TRIP B-2

STRUCTURAL GEOLOGY OF THE TACONIC UNCONFORMITY

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INTRODUCTION

The Hudson Valley is one of the classical areas of North American geology. One of its most prominent geological features is the Taconic unconformity separating the Ordovician and Cambrian sediments from the overlying Silurian and Devonian strata. The Taconic unconformity records the earlier of two (or possibly three) Paleozoic orogenies in the Hudson Valley. The Taconic unconformity has been known since the first half of the nineteenth century and its significance for stratigraphy and the geologic history of eastern North America has been discussed by many authors (Davis,1883a, Schuchert and Longwell, 1932, Rodgers, 1971). It is a favorite subject of textbooks of historical geology which often illustrate and discuss the relationships displayed at the unconformity (for example Dunbar and Waage, 1969, Figs. 9-8 and 9-9, Kay and Colbert, 1965, p. 174, 214).

By contrast, the structural significance of the Taconic unconformity has received little attention. The entire subject of deformation of unconformities has been neglected in comparison to its structural importance. The numerous existing studies of multiple deformation deal mainly with superimposed folding deep in the basement complex and very few of them take into account what happens at or near unconformities. Textbooks of structural geology often do not even mention the subject. The field trip area offers excellent opportunities to study the effects of folding on an unconformity and the underlying as well as the overlying rocks. The plan of the field trip is to start by inspecting the formations involved in places where the structure is simple and then to proceed to outcrops at which folding of the unconformity has complicated the structures.

The present field trip is an outgrowth of class field trips I have conducted for my structural geology class. It is based on study of easily accessible outcrops that are particularly instructive by virtue of the major and minor structures they exhibit. Study of these outcrops has been carried only to the point of developing a conceptual scheme to explain the structures visible. Thus identification of formations is in some cases still tentative and I have made no attempt to record attitudes on an areal basis. Thus much work remains to be done and the field trip area should be a highly rewarding subject for one or more studies of structural details. It is difficult to find two unconformities in which the geometry of the older structures and the mechanical properties of the rocks are exactly alike at the time of the second deformation and the general principles of multiple deformation apply here to a unique array of structural details

UNDERLYING ROCKS

The Taconic unconformity cuts across a number of Ordovician and Cambrian formations. In the field trip area, however, we encounter mainly or only one of the underlying stratigraphic units: the Austin Glen Graywacke

Member of the Normanskill Shale (Berry, 1962). The Austin Glen Member consists of interbedded graywacke and dark shale. The thickness and the spacing of the Graywacke beds vary greatly through the section and intervals dominated by thick, closely spaced graywacke beds follow predominantly shaly intervals containing few and thin layers of graywacke. The mechanical properties of the strata vary accordingly and give rise to variations in structural detail.

We can infer that at the onset of the Taconic orogeny sediments of the Austin Glen Graywacke Member must still have been in a hydroplastic condition. The hinges of many folds in the Austin Glen Graywacke show signs of plastic deformation and the shale layers show signs of much thickening by flexural flow folding (Fig. 1). Development of slaty cleavage went hand in hand with lithification wherever the Taconic orogeny produced strong deformation. In the next orogeny (most probably the Acadian orogeny but conceivable the Alleghanian orogeny) the older strata had to react to the orogenic force in different ways as they had already acquired considerable strength.

Many authors (Davis, 1883b, Dale, 1899, Ruedemann, 1942, Craddock, 1957, Berry, 1962) have noted the intense faulting and shearing in the Austin Glen Graywacke and related stratigraphic units. A few have correctly attributed the various minor structures they observed to a second period of deformation in rocks that already were folded (Dale, 1899, Ruedemann, 1942). None, however, have gone into any detail on the subject.

OVERLYING ROCKS

The Taconic unconformity is overlain by limestones and dolomites of the Rondout Formation which in turn are followed by further limestone units of the Helderberg Group. These strata must have been fairly well lithified by the time of the second (Acadian (?)) orogeny.

