlain thrust in western Vermont is very valuable in providing the framework for detailed work that is presently being done at the University of Vermont and Middlebury College. Although many geologists have contributed to our present understanding of this region, syntheses by Cady 1969, Doll and others 1961, Rodgers 1968, and Zen 1967, 1968 are particularly helpful.

Many students at the University of Vermont have contributed information for the localities in this trip. Data on fractures, faults, and quartz deformation lamellae at the Shel-

burne Access Area were collected by Charles Rubins, John Millett, Edward Kodl, Robert Kasvinsky, Evan Englund, and Jack Chase. The analyses at locality S9 and Mount Philo are largely the work of Arthur Sarkisian. Richard Gillespie, Roger Thompson, Jack Chase, Greg McHone, and Gary French provided information for Pease Mountain.

REGIONAL GEOLOGY

The Champlain thrust extends for approximately 75 miles from Cornwall, Vermont, to Rosenberg, Canada, and places Lower Cambrian dolostone with some quartzite on highly deformed Middle Ordovician shale and minor beds of carbonates. Throughout its northern part the thrust is confined to the lower member (Connors facies) of the Dunham Dolostone. At Burlington the thrust apparently rises 2000 feet in the section to the dolostones and quartzites of the lower part of the Monkton Quartzite. It then truncates major structure in the Ordovician rocks of the lower plate south of Mount Philo to Cornwall, Vermont (Doll and others, 1961). The upper part of the Dunham only reappears along the thrust just south of Buck Mountain (Welby, 1961). The Champlain thrust appears to be primarily restricted to the first massive dolostone interval above the Precambrian.

Throughout most of its extent north of Pease Mountain (figure 1) the trace of the Champlain thrust is somewhat straight and the surface strikes to the north and dips gently to the east at angles less than 20 degrees. South of Pease Mountain the trace of the thrust is irregular because of subsequent folding and faulting (Doll and others 1961, Welby 1961). At Mount Philo, for example, the rocks of the upper plate are folded gently into an east-plunging syncline. Between Burlington and Snake Mountain the thrust is cut by a number of cross-faults that are interpreted as normal faults by Welby (1961, p. 204). Our work indicates that the displacement on some of these faults is predominantly strike slip (Stanley 1969, Sarkisian 1970).

The stratigraphic throw on the Champlain thrust is in the order of 8000 feet at Burlington. To the north the throw decreases as the Champlain thrust is lost in the shale terrain north of Rosenberg, Canada. Part, if not all, of this displacement is taken up by the Highgate Springs and Philipsburg thrust which continues northward and becomes the "Logan's Line Thrust" (Cady 1969). South of Burlington the stratigraphic throw is in the order of 5500 feet. As the throw decreases on the Champlain thrust near Cornwall the displacement is again taken up in part by the Orwell, Shoreham, and Pinnacle thrusts, which place Upper Cambrian and Lower Ordovician rocks on each other and eventually on the Middle Ordovician rocks to the west (Cady 1945).

The configuration of the Champlain thrust at depth is speculation. Where it is exposed the thrust surface is essentially parallel to the gently-dipping beds in the upper plate. This thrust geometry persists for at least 2-3 miles east of its most western limit since the thrust is still essentially parallel to the bedding in the Monkton Quartzite at the base of the upper plate in the center of the recess of the thrust trace on the Monkton culmination. Further to the east the thrust must eventually steepen in dip and pass into Precambrian basement since it does not reappear at the surface on the west side of the Precambrian core of the Green Mountains. This overall configuration is shown in the cross sections accompanying the geologic map of Vermont (Doll and others 1961).

The age of the Champlain thrust is debatable. Cady (1969, p. 75) believes the thrust developed in the Acadian Orogeny although the youngest rocks exposed below the Champlain thrust are Middle Ordovician in age. Welby (1961, p. 221) believes the thrust developed during the Taconic orogeny of Middle to Upper Ordovician age. Thrusting predates the emplacement of the Mesozoic dikes which clearly cut the structures of the Champlain thrust.

Our work shows that the Champlain thrust has undergone an extensive structural history involving possibly more than one period of thrusting. Perhaps the most compelling evidence for a multiple history of displacement is the presence of prograde chlorite in recrystallized fractures in the Monkton on the upper plate and the absence of prograde chlorite throughout the pelitic rocks directly below the thrust. We tentatively suggest that the Champlain thrust was originally developed during the Taconic orogeny, metamorphosed and then reactivated to place a metamorphosed upper plate on an unmetamorphosed lower plate. Although the second event may also be Taconic in age, since rocks of Silurian and Devonian age are not present below the thrust, the additional structural events may have occurred during the Acadian orogeny. These speculations will be discussed during the trip.

STRATIGRAPHY

A composite stratigraphic section and correlation chart for the area of the Champlain thrust and the Hinesburg synclinorium are shown in Table 1 and Table 2 respectively.

COMPOSITE STRATIGRAPHIC SECTION FOR THE HINESBURG SYNCLINORIUM AND AREA WEST OF THE CHAMPLAIN THRUST AND EAST OF THE HINESBURG THRUST

(Cady, 1945; Doll, et al., 1961)

Middle Ordovician

Hathaway Formation*

Missing but present north of the Lamoille River.

Iberville Formation

Noncalcareous shale, rhythmically interbedded with thin beds of silty dolomite and in the lower part with calcareous shale.

Stony Point Formation

Calcareous shale that grades upward into argillaceous limestone and rare beds of dolomite.

Cumberland Head Formation

Missing but well exposed in Grand Isle County.

Glens Falls Formation

Thin bedded, dark blue-gray, rather coarsely granular and highly fossiliferous limestone.

Orwell Limestone

Missing but present south of Charlotte.

Middlebury Limestone

Missing but present south of Charlotte.

Lower Ordovician

Chipman Formation

Missing in the Hinesburg synclinorium but present south of Charlotte.

Bascom Formation

Beds of light bluish gray calcitic marble with laminae and thin beds of siliceous phyllite. Beds of brown-orange weathering dolomite 1 to 3 feet thick. The upper part becomes more phyllitic and is mapped separately as the Brownell Mountain Phyllite. Contact against typical Cutting dolomite is gradational.

Massive whitish to light grayish weathering dolostone, dark gray on the fresh surface. Sand-size quartz grains present in places especially near the base where sandy laminae are more abundant and brecciated in places. Black chert nodules are found in the upper part. Contact is sharp with sandy dolomite above and white calcitic marble of the Shelburne Formation below.

Shelburne Formation

Massive whitish gray weathering calcitic marble that is white on the fresh surface. Laminae of green phyllite present in the eastern part of the Hinesburg synclinorium. Contact is sharp with typical calcitic marble above and gray dolomite with quartz knots below.

Upper Cambrian

Clarendon Springs Dolomite

Massive, gray weathering dolomite with numerous knots of white quartz crystals. Black chert commonly found in the upper part. Contact gradational with the Danby Formation.

Danby Formation

Beds of gray sandstone interlayered with beds of dolomite 1 to 2 feet thick and sandy dolomite 10 to 12 feet thick. Sandstones are cross laminated. Beds 1 to 3 feet thick. Contact gradational.

Cambrian

Underhill Formation

Fairfield Pond Member: Predominantly green quartz - chlorite - sericite phyllite. Quartz grains common.

White Brook Member: Chiefly brown-weathered whitish, tan and gray sandy dolomite.

Pinnacle Formation

Schistose graywacke, gray to buff, with subordinate, quartz-albite-sericite-biotite-chlorite phyllite. Includes the Tibbit Hill Volcanic Member.

*Only those formations encountered in the course of the trip will be described. Kindly refer to the Centennial Geologic Map of Vermont for other formation descriptions.

System	Series	Group	Saratoga Springs, New York Mohawk Valley (Fisher 1965)	West-central Vermont (Doll et al 1961)	West Limb of the St Albans Synclinorium (Doll et al 1961) (Shaw 1958)	Lincoln Mtn - Enosburg Falls Anticline East of Hinesburg Thrust (Doll et al 1961) (Stone and Dennis 1964)
ORDOVICIAN	Middle	Trenton	Schenectady Shale Canajoharie Shale Shoreham Limestone Larrabee Limestone	Hathaway Formation Iberville Formation Stony Point Formation Cumberland Head Formation Glens Falls Formation	Morse Line Formation	
		Black River	Amsterdam Limestone	Orwell Limestone		
		Chazy		Middlebury Limestone		
	Lower	Beekmantown	Chuctanunda Creek Dolostone Gailor Dolostone	Chipman Formation Bascom Formation Cutting Dolomite Shelburne Formation	Highgate Formation	
CAMBRIAN	Upper		Hoyt Limestone Mosherville Sandstone Theresa Formation Potsdam Sandstone	Clarendon Springs Dolomite Danby Formation	Gorge Formation Sweetsburg Fm.: Hungerford Sl., Rockledge Congl., Skeels Corner Sl., Mill River Congl., St. Albans Sl.	
	Middle					
	Lower			Winooski Dolomite Monkton Quartzite Dunham Dolomite Cheshire Quartzite	Rugg Brook Formation Parker Slate Dunham Dolomite Champlain Thrust	Dunham Dolomite Cheshire Quartzite
CAMBRIAN?				Mendon Formation	Not Exposed	Underhill Formation Pinnacle Formation
PRECAMBRIAN			Metamorphic Rocks of the Adirondack Dome	Mount Holly Complex		Mount Holly Complex

Table II Correlation chart for selected areas in western Vermont and eastern New York.

STOP DESCRIPTIONS

General

The trip consists of five stops along the Champlain thrust. These stops are located on figure 1.

Stop 1. Lone Rock Point, Burlington (1, 2a, 2b, figure 2) - This locality is perhaps one of the finest exposures of the Champlain thrust in Vermont and Canada. Here the Dunham Dolomite (Conners facies) of Lower Cambrian age overlies the Iberville Formation of Middle Ordovician age. The thrust contact is sharp and marked by a thin zone of breccia in which angular clasts of dolostone are embedded in a highly contorted matrix of shale. Slivers, several feet thick, of limestone are found along the fault and may represent pieces of the Beekmantown Group (Beldens Member of the Chipman Formation ?). The undersurface of the Dunham Dolomite along the thrust is grooved by fault mullions which plunge 15° to the southeast (figure 2, diagram 1 and 2a). The average southeastward dip of the thrust is 10 degrees.

A variety of minor structures are found in the Iberville Formation whereas fractures are the only structures in the Dunham Dolomite. Many of these faults are filled with calcite and grooved with slickensides. The minor folds in the shale are numerous, and are easily grouped into two ages. The early folds have a well developed slaty cleavage that forms the dominant layering in the Iberville and is concordant to the thrust surface at the base of the Dunham Dolomite.

The younger generation consists of asymmetrical drag folds with short, gently curved hinges and rather open concentric profiles. The axial surface is rarely marked by cleavage but when it is developed, fracture cleavage, filled with calcite, is typical. These folds deform the slaty cleavage of the older generation and are related to movement of the Champlain thrust since they decrease in abundance away from the thrust surface. The orientation of 59 axes with their sense of rotation is shown in diagrams 1, 2a, and 2b of figure 2.

Slip line orientations. Drag folds of the younger generation have been used at 5 localities to determine a direction of movement on the Champlain thrust. Two of these localities are in the Iberville or Stony Point Formations directly below the thrust and 2 localities are in the Monkton Quartzite just above the thrust (diagrams 1, 2a, 2b, 3, 7, 8, figure 2). The remaining locality at Shelburne Point is along a fault zone in the Stony Point Formation less than a mile west of the Champlain thrust. At each of these localities numerous younger folds are developed with nonparallel hinges and short limbs facing in a variety of directions.

