Trip A-1

EFFECTS OF ADIRONDACK BASEMENT UPLIFT ON JOINTS AND FAULT DEVELOPMENT IN THE APPALACHIAN BASIN MARGIN, NEW YORK

[1]JOSHUA D. VALENTINO, [2]DAVID W. VALENTINO, [2]ALEX P. O'HARA, [2]HANNAH VALENTINO

[1]Department of Geosciences, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061
[2]Department of Earth & Environmental Sciences, State University of New York at Oswego, Oswego, NY 13126

Introduction

Recent development of unconventional shale gas plays in the Appalachian Basin has drawn considerable attention to basement structures, and joints and fracture zones in the Paleozoic cover rocks (Figure 1), and nowhere is this more apparent than in the region of central Pennsylvania through western and central New York State (Engelder and Lash, 2009; Engelder, 2008; Jacobi, 2002; Jacobi and Fountain, 1996). Two ubiquitous joint sets occur throughout this region (*J1 and J2 of Engelder*), in addition to significant domains of fracture intensification related to faults (Jacobi, 2002). It was demonstrated that the regional joint sets are largely the result of hydrocarbon maturation fluid pressure under late Paleozoic Alleghanian orogenic stress (Lash and Engelder, 2009), however domains of fracture intensification have been linked to faults in the underlying crystalline basement (Jacobi and Fountain, 1996; Jacobi, 2002). Basement structure controlled the distribution and orientation of brittle faults in the overlying Paleozoic strata (Jacobi, 2002), and in some cases the displacement on basement faults had a substantial influence on patterns of Paleozoic sedimentation (Jacobi and Mitchell, 2002).