TACONIC FOLDS

The folding of the Austin Glen Graywacke took place during the Taconic orogeny. Later deformation in the Acadian (?) orogeny has affected these folds very little, if at all, as the rocks underlying the unconformity responded to the tectonic stress by fracturing.

Typically these older folds are small-scale features, often measuring of the order of tens of feet (Fig. 1). They are often quite tight and chevron folds are common.

ACADIAN (?) FOLDS

The folds of the second orogeny, tentatively identified as the Acadian orogeny, are much broader. Typically their diameter exceeds that of the Taconic folds we see in the Austin Glen Graywacke by an order of magnitude or more. Broad, open folds are typical but locally one can encounter sharply bent and steep limbs and even overturning.

The Acadian folds are typical flexural slip folds as can be seen from the geometry of the folds and the slickensides on bedding planes in many places in the Hudson Valley. This suggests low ductility of the rocks during the deformation (Donath and Parker, 1964). I have not seen any signs of flow folds in the Silurian and Devonian limestones of the area.

Fig. 1 Contrasting styles of deformation in the Austin Glen Graywacke: Chevron fold at top and right consists mainly of graywacke and has been moved as a single unit. It is in fault contact with predominantly shaly unit at bottom and left. Bedding has been entirely disrupted by closely spaced shear fractures in the shaly unit. Note that all planar structures in shaly unit are truncated by fault that follows bedding at bottom of lowest graywacke layer. Stop 7

The rocks above the unconformity differ sufficiently from those below to give rise to disharmonic folds. It is conceivable that the difference in style between the Taconic and Acadian folds could be only an expression of disharmonic folding. To the southwest of Kingston disharmonic folding may have accentuated the unconformity or even locally produced the appearance of an angular unconformity where there is none. In the Kingston area and along the Hudson River this can be ruled out because the minor structures show that the folds in the Austin Glen Graywacke already existed before the Acadian orogeny took place.

DEFORMATION OF THE UNCONFORMITY AND ITS EFFECTS ON THE UNDERLYING STRATA

Our first clue to an understanding of the structures seen on this field trip are the folds in the Silurian and Devonian limestones above the unconformity. The geometry of these folds records the gross amount of deformation that has actually affected the rocks above and below the unconformity. The folds of the plane of unconformity are filled out by the underlying rocks. The folds in the younger rocks could form only if and when the older rocks underwent the same amount of shortening. Overlying strata can be deformed independently from the underlying basement only in the case of decollement. This possibility can be ruled out because of the character of the contact and the properties of the Silurian limestones directly at the unconformity.

The second clue lies in the conditions of deformation during the Acadian (?) orogeny. The Acadian (?) folds attest to deformation at a relatively shallow depth at which the rocks must have been essentially brittle above the unconformity and to some depth below it. This is shown by the flexural slip folding of the formations above the unconformity, as this mechanism involves a minimum of plastic deformation during folding. The Austin Glen Graywacke underneath the unconformity could not undergo further flexural slip folding. The bedding in the Austin Glen Graywacke was already too highly inclined to the tectonic force to permit the process of folding to operate within the layers. Furthermore, the Taconic folds had reached the limit of tightness to which folding could proceed and their dimensions did not fit the new folds that were forming in the overlying strata.

Bedding planes along which slip could occur were truncated by the unconformity. If flexural slip folding took place, slip along the bedding planes would offset the plane of unconformity. The same result would be produced by slippage along fracture planes: faulting. Where the angle between the unconformity and the bedding in the underlying strata is small to moderate, flexural slip folding still could take place. Where the bedding planes that actually permit slip are widely spaced, slip along these bedding planes produces a fault that follows bedding below the unconformity but is propagated across the bedding above the unconformity as was demonstrated by H. Cloos in 1917. The Taconic unconformity differs from the one studied by Cloos along the margins of the Harz Mountains in Germany by much tighter folds underneath the unconformity, consequently folding is at most a minor mechanism in the deformation of the underlying rocks. Limited analogies also exist between the folding of the Taconic unconformity and folding of the unconformity between basement complex and sedimentary cover in the Rocky Mountains during the Laramide orogeny (LeMasurier, 1970, Hudson, 1955).