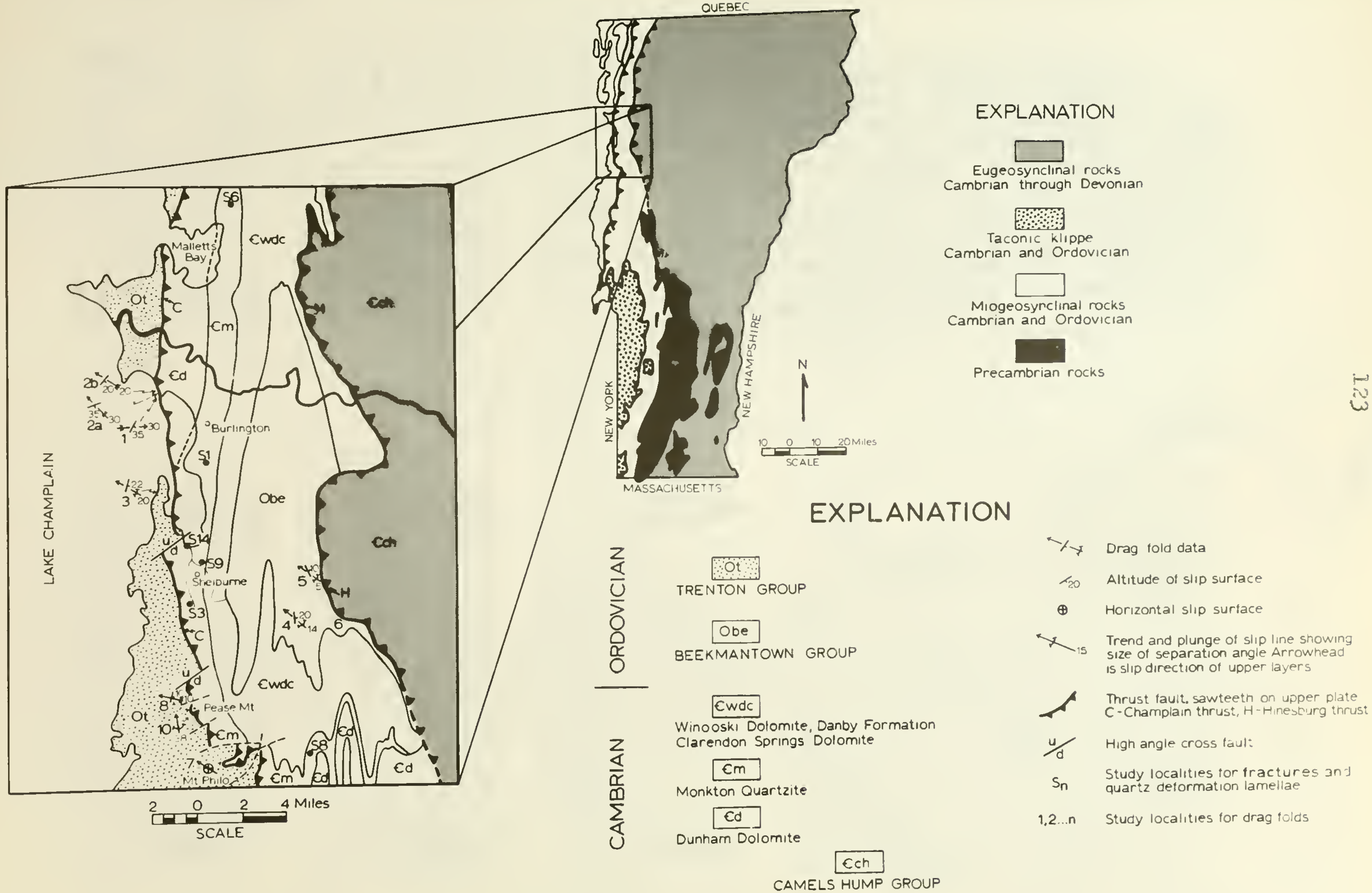
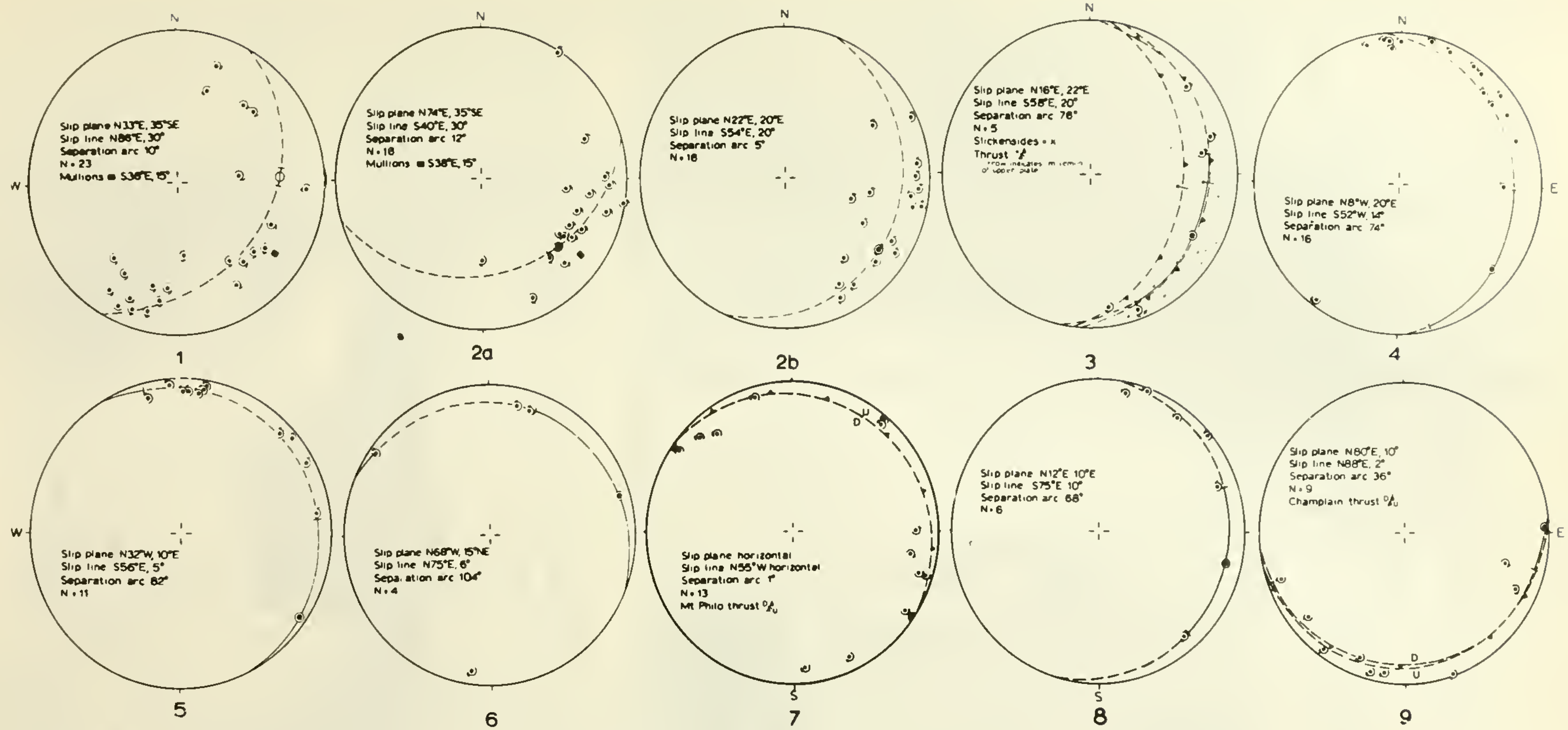


Figure 1. Generalized geologic map of the Hinesburg synclinorium. Slip line directions at localities 1-8, and 10 are shown in more detail in figure 2.



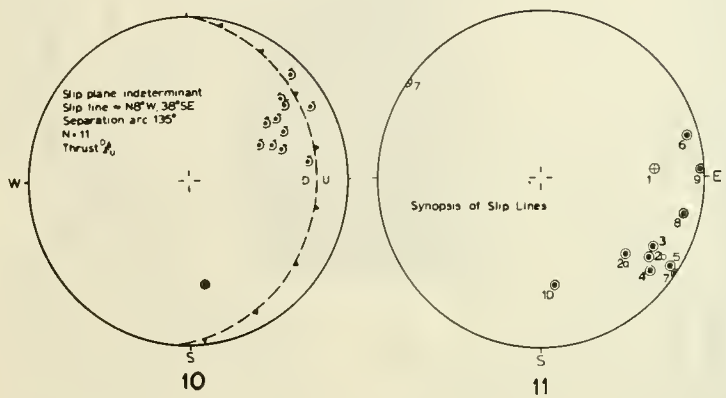


Figure 2. Slip line orientations determined from drag folds. Data shown on lower hemisphere equal area projection. Solid dots represent fold axes. Semicircular arrows show sense of rotation of asym metrical drag folds. Dashed great circles are slip surfaces each of which contains a slip direction shown by a circle with solid dot (movement up of upper beds) or a circle with cross (movement down of upper beds). Diagram 7 is from Mount Philo, diagrams 8 and 10 are from Pease Mountain, diagram 9 is from Snake Mountain approximately 15 miles north of the Taconic klippe of Figure 1. Numbers correspond to locations shown on Figure 1.

A slip line or movement direction was determined at three stations along the 2000 feet of exposure at Rock Point (diagram 1, 2a, 2b, figure 2) using the methods described by Hansen (1967, 1971). The hinge orientation and sense of rotation for 18 to 23 younger folds were plotted at each station on a lower hemisphere equal area net. The great circle that best approximates the spatial distribution of axes defines the slip plane which is approximately parallel to the older cleavage and the Champlain thrust. At Rock Point this cleavage is of compact shale separated by thinner layers of extremely fissile shale. In all the diagrams in figure 2 clockwise or dextral folds occupy one part of the great circle, whereas counterclockwise or sinistral folds occupy the other. The arc that separates the opposite senses of rotation contains the slip direction. This is uniquely defined when the separation arc is zero. In most localities the separation arc is greater than zero and the bisector of the separation arc is arbitrarily designated as the slip direction. The overall symmetry of the fabric is monoclinic with the plane of symmetry oriented parallel to the slip direction and perpendicular to the slip plane.

The location of clockwise and counterclockwise arrows on either side of the separation arc indicates the direction of movement of the upper layers along the deduced slip line. In diagrams 2a and 2b (figure 2) the upper layers moved to the northwest approximately along a line striking N40W for 2a and N54W for 2b. In contrast , the upper layers moved eastward along a line striking N86E for the southern part of the Champlain thrust at Rock Point (diagram 1, figure 2). In all three diagrams the separation arc ranges in size from 5 to 12 degrees.

Discussion of Results. The kinematic basis for drag fold analysis has been worked out in such geologic environments as tundra and sod slides, glacial lake clays, lava flows, and metamorphic rocks of all grades (Hansen 1967, Hansen and others 1967, Howard 1968, Hansen 1971). Scott (1969, p. 251-254) has verified these methods in the laboratory using substances of different viscosities. In all these studies it has been shown that the separation arc contains the slip line and that the drag folds are a product of one overall movement regimen.