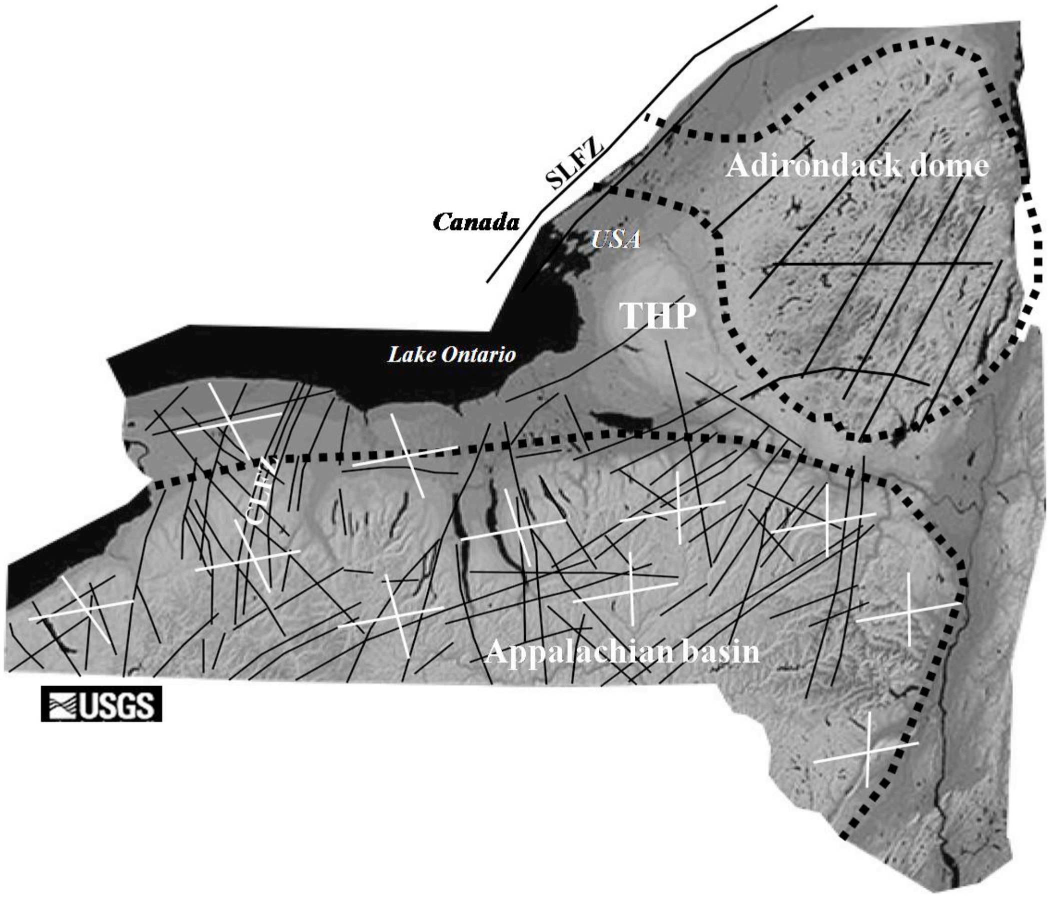


Figure 1 - Physiographic map of New York State (USGS) with generalized faults, fracture zones and joint patterns. The Appalachian basin and Adirondack dome are outlined by heavy dashed lines. Within the Appalachian basin, the dark lines represent inferred faults, and the white lines represent the strike direction

of steeply dipping joints (Jacobi, 2002; Jacobi and Fountain 2002; Jacobi and Mitchell 2002; Lash and Engelder 2009; Engelder and Geiser 1980; Engelder and Gross 1993; Engelder and Lash 2008; Engelder et al. 2001; Engelder and Whitaker 2006; Fakundiny, 1986; Fakundiny et al., 1996; Isachsen et al., 1993; Isachsen and McKendree, 1977; Isachsen et al., 1991; Zho and Jacobi 1996). THP – Tug Hill Plateau.

The direct observation of basement faults that had control on the distribution and subsequent deformation of Paleozoic cover is limited to the exposure of Proterozoic rocks of the Adirondack dome (i.e. Isachsen, 1975; Isachsen, 1981; Roden-Tice et al., 2000; Jacobi and Mitchel, 2002). Roden-Tice et al. (2000) and Jacobi and Mitchel (2002) suggested that the Adirondack dome uplifted in segments that were accommodated by faults related to the Iaptian rift. Jacobi and Mitchel (2002) also discovered that the distribution of the Ordovician strata was controlled by fault bounded structural blocks, demonstrating fault activity during that period. Roden-Tice et al. (2000) and Roden-Tice and Tice (2009) demonstrated that the Adirondack region underwent differential uplift with the formation of the dome, and was controlled by change in bulk compression direction and reactivation of faults. Through apatite fission track dating, Roden-Tice et al. (2000) constrained the age of the dome uplift to mid-Jurassic through the Cretaceous. Wallach and Rheault (2010) suggested that the gentle southwestern incline of the Ordovician strata west of the Adirondacks, to be directly the result of basement faulting and uplift of the Adirondack dome. They further suggested that reactivation of the Carthage-Colton shear zone and movement on the Black River fault contributed to the formation of the Tug Hill plateau. Earlier, Isachsen (1981) reported on Adirondack fault zones that form small graben that contain remnants of the Paleozoic strata that covered the Adirondacks prior to uplift. Additionally, Isachsen (1975; 1981) proposed that neotectonic activity continues in the Adirondacks, and this is partially supported by seismic activity on the Saint Lawrence fault zone and in the Champlain Valley (Barosh, 1986; 1990; 1992; Faure et al., 1996; Mareschal and Zhu, 1989; Wallach, 2002). A statistical correlation between faults and seismic activity led Deneshfar and Ben (2002) to conclude that northwest striking faults in the Adirondacks are more likely to exhibit seismic activity.

It is apparent that faulting in the Proterozoic basement of the Adirondack dome exhibits a protracted history, ranging from late Proterozoic through the Cretaceous, and possibly even neotectonic in nature. Although it was demonstrated that basement faults penetrate the Paleozoic rocks adjacent to the Adirondack dome, the extent of joint and fracture zone development associated with rise of the dome has yet to be described. The intent of this investigation was to address this issue though a detailed study of joints and fracture zones in the Middle Ordovician rocks that directly overly the western flank of the Adirondack dome. This is the region of the Tug Hill plateau, where Wallach and Reault (2010) recently identified basement faults that extend into the Paleozoic strata (Figure 2), and where deformation associated with the Appalachian basin (i.e. Jacobi, 2002; Engelder, 2009) is most likely overlapped by deformation related to the uplift of the Adirondack dome.