The folds of the Silurian and Devonian limestones act as a measure of the amount of deformation the rocks underneath the unconformity actually

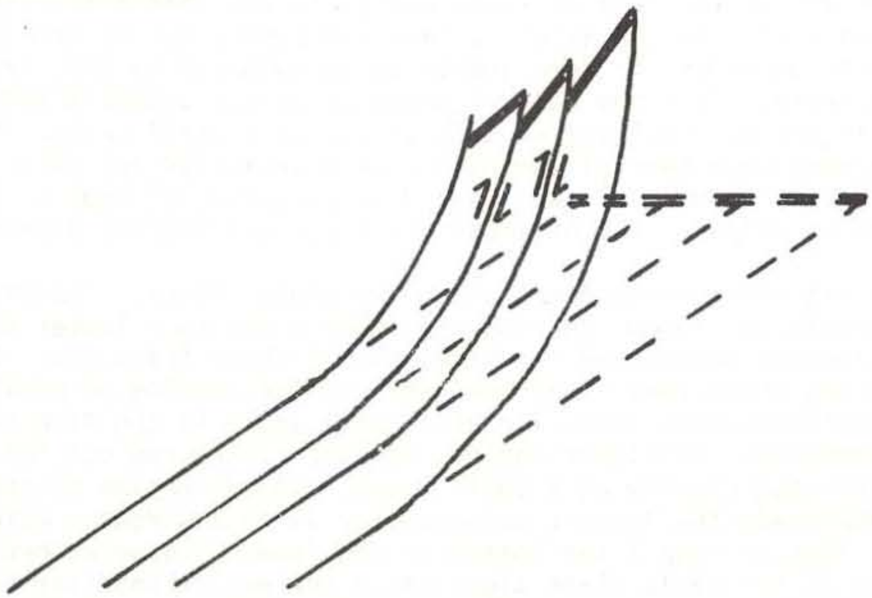

Fig. 2. Offsets of unconformity produced by folding of underlying strata. (schematic diagram modified after Cloos, 1917)