As shown in diagram 11 of figure 2, the deduced slip lines are nearly parallel along 25 miles of the Champlain thrust. These slip directions are essentially parallel to fault mullions on the thrust surface at Lone Rock Point and slickensides on calcite-veneered surfaces at Shelburne Point (diagram 3) and elsewhere in the Middle Ordovician shale of the lower plate (Hawley 1957, p. 81). Although the origin of the diversity in hinge orientation in the rocks along the Champlain thrust is still unclear, the approximate parallelism among slickensides, mullions, and slip lines indicates that the slip lines deduced from drag folds are a reliable movement indicator.

A generalized principal plane of stress and strain can be determined from slip line and plane information if rotation about the pole to the slip plane is assumed to be zero. With this restriction the slip line and the pole to the slip plane define the plane of σ_1 and σ_3 and λ_1 and λ_3.[1)] This plane, known as the deformation plane, is also the plane of monoclinic symmetry of the drag fold diagrams. The location of σ_1 in the deformation plane depends on the sense of shear across the slip surface, the coefficient of internal friction of dolostone on shale and the strong planar anisotropy along the Champlain thrust.

The anomalous easterly slip direction for the southern part of Lone Rock Point (diagram 1, figure 2) will be discussed during the trip.

Stop 2. Shelburne Access Area (S14, figure 1) - The fractures and faults at this locality are ideal for dynamic analysis. The outcrop is located in the upper member of the Monkton Quartzite approximately 900 feet above the Champlain thrust. A high angle cross fault offsets the thrust just to the northwest (figure 1).

The location, orientation and relative displacement on faults and feather fractures are shown on the geologic map (figure 3). At each numbered station the orientations, relative abundance and surface features of 10 fractures were measured. Diagram A of figure 4 shows the poles to 248 fractures and diagram B shows four planes corresponding to the maxima in diagram A. The trend and deduced sense of displacement of the feather fractures are shown in diagram D of figure 5.

The faults in figure 3 are generally vertical, contain a very narrow zone of gouge and are divided into an east-west group and a north-south group according to their general strike. The north-south group are few in number and displace the east-west faults and hence, are younger in age. The faults of both generations are wrench faults since the dip slip displacement is only several inches and the strike slip displacement is as large as 3 feet. Furthermore, feather fractures adjacent to many of the faults are only present on the horizontal surfaces. Petrofabric analysis of quartz deformation lamellae in samples M1, M3, M4 (figure 4) further supports this conclusion (figure 6).

[1)] σ_1, σ_2 , σ_3 refer to the principal axes of stress with σ_1 representing the maximum compressive stress. λ_1, λ_2 , λ_3 are the principal directions of quadratic elongation with λ_1 representing the direction of maximum elongation.

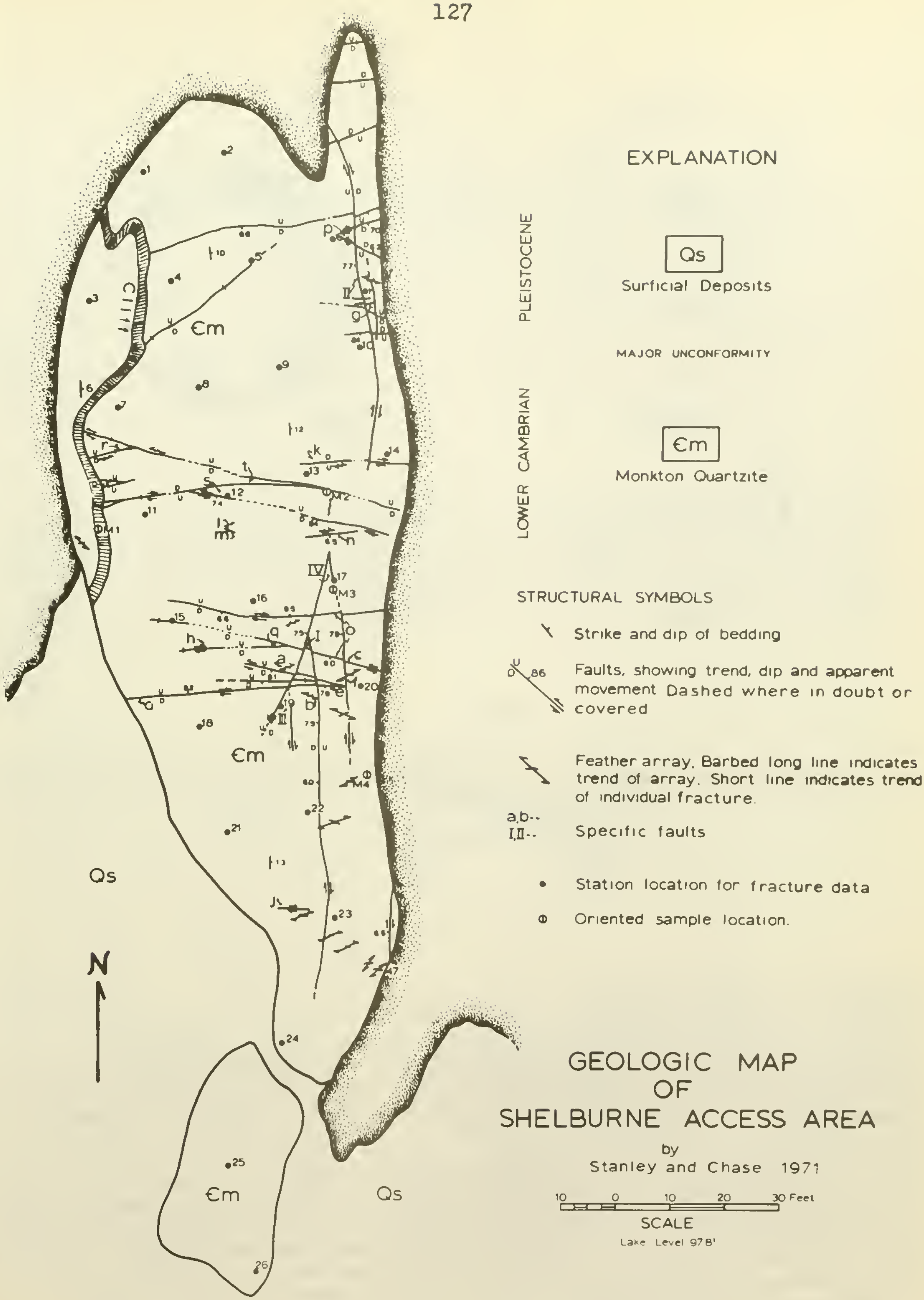


Figure 3. Structures in the Monkton Quartzite at the southern end of Shelburne Bay, western Vermont. Located at station S14 on figure 1.

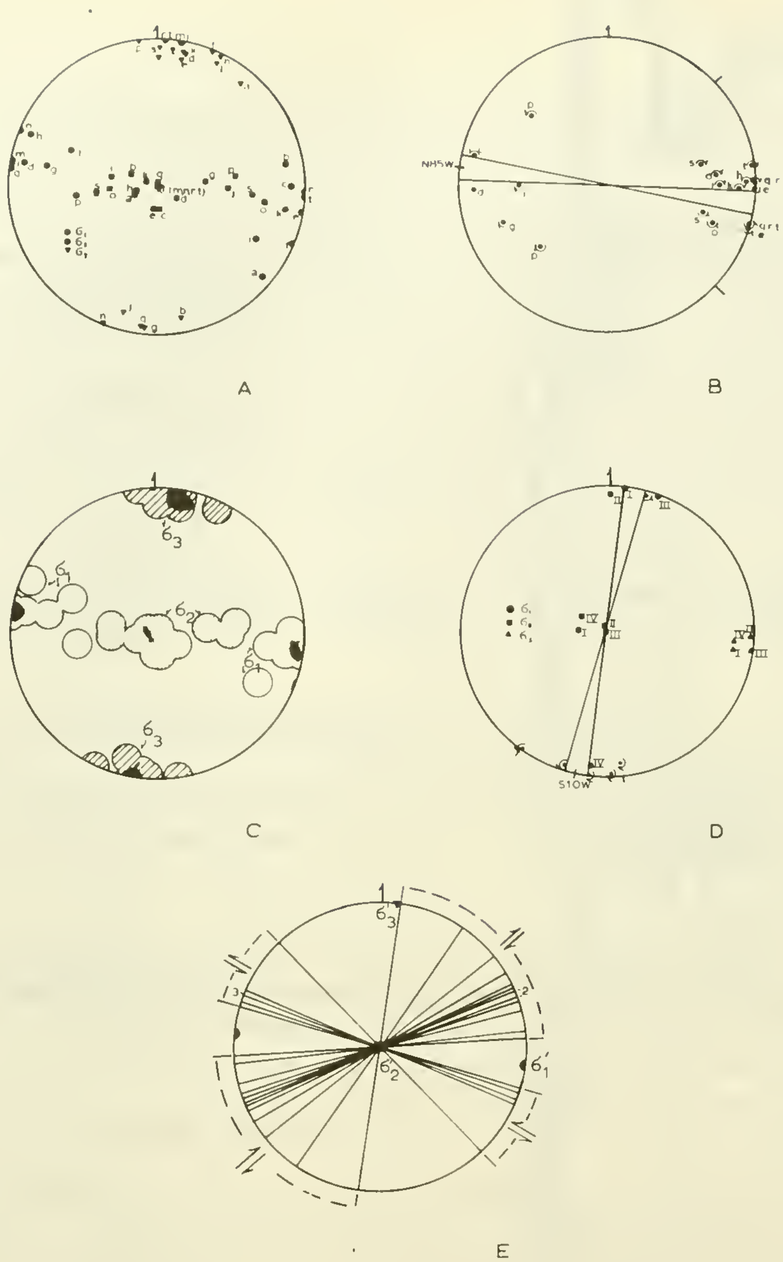


Figure 5. Lower hemisphere equal area diagrams of faults and feather fracture arrays at Shelburne Access area. Diagram A shows the principal stresses deduced for the complimentary faults (e,o,p,q) and fault-feather fracture sets (c,d,g,h,i,j, k) of the first generation of wrench faults in figure 3. These directions are contoured in diagram C. Contour interval 9.1, 18.2 percent per 1 percent area. Diagram B shows the slip directions (solid dot) with their respective senses of shear for each of the faults in diagram A. Diagram D shows the principal stresses deduced for the second generation of complimentary wrench faults. Their respective slip directions and senses of shear are indicated by a solid dot with concentric arrows. Diagram E shows the trend and relative displacement deduced from 21 feather-fracture arrays.

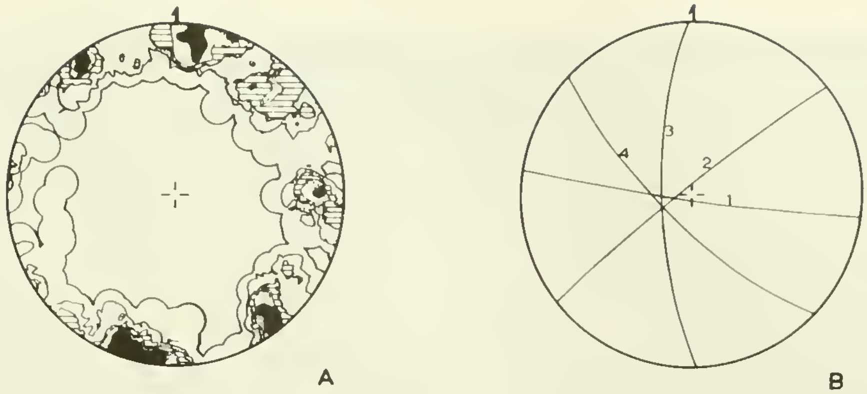


Figure 4. Lower hemisphere equal area projections of macroscopic fractures in the Monkton Quartzite at the Shelburne Access area. Diagram A shows 248 poles to fractures. Contour intervals are 0.4, 1.2, 2.0, 2.8, 3.6 respectively per 1 percent area. Diagram B shows planes corresponding to the 3.6 percent maxima of diagram A.