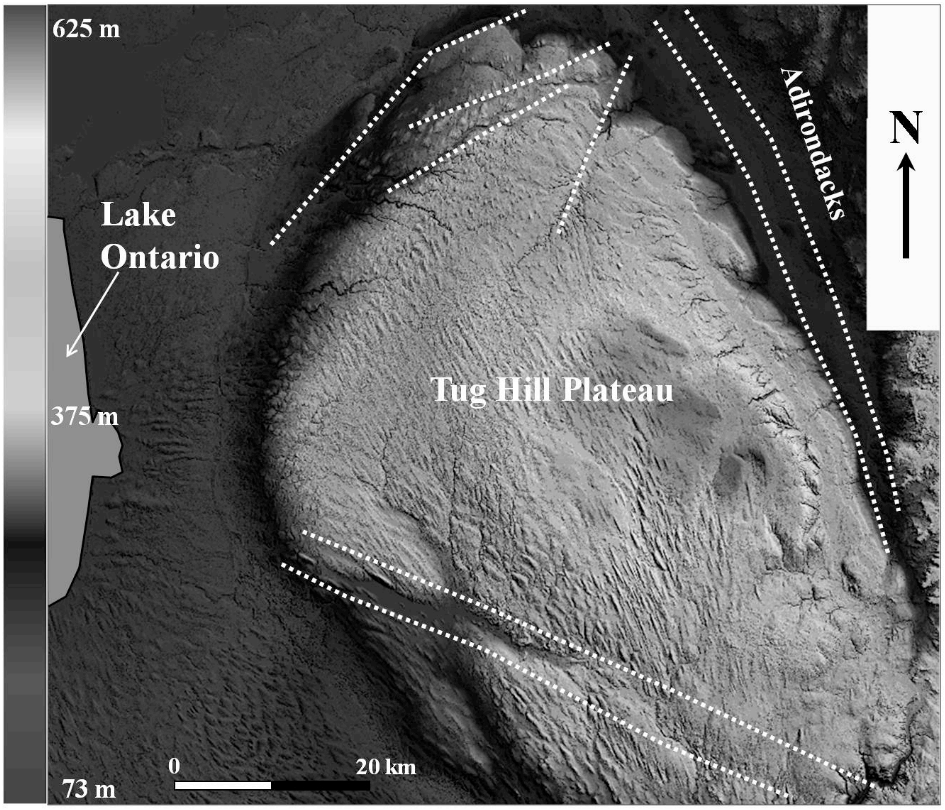


Figure 2 - Digital elevation model for the Tug Hill plateau. The dashed lines are faults of Wallach and Reault (2010).

THE TUG HILL PLATEAU

Situated between the Adirondack dome to the east and Lake Ontario to the west, the Tug Hill plateau rises about 500 meters from the lake shore to the highest point (Figure 2). The plateau covers an area approximately 3500 square kilometers and is underlain by Middle Ordovician strata that sit nonconformably on the Mesoproterozoic basement. These strata are inclined 2^o to 5^o toward the southwest, and Wallach and Reault (2010) propose that this incline to be the result of faulting in the basement during the uplift of the Adirondacks (Roden-Tice, 2000; Roden-Tice et al., 2009). Approximately 500 meters of strata are exposed along the rim of the plateau through river beds, gulfs, road outcrops, and quarries, but the center of the plateau is concealed by ground moraine, drumlins and wetlands. There are long linear escarpments and valleys on the southern, northern, and eastern flanks of the plateau, that were proposed to be the locations of faults (Wallach and Rheault, 2010). The southern flank of the plateau is bound by the Prospect Fault (Jacobi, 2002) and the northern flank of the plateau is coincident with the southwestern extension of the Carthage-Colton shear zone (Wallach and Rheault, 2010). Finally, the eastern flank of the plateau is the steepest slope, and the location of the proposed Black River fault (Wallach and Rheault, 2010). Superficially, it appears that the general geomorphology of the Tug Hill plateau was controlled by faults within the underlying basement that extend upward into the overlying sedimentary strata.