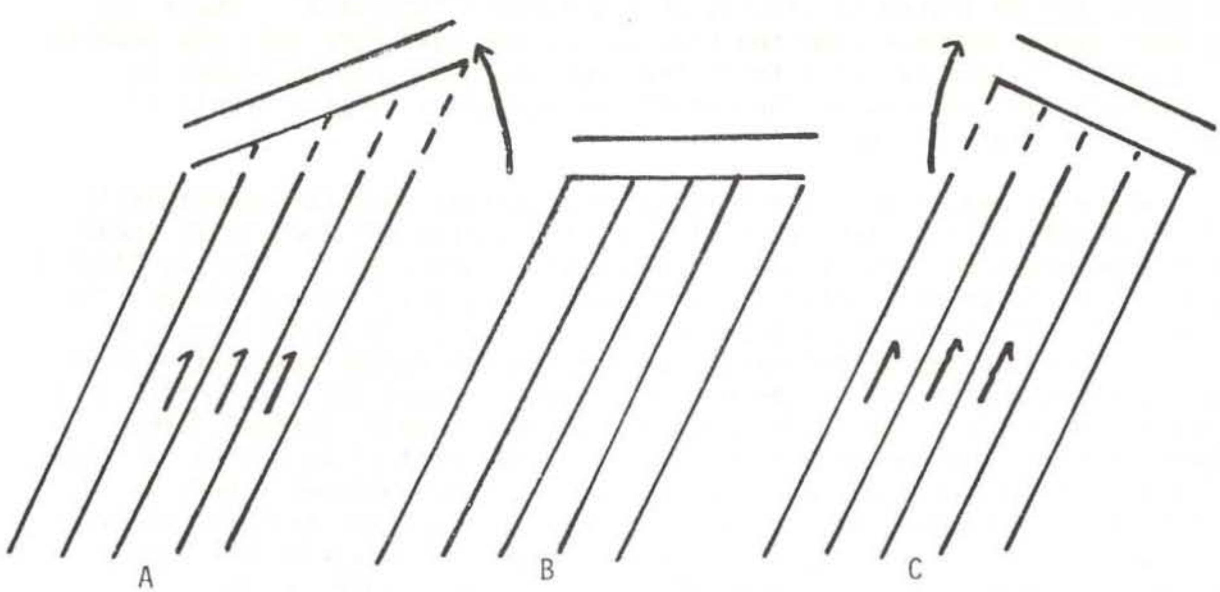

Fig. 3. Changes in angle of unconformity from original angle (B) decreasing (A) or increasing (C) as overlying strata are folded while underlying units are displaced parallel to themselves.

have undergone. The folds indicate extension in a direction that lies in the axial surface of the fold at right angles to the fold axis. In a direction perpendicular to the axial surface shortening has occurred. The rocks below the unconformity were unable to accommodate to this deformation by further folding. Thus the bulk of deformation was accomplished by slip along shear fractures: faulting on a small and very small scale. Much of the movement must have been of the nature of translation but small amounts of rotation are evident. This was caused by curvature of some of the shear fractures and by intersection of shear fractures and bedding planes (Fig. 4).

Two factors affected movement along the shear planes. The direction of planar structures, in our case mainly bedding but to a lesser extent also slaty cleavage determined the direction of shear fractures. Donath (1962, 1965) has shown that shear fractures follow bedding or previous cleavage directions where these lie at a small angle to the direction of maximum compression. At higher angles the shear fractures cut obliquely across bedding, but usually at a small angle. The direction of shear fractures underneath the Taconic unconformity is in accordance with these principles. Thus at stop 7 the bottom of the lowest graywacke bed in the syncline acts as the fault plane along which the entire snycline has been faulted against a predominantly shaly sequence. (Fig. 1). On the other hand in almost every outcrop we find graywacke layers cut off by shear fractures oblique to the bedding.

The thickness and spacing of graywacke beds controls the spacing of the shear fractures. Where graywacke beds are thick and closely spaced, shear fractures tend to be widely spaced and form few but conspicuous faults. At stop 7 a sequence of several small folds forms a single block a few tens of feet across which has moved as one unit. Faults bounding such large rigid blocks must have had considerable effects on the limestones overlying the unconformity. They could accommodate themselves to large offsets at the bottom of the unconformity only by faulting (Stop 4) or by sharp flexures (Stop 6). Many faults in the Silurian and Devonian limestones probably can be traced to offsets of the Taconic "basement". Where the younger strata deviate from the kind of regular curvature that one expects to develop in flexural slip folds the probable cause can be sought in irregularities produced in the underlying unconformity as a result of shifting of rigid blocks.

Where graywacke beds are thin and the section consist predominantly of shale deformation also takes place by fracturing but individual shear fractures are more closely spaced, often only inches apart (Fig. 6, Stops 7 and 8). As movement is distributed between innumerable shear planes, the megascopic effect closely approaches that of flow. In such places the rocks underneath the unconformity can accommodate themselves perfectly to the curvature of folds in the overlying beds by what amounts to flow in a statistical sense. The folds thus can assume a regular rounded form. Where intense shearing of the rock went to the point of an overall effect of flow deformation individual slivers of shale and graywacke were torn out of their stratigraphic context and the rock mass was transformed into a tectonic breccia (Fig. 6) which in appearance closely resembles some tectonic melanges such as those illustrated by Hsu (1968, pl 1).