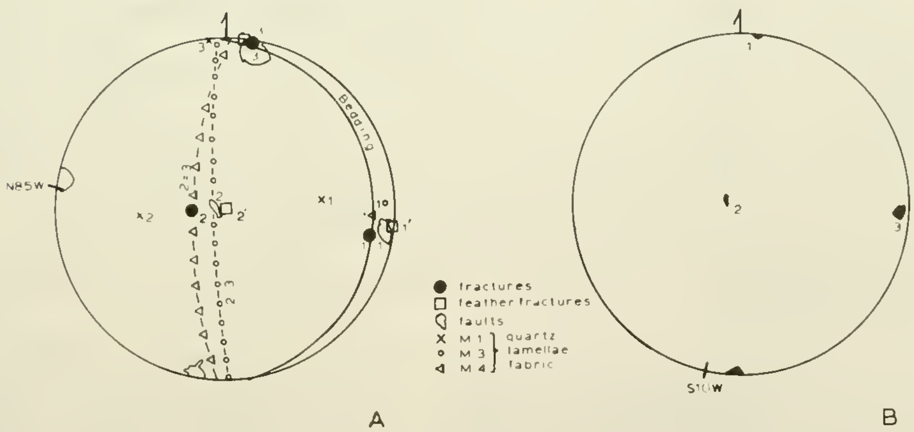


Figure 6. Synoptic diagram of the principal stress positions deduced for generation one and two wrench faults, megascopic fractures, feather fracture arrays and quartz deformation lamellae at Shelburne Access area.

The dihedral angle between complementary wrench faults (for example, e, p, i figure 3) ranges from 15 to 70 degrees with an average of 27 degrees which implies either a high value for the angle of internal friction, or fracturing under low effective confining pressures (less than 500 bars perhaps). These conditions were probably near the earth's surface since the pressure effect of a pore fluid was minimal after low grade metamorphism.

Microscopic planes of hematite inclusions, recrystallized quartz veins, unfilled fractures, quartz deformation lamellae, and undulose extinction in quartz pervade all thin sections. Prograde chlorite occurs between grains and along recrystallized quartz veins. Thus, the early sets of fractures were metamorphosed at the chlorite grade forming the recrystallized quartz veins and planes of inclusions. The unfilled fractures and quartz deformation lamellae were then superposed on and influenced by this annealed fabric.

Dynamic Analysis. Fractures, faults and quartz deformation provide information on the orientation and relative magnitudes of the principal stresses.

1) Fractures: Dynamic interpretation of fractures is based on geometry and the identification of shear or extension fractures. The intersection of the 4 fracture sets in diagram B (figure 4) defines the σ_2 position. The σ_1 direction is oriented 90 degrees to σ_2 in the plane that bisects the acute angle between shear fractures. The acute angles between fracture sets 1 and 3 and 2 and 4 are 80 and 83 degrees respectively. Set 1 fractures are in the extension position because they parallel the fractures in the feather arrays. Fracture sets 2 and 4 are, therefore, shear fractures and σ_1 plunges eastward at 10 degrees in the plane of fracture set 1. σ_3 trends northward and corresponds to the pole of fracture set 1. The deduced principal stresses are compatible with the stress configuration indicated by the wrench faults of generation 1.

2) Feather fractures: The feather arrays in diagram D (figure 5) with their respective senses of shear indicate that σ_1 is oriented east-west, σ_3 trends north-south and σ_2 is vertical. The principal stresses deduced for fractures and feather arrays agree in trend but differ by 10 degrees in dip since only the trend can be measured and not the dip of feather arrays.

3) Wrench faults of generation 1: Diagram A in figure 5 shows the deduced positions for the principal stresses calculated for faults labelled a through q on figure 3. These calculations were based on complementary faults (e,o,p,q) and faults with their associated feather fractures (c,d,g,h,i,j,k). The principal

stress positions are contoured in diagram C of figure 5 which shows that σ_1 plunges gently eastward, σ_3 trends northward, and σ_2 is nearly vertical. Diagram B (figure 5) shows that right lateral faults trend northeasterly whereas left lateral faults trend northwesterly.

4) Wrench faults of generation 2: The deduced positions for the principal stresses calculated from complementary faults (I, III, and IV, figure 3) and offset structures cut by fault II (figure 3) are shown in diagram E of figure 5. A comparison of diagrams C and E of figure 5 indicates that σ_2 for fault generations 1 and 2 are parallel. The positions of σ_1 and σ_3 however are interchanged. This orthogonal relationship implies that the second generation may have been caused by displacements associated with the first generation. As movement occurred during generation 1 the east-west stresses were reduced to a minimum value and the north-south stresses were simultaneously increased to the maximum compressive value. The stage was then set for generation 2 faulting.

5) Deformation lamellae in quartz: The lamellae are similar in character to those described by Carter and others (1964). The results were analyzed using methods described by Carter and Friedman (1965), and Scott and others (1965). The deduced orientation for σ_1, σ_2 , and σ_3 are shown in figure 6. In M3 and M4, σ_1 lies in the bedding and σ_2 appears to be equal to σ_3 in magnitude. In M1, σ_1 is inclined 40 degrees to the east, σ_2 dips 50 degrees to the west and σ_3 trends northward and is horizontal. Although these orientations are not parallel in all samples, they are consistent with the stress positions deduced from the fractures, feather fractures, and first generation faults. The stress configuration in M1 is triaxial with $\sigma_1 > \sigma_2 > \sigma_3$ whereas the configuration in samples M3 and M4 is biaxial with $\sigma_1 > \sigma_2 = \sigma_3$. These patterns indicate that the quartz lamellae formed during and slightly after the wrench faults of generation 1.

<u>Relationship to major faults</u>. Wrench faults are commonly associated with thrust faults. Both can be related to the same σ_1 direction and only require a switch of σ_2 and σ_3 in the stress configuration during thrusting to develop wrench faults. The small wrench faults in the Monkton Quartzite bear the same relationship to the Champlain thrust and as such, suggest that some cross faults shown on the Geologic Map of Vermont (Doll, and others, 1961) are indeed wrench faults.

One of these cross faults was mapped by Welby (1961) just to the northwest of the Shelburne Access Area (figure 1). It strikes northeasterly and displaces the upper and lower plates of the Champlain thrust in a right lateral direction. Because the deduced sense of σ_1 for first generation faults and associated structures dip eastward more gently than the Champlain thrust (approximately 10 degrees) the inferred horizontal displacement on the cross fault would result in the same apparent vertical movement as indicated on the map (figure 1). This movement geometry also characterizes the right lateral faults of generation 1 at Shelburne Access Area. The cross fault of the west side of Shelburne Bay and the first generation faults and their associated structures are considered to be coeval, and therefore, younger than the Champlain thrust since the major cross fault clearly cuts both the plates of the thrust.

Structural History. The structural history for this outcrop and nearby major faults is summarized in figure 7.

Stop 3. Location S9 - Route 7 a mile north of Shelburne (S9, figure 1) - As shown on figure 8 the Winooski Dolomite is downthrown against the Monkton Quartzite along a normal fault trending slightly north of east. Eight smaller normal faults of similar trend cut parts of the Winooski (one is in the Monkton). Three small faults trend east of north and may be related to a larger fault which offsets the fault between the Monkton and the Winooski. This fault was apparently excavated when Route 7 was constructed. Several of the northeasterly-trending faults have well defined gouge zones ranging in thickness from less than an inch to slightly more than a foot. The most obvious zone is along the fault between the two formations. Well developed slickensides indicate a dominant dip slip component for all displacements (figure 9). A second nearly horizontal slickenside is present on the fault directly north of station 19 in the Monkton Quartzite on the east side of Route 7.

Dynamic interpretation. The synoptic diagram in figure 9 shows the orientation of the faults and associated slickensides. These normal faults indicate a state of stress in which σ_3 would be horizontal and trend northwesterly, σ_2 would parallel the general strike of the faults, and σ_1 would plunge to the southwest almost vertically. Inasmuch as the north-northeasterly faults cut the east-northeasterly faults the principal axes of stress probably rotated counterclockwise during this second event.

Thirty-seven quartz deformation lamellae were measured in 150 grains from the west side of the outcrop in the Monkton Quartzite (station S9, figure 8). The deduced positions are very similar to the stress positions deduced for the deformation lamellae at Shelburne Access Area, and hence the two are considered coeval (compare figures 6 and 9). The lamellae at S9 are thought to be older than the normal faults since horizontal slickensides indicating strike slip displacement are not present. If these faults were genetically related to the deformation lamellae then all but one should show right lateral displacement. According to figure 1 the Monkton-Winooski contact should be offset in a

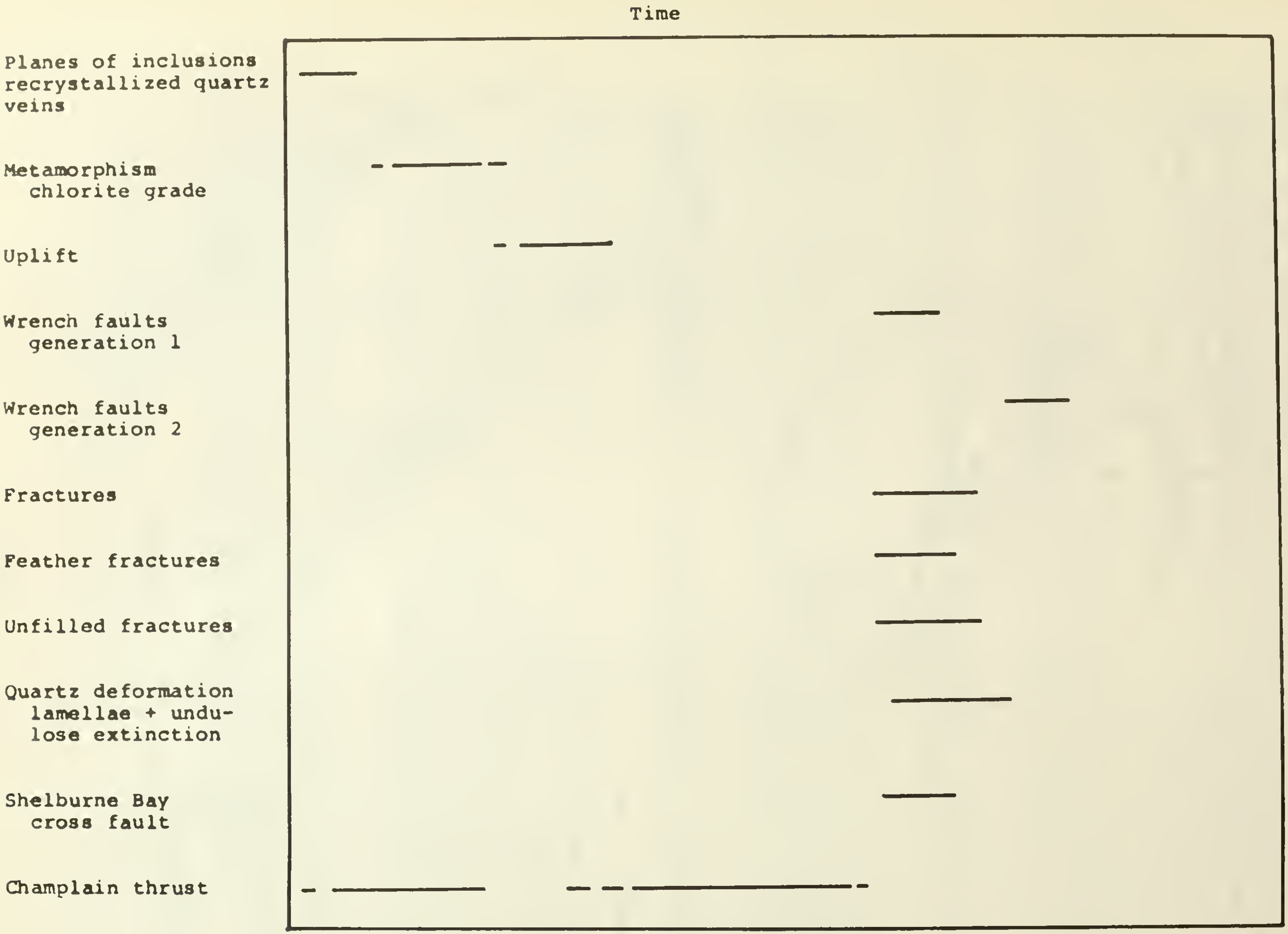


Figure 7. Chronology of structural events at Shelburne Access area Shelburne Bay, western Vermont.