GENERAL STRATIGRAPHY

The Middle Ordovician strata of the Tug Hill plateau record the transition from marine to terrestrial deposition associated with carbonate sedimentation during the late stage of the Laurentian passive margin (Black River and Trenton groups), and siliciclastic deposition related to the onset of the Taconic orogeny (Lorraine Group) (Figure 3). The Tug Hill plateau sequence includes the Black River and Trenton Group carbonates that reside nonconformably on the crystalline basement, and the unconformity is exposed in the Black River valley. The thick limestone sequence that makes up the Trenton Group is directly overlain by the Utica black shale across an abrupt disconformity contact. With a progressive increase in the occurrence of siltstone beds, the Utica Formation transitions upward into the Whetstone Gulf Formation, and in turn the Whetstone Gulf Formation grades upward into the Pulaski Formation with the increase in the number of sandstone beds. Finally, with a marked decrease in the number of shale beds, the Pulaski Formation grades upward into the thick bedded sandstone of the Oswego Formation. Although earlier geologic maps (Isachsen and Fisher, 1970) show a few isolated occurrences of Queenston shale, the cap-rock for the Tug Hill plateau is primarily the Oswego sandstone.

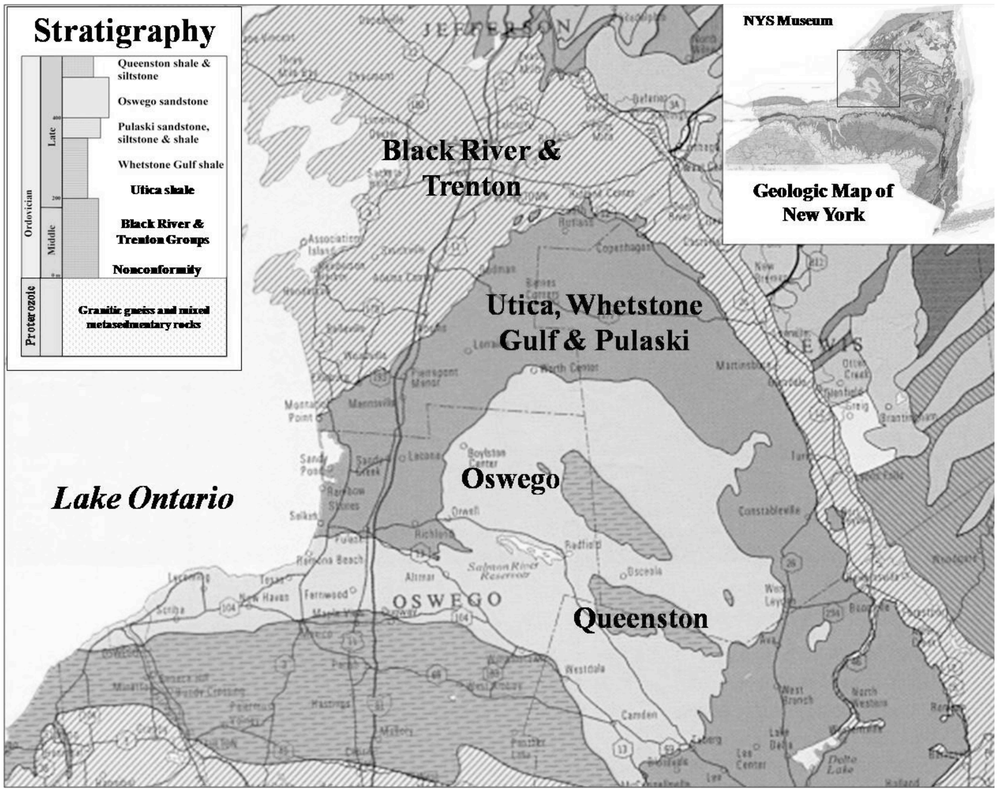


Figure 3 - Geologic map of the Tug Hill plateau (Isachsen and Fisher, 1970). The inset shows the general stratigraphy.

JOINTS, FRACTURE ZONES AND FAULTS

Three field seasons were spent documenting the orientation and density of various joint sets, fracture zones and faults in the strata of the Tug Hill – Eastern Lake Ontario region. Early in the investigation, it was noted that the orientation, spacing and even the occurrence of specific joint sets, vary from bed to bed within outcrops. In addition to mapping and characterizing joints and fracture zones throughout the region, it was prudent to document examples of the detailed variation to further understand the significance of lithology and bed thickness in the brittle deformation of each formation.