As a result of folding the limestones of the Silurian and Devonian were rotated through angles of as much as 90^{o} and occasionally even more. Below the unconformity deformation consisted mainly of slip along fractures and bedding planes. In this process some individual blocks and slivers of rock were rotated, but rarely through angles of much over 30^{o}. The aggregate effect of this deformation more closely approaches translation than rotation so that the overall average orientation of the older

Fig. 4 Graywacke block partly bounded by shear fractures (left of hammer). Intensely sheared shale acts as filler. Stop 5

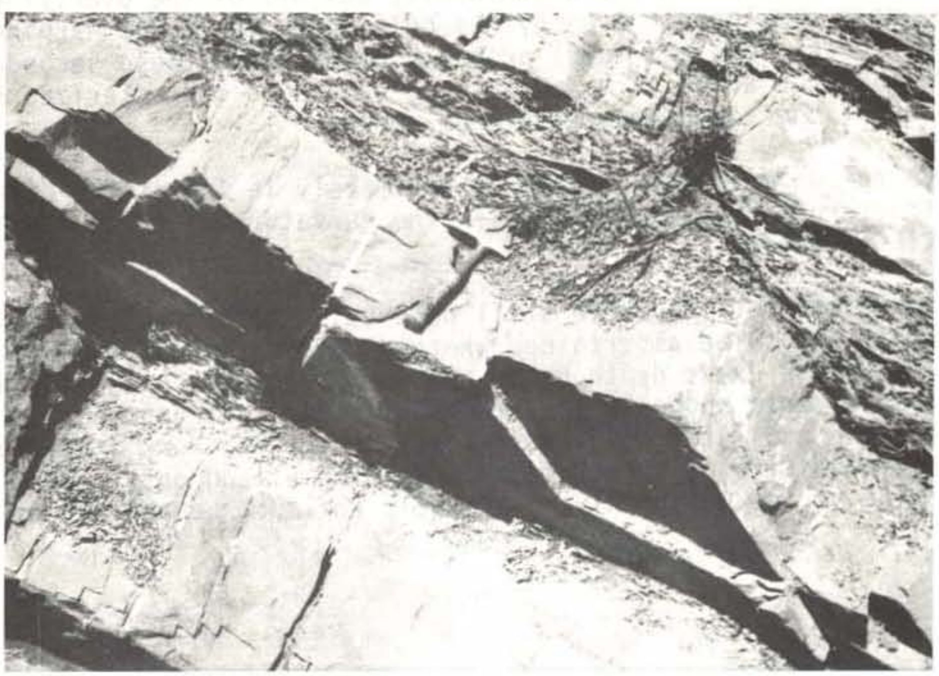

Fig. 5 Tension gashes in graywacke bed. (Close-up of part of structure seen in Fig. 1.

structures did not change. As a consequence the angle between the plane of unconformity and the underlying strata had to change. The angle could increase or decrease, depending on the dip of the bedding below the unconformity and the sense of rotation of the overlying strata. (Fig. 3). In most cases the angle at the unconformity would decrease. If the angle of unconformity changes, the unconformity itself tends to be torn open except in cases of extreme fracturing of the underlying rocks. At Stop 5 quartz veins can be found marking the unconformity.

While the overall deformation during the Acadian (?) orogeny was compressional in nature, the geometry of the folds above the unconformity requires extension in direction of the axial plane of the folds as a secondary effect, particularly in the cores of anticlines. Graywacke layers oriented in directions close to that of the axial surface of the folds therefore show tensional fractures which tend to be occupied by quartz veins. Boudinage can be observed in a few graywacke layers (Stop 5). Tension gashes also are present locally in shaly units (Stop 8). There they cut across the slaty cleavage.

REGIONAL IMPLICATIONS

Such features as boudinage, tension gashes in folded beds of graywacke or cutting across slaty cleavage, disruption of bedding by closely spaced shear fractures etc. are all signs of a second orogeny acting upon rocks that already have undergone considerable folding in a previous orogeny. Presence of these features shows promise as a criterion for delimiting areas in which the Taconic orogeny has produced major deformation, even where erosion has removed the unconformity and all of the overlying strata. Areas in which the Taconic orogeny has only produced gentle warping of the strata in typical foreland folds probably do not show these secondary structures but the areas of major folding should be characterized by some combination of the structures mentioned above.