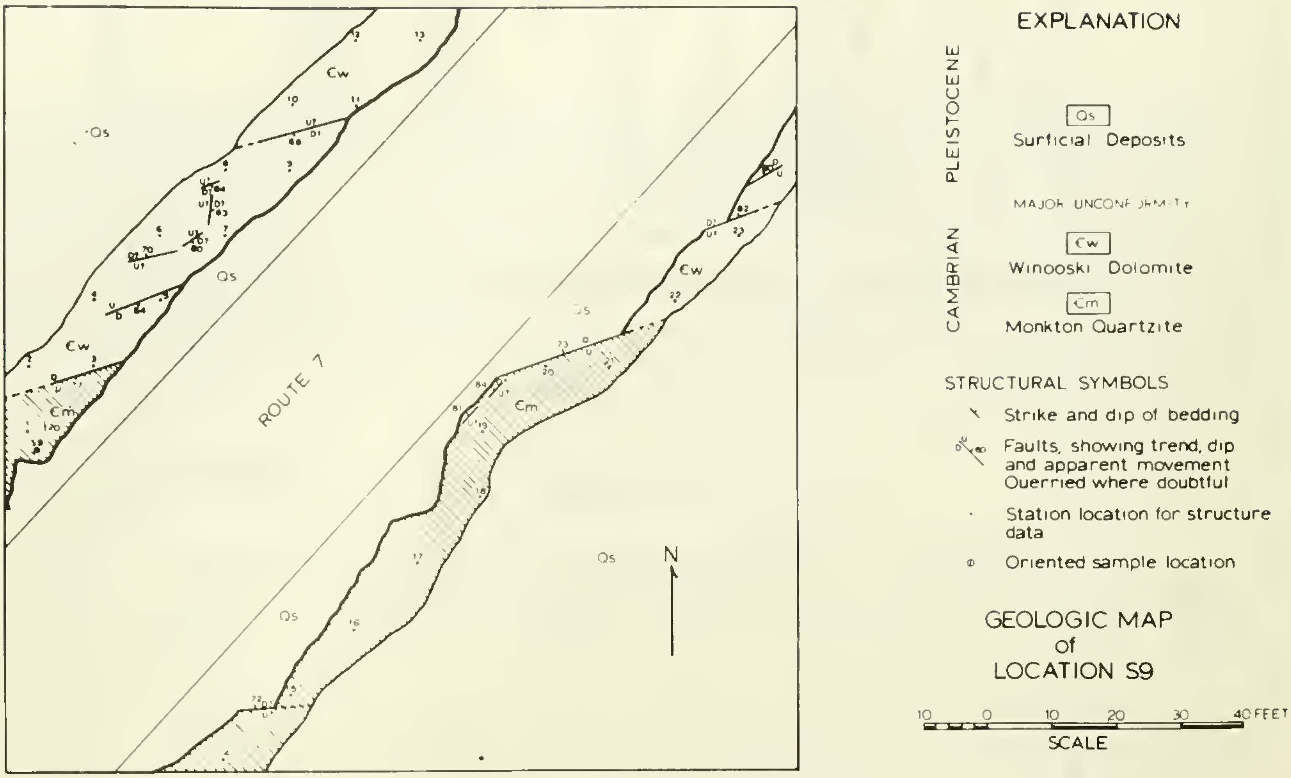


Figure 8. Geologic map of the normal faults at S9 just north of Shelburne, Vermont.

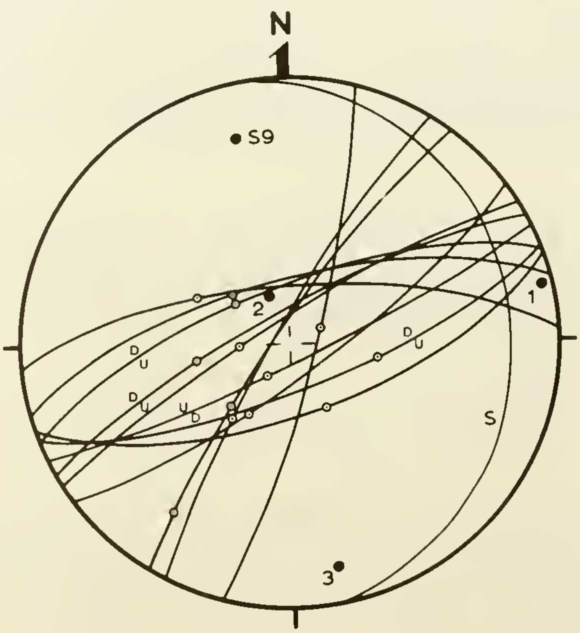


Figure 9. Lower hemisphere equal area projection showing the normal faults and associated slickensides at S9. The principal stress positions (1,2,3) deduced from quartz deformation lamellae in the Monkton Quartzite west of Route 7 are represented by solid dots. The generalized bedding at locality S9 (see figure 8) is shown by the great circle labelled S.

left lateral sense due to movement on the normal faults at this stop (figure 8).

In summary the structural chronology at S9 begins with the quartz lamellae which developed as a result of east-west compression associated with the generation 1 wrench faults at Shelburne Bay. Northwest-southeast extension then produced the normal faults which dominate the outcrop. This stress configuration is reflected in quartz lamellae from an outcrop 2 miles to the south of S9.

Stop 4. Pease Mountain near Charlotte (8, 10, figure 1) - The Champlain thrust and associated minor thrusts in its lower plate are well exposed on Pease Mountain (figure 10). The area was mapped by Cady (1945) and later remapped in greater detail by Welby (1961) and discovered outcrops of Bridport Dolomite on the western peak of the mountain. The area was mapped in still greater detail by students in field geology at the University of Vermont in 1969 and 1970. Our work has shown that the Bridport consists of two thrust slivers that have been subsequently deformed so that the bounding thrusts are systematically folded.

Stratigraphy: The abbreviated section at Pease Mountain includes part of the lower and upper members of the Monkton Quartzite which forms the upper plate of the Champlain thrust underlying the top and eastern slopes of the mountain. The Monkton is thrust on an overturned Middle Ordovician section that includes the upper part of the Glen Falls Formation, the Stony Point Formation, and the Iberville Shale. Slivers of Bridport Dolomite, a member of the Chipman Formation of Lower Ordovician age, are mapped along the western peak of the mountain. A few primary structures in the Bridport show that it is generally right side up.

Structure: Although thrusts dominate the structure on Pease Mountain, cleavage, folds and high angle faults are important aspects of the area.

Cleavage dips gently to the east in the shaly rocks of the Monkton Quartzite, the Bridport Dolomite, and the shales of middle Ordovician age. In the Monkton Quartzite the cleavage dips more steeply than the bedding which is a common relationship along the Champlain thrust (diagram A, figure 12).

Asymmetrical folds that deform the cleavage are restricted to the lower member of the Monkton Quartzite near the Champlain thrust. Six of these folds define a 65 degree separation arc with a deduced slip line that indicates movement of the upper plate in a N75W direction (diagram B, figure 12).

In the Iberville Formation on the east side of Route 7 (figure 10) two generations of folds are well developed and are

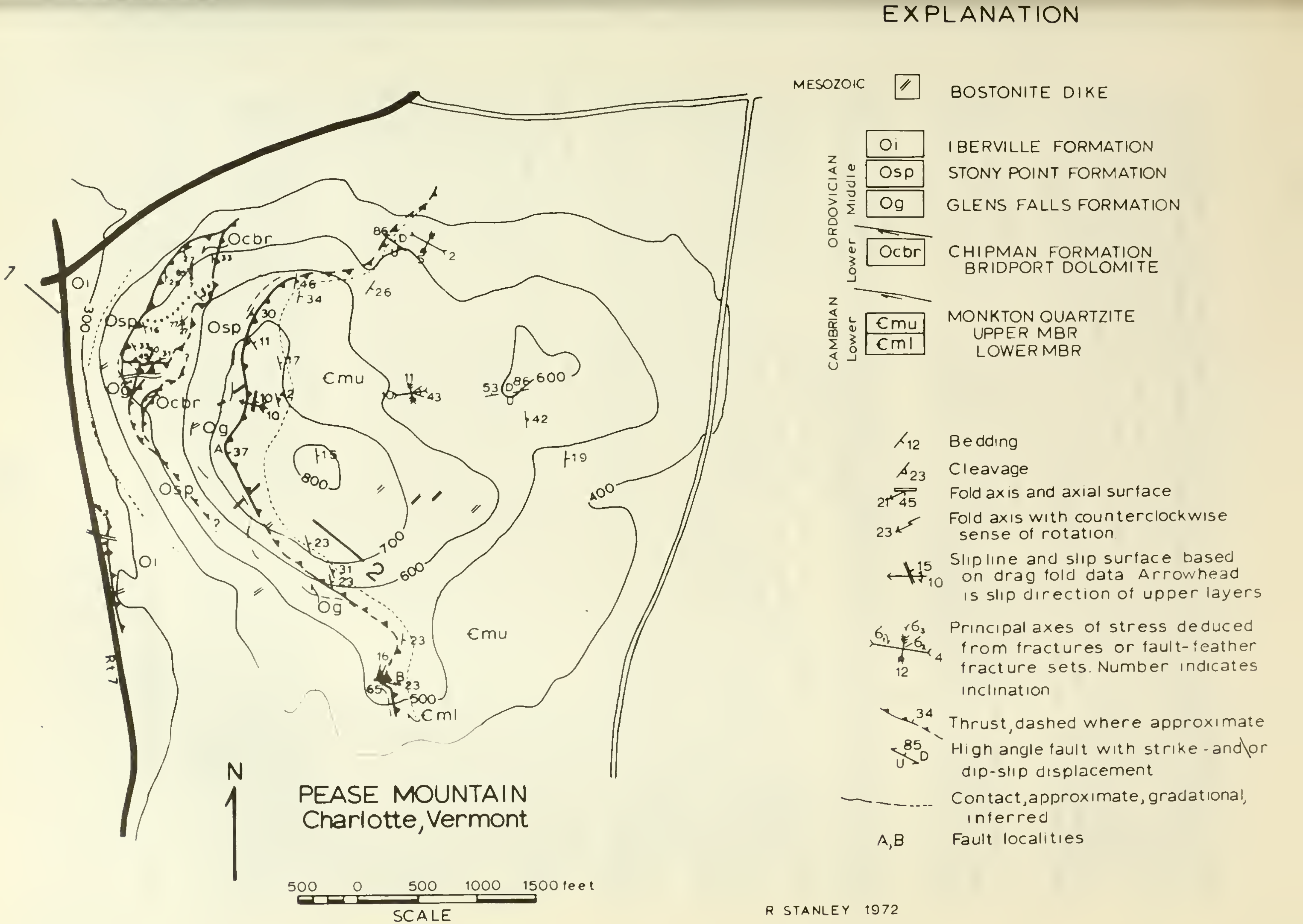


Figure 10. Geologic map of Pease Mountain just east of Charlotte, western Vermont.

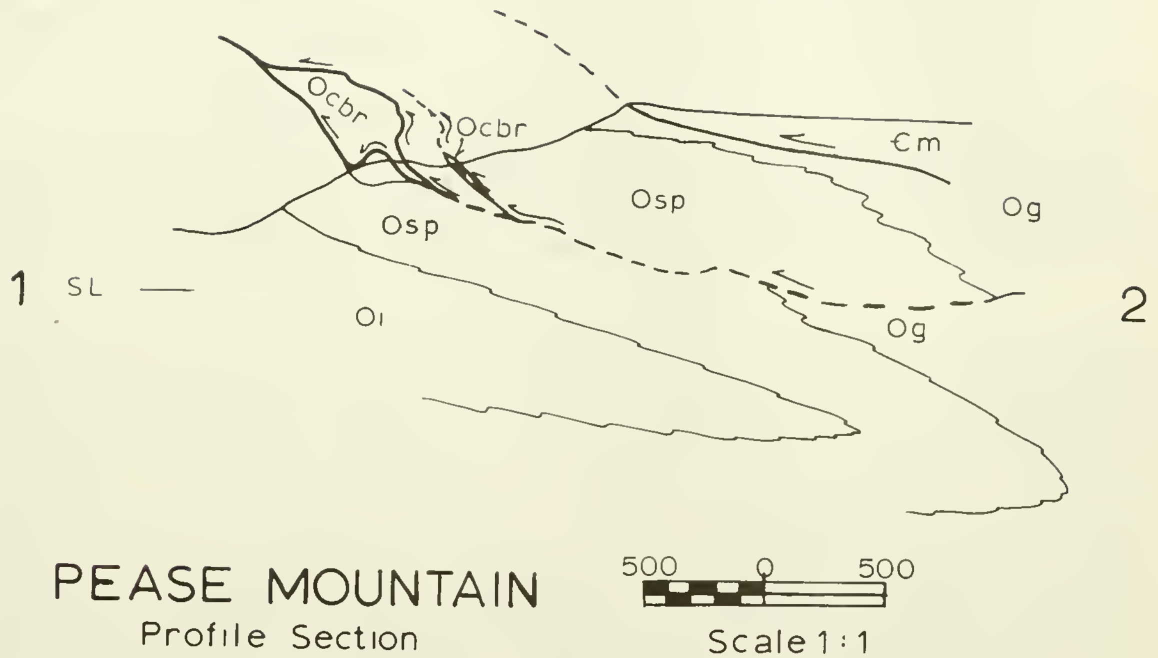


Figure 11. Modified profile section of Pease Mountain along a line of section labelled 1-2 on figure 10. No vertical or horizontal exaggeration. Displacement arrows only represent a component of the true direction of movement which is indicated by the slip direction deduced from the drag fold data shown in figure 10 and diagram B of figure 12.

Figure 12. Lower hemisphere equal area projections of selected structures on Pease Mountain. Diagram A shows poles to bedding and cleavage in the Monkton Quartzite. The intersection of bedding and cleavage and their anticlinal sense are represented by a solid dot with a concentric arrow. Diagram B shows the orientation of six drag folds which deform cleavage in the lower member of the Monkton Quartzite directly above the Champlain thrust north of point A on figure 11. Diagram C shows the orientation of generation one and two folds and the thrust fault in the Iberville Formation just east of Route 7 on figure 11. Diagrams D and E represent poles to bedding in the Bridport Dolomite. Dashed great circle represents the great circle that best approximates the distribution of poles. Diagram D contains 32 poles and diagram E contains 22 poles.

similar to the folds in the Stony Point Formation directly below the Champlain thrust at Lone Rock Point. At Pease Mountain the older folds are far more abundant than the younger folds which are only developed below a fairly continuous thrust at the south end of the outcrop. The orientation of each of these generations and the thrust is shown in diagram C of figure 12. The senses of rotation of the folds in both generations indicate movement to the northwest of upper beds over lower beds with a more northerly direction for the older set of folds.

The Champlain thrust is exposed at two localities (A and B, figure 10) where the lower member of the Monkton overlies highly deformed shaly limestones of the Glens Falls Formation. Silicified minor faults are common in the Monkton just above the thrust and suggest an earlier deformation perhaps associated with early movements on the Champlain thrust.

The Bridport slivers: The stratigraphic gap between the Bridport Dolomite and the surrounding Stony Point Formation leaves little doubt that the Bridport is bound by thrusts on the western part of Pease Mountain. Although the actual thrust surfaces are covered the systematic change in orientation of bedding in the dolostones and limestone of the Bridport near the thrust throughout the sliver and in the limestone and shale at the southern end below the thrust indicates that the bounding thrusts are systematically folded which is best seen around the southern end of the larger sliver. Poles to bedding in the Bridport define two diffuse great circles whose π pole (β point) plunges S36E at 25 degrees for the northern part and N40E at 25 degrees for the southern part (diagrams D and E, figure 12). Since there is no evidence supporting superposition of one of these folds on the other, it is concluded that the fold axis in the Bridport sliver curves through 80 degrees from the southern end of the sliver to the northern end.

The folded shape of the Bridport sliver indicates that it was systematically deformed after it was emplaced. It is suggested that the sliver was formed during the early stages of movement on the Champlain thrust and then was folded during subsequent movement on the thrust.

<u>Stop 5. Mount Philo near Ferrisburg</u> (7, figure 1) - Mount Philo is located along the Champlain thrust on the north limb of the Monkton culmination (Cady, 1945; Doll, and others, 1961) just south of Charlotte, Vermont (figure 1). Although the Champlain thrust is not exposed in this area, numerous east-west faults, folds, and several thrusts are well developed in the Monkton Quartzite which forms the upper plate of the thrust. Five oriented specimens of quartz deformation lamellae were analyzed by Sarkisian (1970) from three separate localities (S11, S2, SF) located in figure 13.

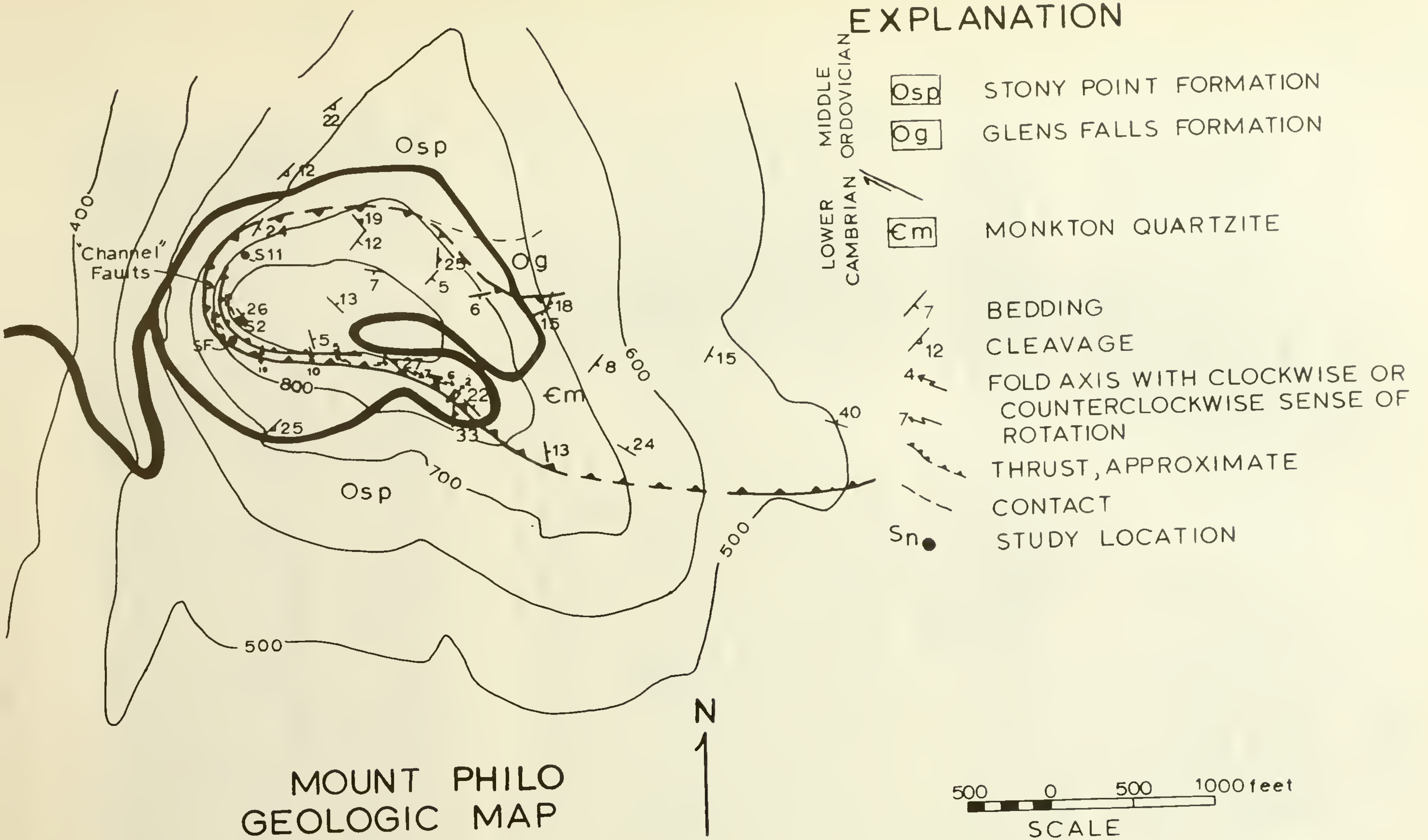


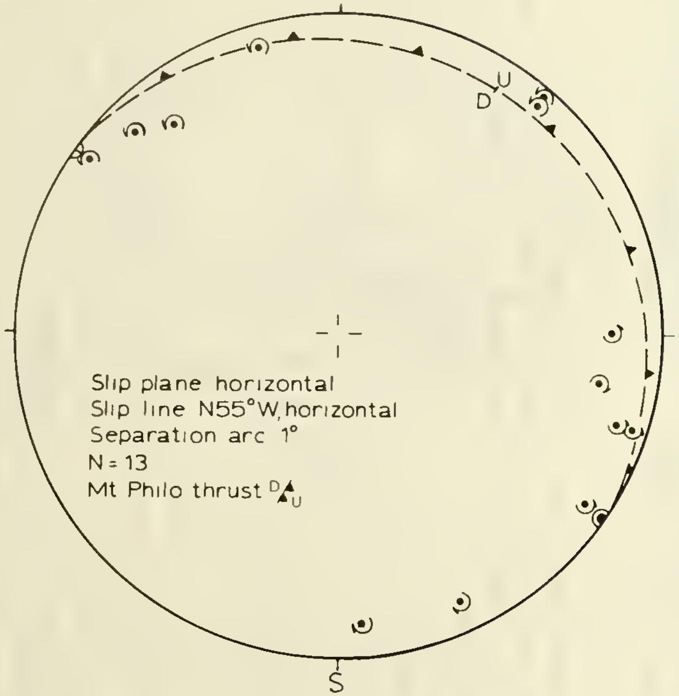
Figure 13. Geologic map of Mount Philo, North Ferrisburg, Vermont, near the southern boundary of the map in figure 1.