Above the unconformity faults approximately in the strike direction of the structure and irregularities in the curvature of folds may have similar significance.

The criteria outlined here still need to be tested in the field. In particular it has to be ascertained whether deformation of the same intensity persists to a great depth below the unconformity. A cursory application of the criteria suggests that Taconic folding extended not as far west as Acadian and later folding at least in the New York State region. Structures suggestive of strong Taconic folding extend only a very short distance west of the Hudson River, probably not much beyond two miles.

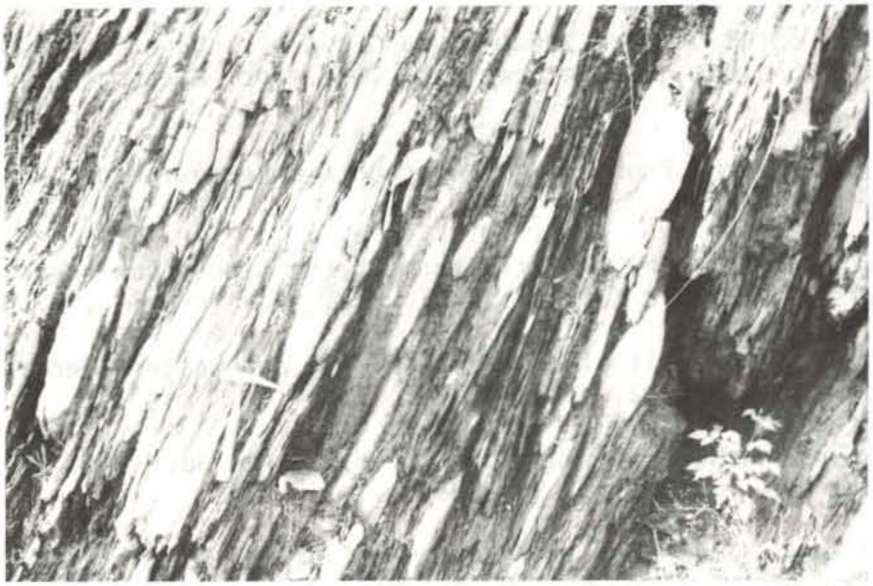

Fig. 6 Tectonic breccia consisting of sheared slivers of graywacke floating in a shale matrix. Stop 8

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ROAD LOG FIELD TRIP B-2

From the Vassar College student parking lot at Raymond Avenue and Route 376 the field trip will turn unto Route 376 (Hooker Avenue) heading west and follow it for approximately 2 miles to a five-point intersection. Bear left onto Montgomery Street at the five-point intersection and follow it for approximately 1/2mile, then turn right on Jefferson Street following it for approximately 1/2 mile to the approach to Mid-Hudson Bridge, turn left onto Mid-Hudson Bridge. The formal road log starts at the west end of the Mid-Hudson Bridge.

Cumulative Mileage	
0.0	West end of Mid-Hudson Bridge. Start of a long road-cut in Austin Glen Graywacke.
1.0	Turn right on Route 9W heading north.
3.5	Turn left on Route 299.
3.6	Note large erratic boulder in road-cut on left side.
5.9	STOP 1 (not included in Sunday trip). Beds of sandstone and shale in the Austin Glen Graywacke exhibit here very regular structures indicating that only one orogeny produced major deformation in this locality. Good slaty cleavage developed in shaly layers.
6.9	Slate in road cut.
8.6	Entrance to New York Thruway at left.
9.4	Entering Village of New Paltz.
9.5	Junction Route 32, proceed straight ahead.
9.9	Turn right on Route 32 heading north.
10.1	Another right turn following Route 32.
10.8	For next two miles there are several small road cuts in shale (possibly Snake Hill).
14.7	Turn right on Route 213.
15.0	Underpass under New York Thruway.
15.2	Outcrops of Austin Glen Graywacke show only gentle deformation.
15.6	Bear left following Route 213.
16.1	Enter Rifton.