Megascopic Structures: Bedding, slaty cleavage, asymmetrical concentric folds, fractures, and faults are well displayed along the southern and western cliff of Mount Philo (figure 13). Crossbedding and ripple marks indicate that the Monkton Quartzite is right-side-up throughout the area. Cleavage is well developed in the thin shaly beds of the Monkton and dips eastward more steeply than the bedding where it is not folded. Large asymmetrical folds in the southern and western cliffs deform the cleavage and plunge at very gentle angles in various directions. The sense of rotation of 12 of these folds on the upper plate of the Mount Philo thrust locate a horizontal slip line that trends N55W and indicates movement of the upper beds northwestward (figure 14). Four fairly large folds are also present directly below the Mount Philo thrust and indicate a slip direction slightly south of east. On the western cliff of Mount Philo below the thrust high angle faults commonly dip northward and southward. Although movement on the surfaces are commonly normal, movement in the reverse sense was noted. In two key areas north-dipping faults high on the cliff flatten at a lower elevation and pass into high angle south-dipping faults further on and up the cliff. These fault surfaces, therefore, form U-shaped channels and show either normal or reverse movements across the fault surface. The Mount Philo thrust cut these high angle faults and hence is younger in age.

The Mount Philo thrust crops out for at least 700 feet along the southern and western cliffs of Mount Philo (figure 13). It is a sharp, undeformed surface that dips gently eastward and truncates the asymmetrical folds within the lower portion of the Monkton Quartzite.

Several fracture sets are well developed on Mount Philo. They cut the folds, high angle faults, and the Mount Philo thrust. At locality S2 (figure 15) Sarkisian measured 163 fractures across one of the asymmetrical folds. The resulting fabric (figure 15) shows three statistical fracture sets which correspond to the maxima in the contoured equal area diagram. This fabric is undeformed by the fold since separate plots on opposite limbs of the fold are similar to the diagram in figure 15. The plane of symmetry bisecting fractures 1 and 3 is perpendicular to fracture 2 and is approximately parallel to the slip line determined from the asymmetrical folds.

Microscopic Structures: Five oriented samples of Monkton Quartzite were collected from three separate localities on the western side of Mount Philo (S11, S2, SF, figure 13). One sample (S11) was collected below one of the east-west faults, another (S2) comes from the locality where 163 fractures of figure 15 were analyzed and the remaining three (S10, S12, S13 at locality SF) were collected from the limbs and hinges of an asymmetrical



7

Figure 14. Lower hemisphere equal area projection of 13 drag folds that deform cleavage in the lower member of the Monkton Quartzite just above the Champlain thrust on Mount Philo. The orientation of fold axes and their respective sense of rotation are shown by solid dots and concentric arrows. The number 7 refers to diagram 7 in figure 2.

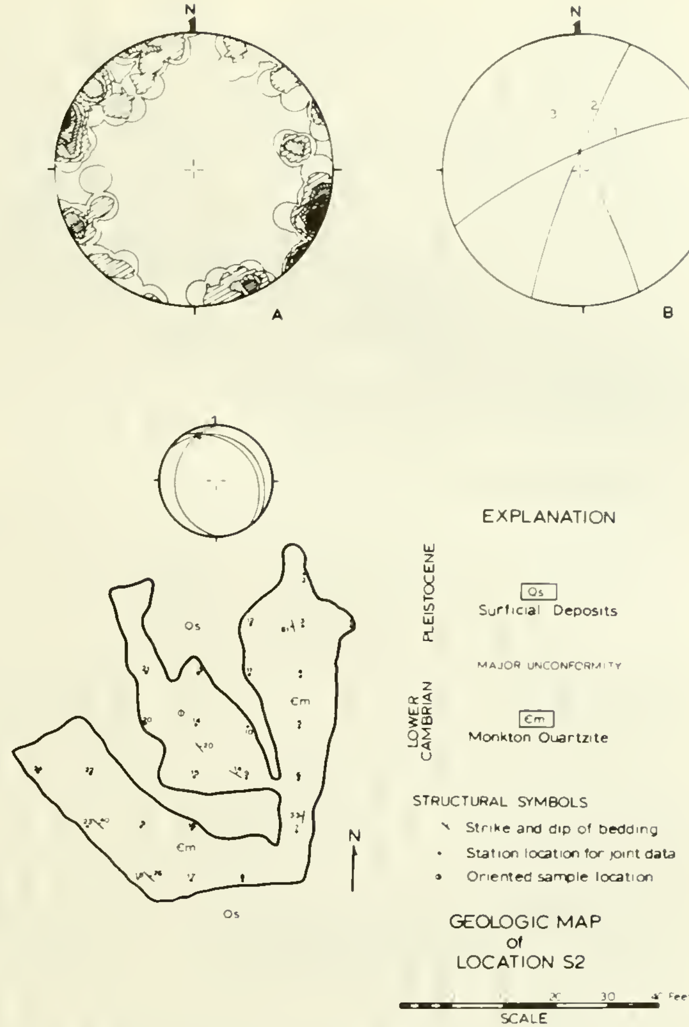


Figure 15. Geologic map and lower hemisphere equal area projections of fractures in a syncline in the upper member of the Monkton Quartzite at locality S2 in figure 13. The orientation of the synclinal fold axes is shown in the small equal area projection.

drag fold. Oriented samples were, therefore, selected from all of the megascopic structures except the Mount Philo thrust.

For each sample 75 (50 for S11) quartz grains were studied from each of three mutually perpendicular thin sections. The quartz lamellae are similar to those described for the Shelburne Access Area and locality S9.

Synoptic diagram A in figure 16 shows the principal stress positions deduced from deformation lamellae on Mount Philo. For all the samples the poles to lamellae define small circle girdles with radii that range from 55 to 64 degrees. This pattern corresponds to a cone of lamellae oriented less than 45 degrees to the central cone axis, σ_1 . The principal stress directions deduced from the five specimens are remarkably constant in orientation and configuration. The σ_1 directions fall in a narrow 30 degree arc oriented north of west (average direction, N75W). The σ_2 and σ_3 directions are approximately equal in value and hence, define the plane perpendicular to σ_1 . The trend of σ_1 is approximately 20 degrees counterclockwise to the trend of the slip direction (N55W) deduced from the asymmetrical drag folds (figure 16).

Since the quartz fabric axes have not been rotated by the folds at SF, the quartz deformation lamellae were superposed on this fold after it had fully developed. East-west fractures in sample S11 collected near the high-angle faults offset the deformation lamellae and suggest that the lamellae are older than the Mount Philo thrust and its associated channel faults.

Relationship of Quartz Deformation Lamellae to the Megascopic Structures: The quartz deformation lamellae on Mount Philo have resulted from a nearly horizontal maximum compressive stress generally oriented in N75W direction. The values of σ_2 and σ_3 were approximately equal during lamellae development. The quartz lamellae reflect a stress configuration that is compatible with the north-trending Champlain thrust. It is also similar to the stress configurations deduced from samples M3 and M4 at Shelburne Access Area which are in turn correlated with the first generation wrench faults and the Shelburne Bay cross fault. Thus the lamellae at Mount Philo probably developed with the younger wrench faults which cut the Champlain thrust.

At Mount Philo the deformation lamellae are younger than the asymmetrical drag folds since the lamellae fabric axes remain constant in orientation across the fold. In sample S11 small shear fractures offset quartz deformation lamellae. These fractures parallel the east-west channel fault and hence are considered younger than the deformation lamellae. This temporal relationship would further support the conclusion that the high

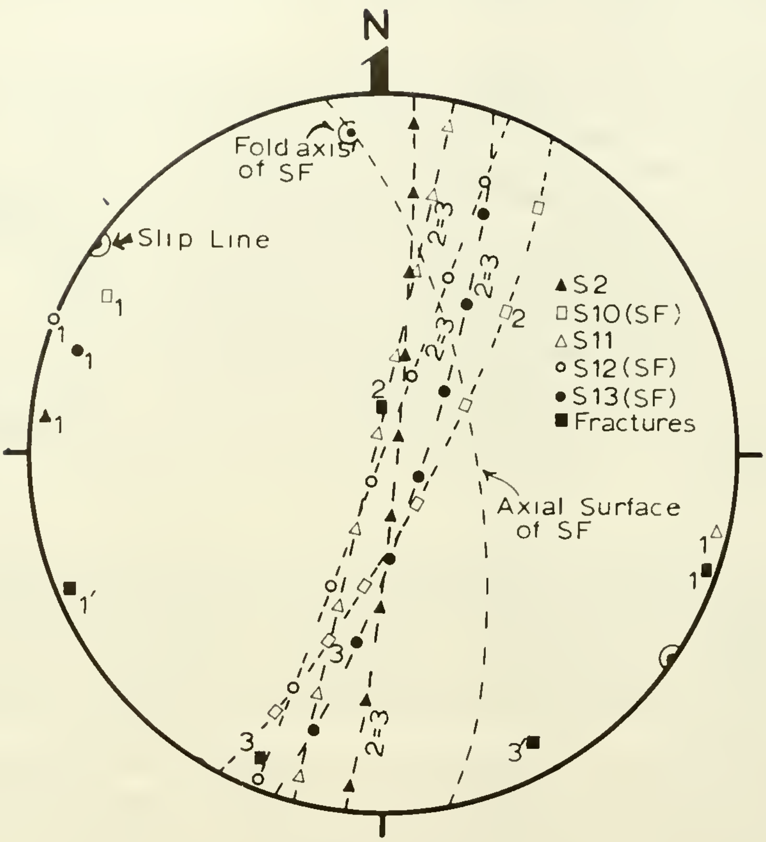


Figure 16. Synoptic diagram of principal stress positions deduced from quartz deformation lamellae (S2, S10, S11, S12, S13) and fractures. The numbers 1, 2, 3 correspond to the principal compressive stresses with 1 representing the direction of maximum compressive stress. Alternative principal stress positions for fractures are represented by primed and unprimed numbers. The slip line deduced from the drag folds in figure 14 is also included in the projection.

angle faults and the Mount Philo thrust are younger than the asymmetrical folds.

In summary the structural sequence at Mount Philo begins with the development of cleavage and is followed by the folding of the Monkton into west-facing folds possibly as a result of movement of the Champlain thrust to the northwest. Subsequent deformation produced the quartz deformation lamellae which are thought to be coeval with the first generation of wrench faults at Shelburne Bay. Continued west northwest - east southeast compression resulted in the channel faults and the Mount Philo thrust. Fracturing subsequently developed and may reflect a change in orientation of the principal stresses although the fracture can be related to the previous stress configuration.

Summary of structural chronology. The temporal relationship among the structures at the five localities along the Champlain thrust are summarized in figure 17. Reasons supporting their age assignments are discussed at each locality and will not be repeated here. The following comments will be restricted to the relationship of these structures to such major structures or events as the Champlain thrust, Hinesburg synclinorium, Hinesburg thrust, and the various orogenies known in the Appalachians.