20.6 STOP 2. Two roadcuts in the Austin Glen Graywacke show some of the variations in lithology in the unit. Again the structure is very simple, suggesting that the Taconic orogeny had little effect at this locality.

21.2 Bridge across Rondout Creek.

22.2 Gravel pits on left side of road.

22.7 Turn left on Wilbur Avenue following Route 213.

23.9 Turn right at traffic light following Route 213.

24.0 After one block turn left on Clinton Following Route 213.

24.1 Turn right, junction Route 32.

24.4 Turn right on Route 28 heading east (Broadway).

25.1 Turn left on Route 9W.

26.4 Junction Route 32, continue straight.

26.5 Roadcut in Onondaga Limestone.

26.9 For next mile outcrops of Onondaga in roadcuts and in back buildings.

28.5 Turn right on Route 199.

28.9 Road cut in Espous and Schoharie Formations.

29.2 STOP 3. Anticline in Lower Devonian Becraft, Alsen and Port Ewen formations exposed in roadcut on both sides. The regular curvature for the formations is characteristic of flexural slip folding where there are not complications caused by the underlying rocks.

29.5 Road cut in Coeymans, Kalberg and New Scotland formations

29.6 Turn right on exit to Route 32.

29.9 Turn left on Route 32 heading south.

30.2 STOP 4. The Austin Glen Graywacke forms the bottom part of the outcrop at the north end. It is unconformably overlain by the Rondout Formation but the unconformity itself is not well exposed because of weathering of the contact. A number of faults cut through the limestones above the unconformity. Their presence lets one to expect massive graywacke underneath the unconformity. Continue south.

30.7 STOP 5. One of the best outcrops of the Taconic unconformity in the Hudson Valley. In places the unconformity is torn open into a tension gash and occupied by a quartz vein. Walking a short distance south along the outcrop one can see numerous slickensided shear fractures, blocks of shale displaced along curved or irregular shear fractures and rotated as a result so that the directions of the slaty cleavage vary in the outcrop. Note the contrast between the highly complex and irregular structure in this outcrop and the very simple and regular structures at Stops 1 and 2.

31.6 STOP 6. (not included in Sunday trip) Sharp flexure in Schoharie Formation. It probably lies in the continuation of a fault separating relatively large rigid blocks below the unconformity.

32.6 Junction Route 9W. Turn right retracing route to Route 199. (On Saturday we will depart from regular field trip route at this point to go for a lunch stop in Kingston. After lunch we will pick up the road log at this point again heading north on 9W).

34.7 Turn right on Route 199.

35.9 Continue straight past exit to Route 32.

36.2 Toll booth, Kingston-Rhinecliff Bridge.

38.0 STOP 7. Long roadcut. A variety of structures can be observed on the north side of the highway. A series of folds including chevron folds and isoclinal folds in a predominantly graywacke unit has moved as a single rigid block. It is in fault contact (Fig. 1) with a predominantly shaly sequence that is intensely sheared so that the original continuity of the beds is destroyed. Tension gashes can be seen cutting some graywacke beds. Shale layers in the chevron folds are greatly thickened in the hinges by flow folding. Some graywacke layers exhibit sole markings at their bottom.

38.6 Folds in Austin Glen Graywacke.

39.2 Junction with Route 9G, turn left following Route 199.

41.1 Turn right following Route 199.

41.2 Roadcuts in Austin Glen Graywacke.

42.2 Entering Red Hook.

42.8 Intersection with Route 9. Continue straight ahead following Route 199.

45.1 Note quartz veins in outcrop at right.

45.2 STOP 8. Intensely sheared shale and graywacke. In places the strata have been turned virtually into a tectonic breccia with an appearance resembling a melange. Note slivers of graywacke floating in a shale matrix. The direction of the slaty cleavage is variable. Close study is needed to determine whether two intersecting directions of cleavage actually exist or whether different slices of shale have been rotated out of their original position.

46.5 Turn right on Route 308. Follow Route 308 to junction with Route 9 and follow Route 9 to Poughkeepsie and return to starting point.