As shown in figure 17. and emphasized at different localities, the Champlain thrust is thought to have undergone a multiple history beginning with initial emplacement during the Taconic orogeny and ending with renewed movement in a subsequent orogeny, probably the Acadian of Middle Devonian age. Since the youngest rocks below the Champlain thrust are Middle Ordovician in age it seems unjustified to restrict its development to the Acadian orogeny as suggested by Cady (1969, p. 75). Subsequent movement apparently did occur during the Acadian or possibly the Allegheny orogeny since the chlorite-grade rocks of the upper plate now rest on essentially unmetamorphosed rocks of the lower plate. Radiometric work in the northern Taconics (Harper, 1968), along the Sutton-Green Mountain anticlinorium (Cady, 1969, p.104), and in Quebec (Rickard, 1965) indicate that recrystallization in northwestern Vermont was older than 400 m.y. and hence of Taconic age. Petrologic work by Albee (1968) lends further support to this conclusion. Thus renewed movement on the Champlain thrust is restricted to post Taconic activity.

Based on the foregoing conclusions the second generation of younger folds in the lower plate, the asymmetrical folds which deform cleavage in the upper plate, and the deformation of the Bridport sliver on Pease Mountain are contemporaneous with renewed activity on the Champlain thrust. The older generation of folds in the lower plate, the original emplacement of the Bridport sliver, the formation of cleavage in the Monkton, and low grade metamorphism may well be associated with, or just after,

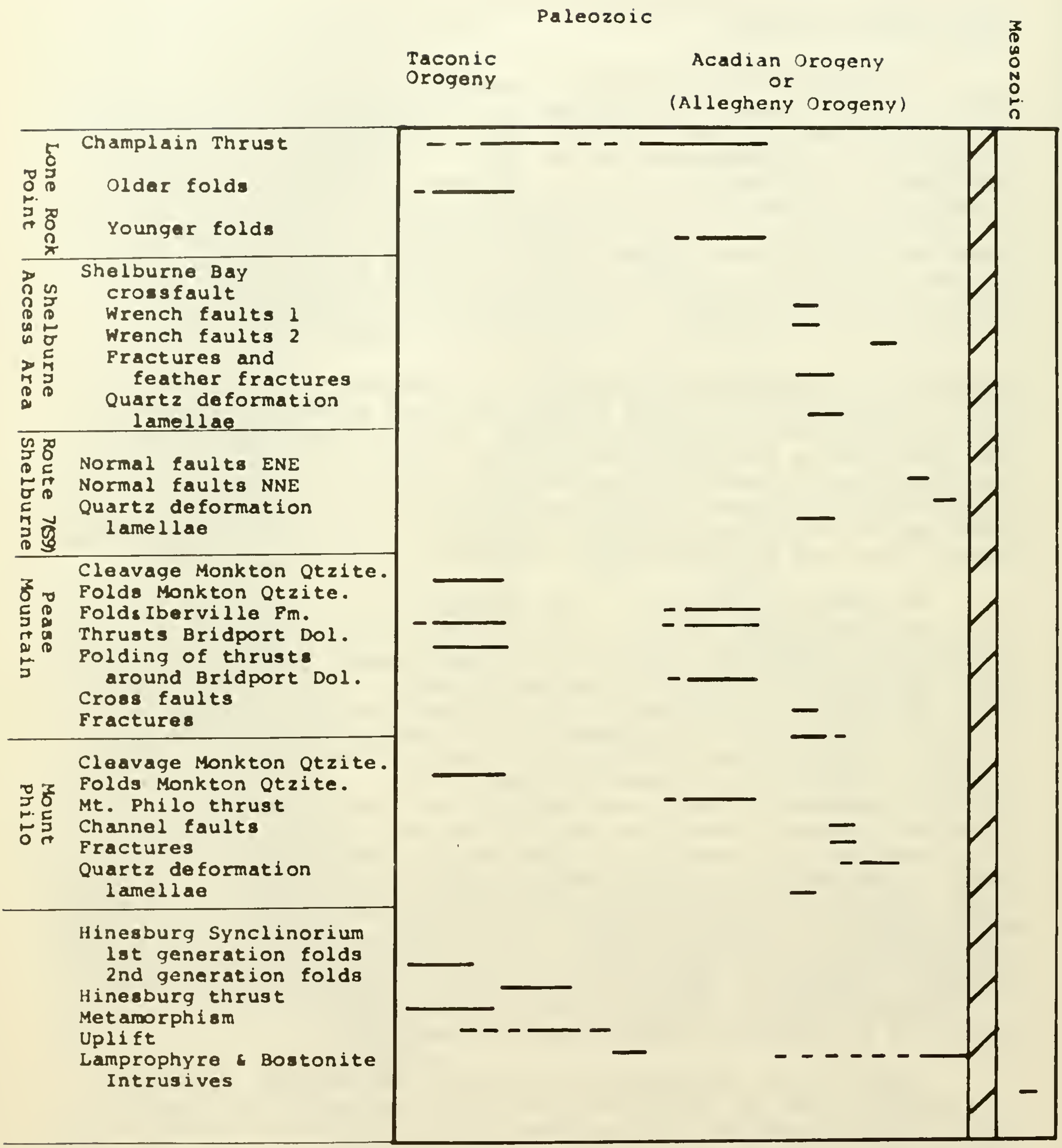


Figure 17. Chronology of selected structural events in the Hinesburg synclinorium and along the Champlain thrust in the central part of western Vermont.

early development of the thrust. The two generations of wrench faults, the normal faults, and the quartz deformation lamellae are younger than the Champlain thrust and are probably Acadian in age although an Allegheny age is certainly possible.

The structures in the Hinesburg synclinorium and along the Hinesburg thrust can be placed in this chronological sequence although our work is still in progress (Gillespie and others, this guidebook). The rocks in the southern part of the synclinorium have been involved in at least two, and in some places, three generations of folds. The axes of the first generation of tight folds plunges gently southeastward with a well-developed closely spaced cleavage. These folds are, in turn, folded into rather open folds with north plunging axes and steep eastward dipping axial surfaces. The map pattern in the southern part of the Hinesburg synclinorium is actually a product of both of these fold events (figure 1, Doll and others, 1961). Analysis of quartz lamellae in the Monkton at Mount Philo, S8 and farther east by Sarkisian and Marcotte indicate the lamellae are younger than the second generation of folds since the deduced stress positions are not deflected by the major folds. Thus the formation of the Hinesburg synclinorium predates the wrench faults and associated quartz deformation lamellae. Since there has been recrystallization of micaceous material in the axial surfaces of the first and possibly the second generation of folds, these events are probably Taconic.

The Hinesburg thrust is clearly folded by the second generation of folds in the synclinorium and therefore is also considered to be Taconic in age.

The lamprophyre and bostonite dikes that cut the Champlain thrust, the Hinesburg synclinorium and the upper plate of the Hinesburg thrust are the youngest structures recognized in west-central Vermont. These intrusives are Mesozoic in age since K-Ar measurements on biotite from the syenite stock at Barber Hill in Charlotte indicate an age of 111 + or - 2 m.y. (Armstrong and Stump, 1971). Similar work on a lamprophyre from Grand Isle yield an age of 136 + or - 7 m.y. (Zartman and others, 1967).

REFERENCES CITED

Albee, A. L., 1968, Metamorphic zones in northern Vermont, p. 329-341, in: Zen, E-an, White, W. S., Hadley, J. J., and Thompson, J. B., Jr., Editors, Studies of Appalachian Geology, Northern and Maritime: New York Interscience Publishers, John Wiley and Sons, Inc., 475 p.

Armstrong, R. L., and Stump, Edward, 1971, Additional K-Ar dates, White Mountain magma series, New England: Am. Jour. Sci., v. 270, p. 331-333.

Cady, W. M., 1945, Stratigraphy and structure of west-central Vermont: Geol. Soc. America Bull., v. 56, p. 515-587.

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

Clark, T. H., 1934, Structure and stratigraphy of southern Quebec: Geol. Soc. America Bull., v. 45, p. 1-20.

Doll, C. G., Cady, W. M., Thompson, J. B., Jr., and Billings, M. P., Compilers and Editors, 1961, Centennial Geologic Map of Vermont: Montpelier, Vermont, Vermont Geol. Survey, scale 1:250,000.

Hansen, Edward, 1967, Methods of deducing slip-line orientations from the geometry of folds, in: Carnegie Inst. Wash., Yearbook 65, p. 387-405.

_____, 1971, Strain facies: Springer-Verlag, New York, Inc., 220 p.

_____, Scott, W. H., and Stanley, R. S., 1967, Reconnaissance of slip-line orientations in parts of three mountain chains, in: Carnegie Inst. Wash., Yearbook 65, p. 406-410.

Harper, C. T., 1968, Isotopic ages from the Appalachians and their tectonic significance: Canadian Jour. of Earth Sci., v. 5, p. 50-59.

Hawley, David, 1957, Ordovician shales and submarine slide breccias of northern Champlain Valley in Vermont: Geol. Soc. America Bull., v. 68, p. 155-194.

Hitchcock, Edward, Hitchcock, Edward, Jr., Hager, A. D., and Hitchcock, Charles, 1861, Report on the geology of Vermont, vol. 1, 558 p.; vol. 2, p. 559-988, Claremont, Vermont.

Howard, K. A., 1968, Flow direction in triclinic folded rocks: Am. Jour. Sci., v. 266, p. 758-765.

Keith, Arthur, 1923, Outlines of Appalachian structure: Geol. Soc. America Bull., v. 34, p. 309-380.

_____, 1932, Stratigraphy and structure of northwestern Vermont: Washington Acad. Sci. Jour., v. 22, p. 357-379, 393-406.

Rickard, M. J., 1965, Taconic orogeny in the Western Appalachians: Experimental application of microtextural studies to isotope dating: Geol. Soc. America Bull., v. 76, p. 523-536.

Rodgers, John, 1968, The eastern edge of the North American continent during the Cambrian and Early Ordovician, p. 141-149, in: Zen, E-an, et al., 1968, Editors, Studies of Appalachian geology, Northern and Maritime: New York Interscience Publishers, John Wiley and Sons, Inc., 475 p.

Sarkisian, A. C., 1970, A petrofabric analysis of the Monkton Quartzite in west-central Vermont: M. S. thesis, University of Vermont, Burlington, Vermont, 120 p.

Scott, W. H., 1969, Experiments in flow deformation, in: Carnegie Inst. Wash., Yearbook 67, p. 251-254.

Stanley, R. S., 1969, Bedrock geology of the southern portion of the Hinesburg synclinorium, in: Guidebook to field excursions of the New York State Geological Association, 41st Annual meeting, Plattsburg, New York, p. 37-64.

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

Zartman, R. E., Brock, M. R., Heyl, A. V., and Thomas, H. H., 1967, K-Ar and Rb-Sr ages of some alkalic intrusive rocks from central and eastern United States: Am. Jour. Sci., v. 265, p. 848-870.

Zen, E-an, 1967, Time and space relationships of the Taconic allochthon and autochthon: Geol. Soc. America Special Paper 97, 107 p.

_____, 1968, Nature of the Ordovician orogeny in the Taconic area, p. 129-139, in: Zen, E-an, et al., 1968, Editors, Studies of Appalachian geology, Northern and Maritime: New York Interscience Publishers, John Wiley and Sons, Inc., 475 p.