Outcrop scale analysis

Trenton Limestone.

Figure 3 is an example of a short stratigraphic column from the middle part of the Trenton limestone on the eastern flank of the plateau. In general, the Trenton limestone is made up of varied thickness inter-layered carbonate rocks. In this analysis, the orientation and density of various joint sets is shown. The structure symbols located to the right of each bed represent the averages of joint data collected for that bed. They are plotted as map symbols with north toward the top of Figure 3. As an example, within the bed of micrite located at 100 cm, there are three different joint sets that strike toward the northwest, east and south. The small numbers at the end of each symbol are the joint densities. In this case, the joint density was quantified for each joint set by counting the number of joints encountered over an average distance of 1 meter in the direction orthogonal to the joint surface. Therefore, the joint density is reported in joints per meter. Note the variability in joint attitude and density throughout this small example of Trenton limestone (Figure 4). To extrapolate these results in a regional analysis, the number of data collected is important due to the extreme variability. A minimum of several hundred joint orientations were measured at field sites to overcome the variability that occurs in some formations, as shown in this example.

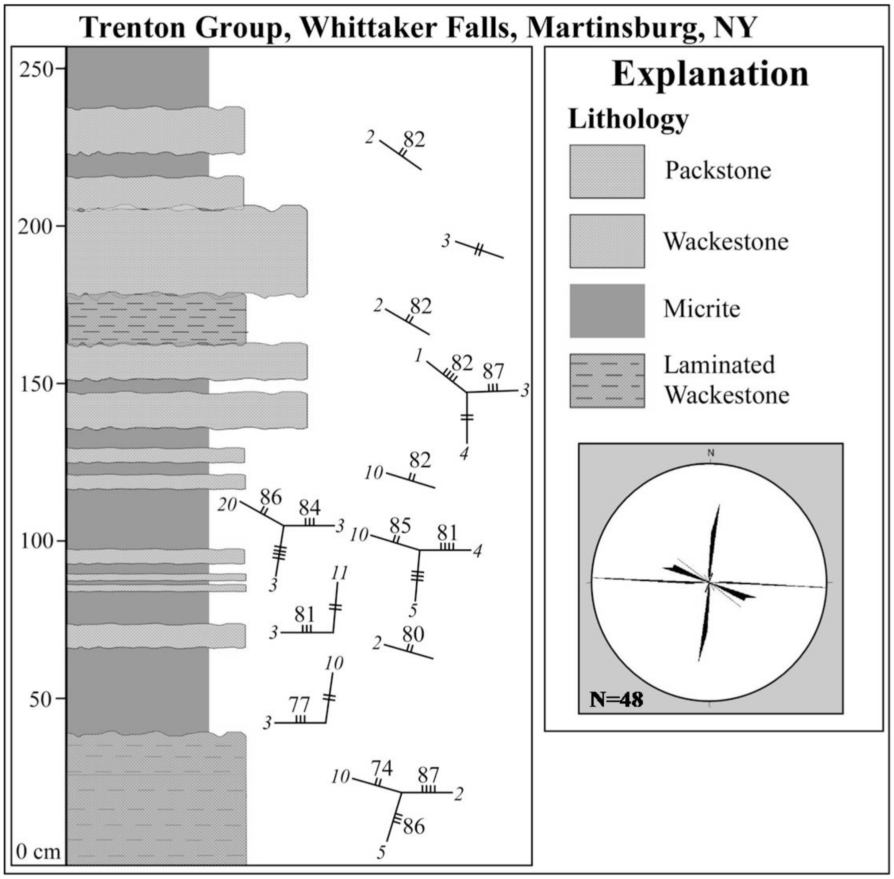


Figure 4 - Representative stratigraphic column for the middle section of the Trenton limestone showing the orientation of joints per sedimentary bed. The rose diagram represents all of the data for this section.

Within the Black River and Trenton limestone units, there are southeast striking normal faults with minor displacement on the order of several decimenters (Figure 5). Some of these faults exhibit no obvious throw, suggesting that they have a lateral displacement component. In some cases, the faults merge with bedding plane shear fractures (Figure 3), forming domino structure and mineralized slicken-sides. This class of fault was only observed in the limestone units.

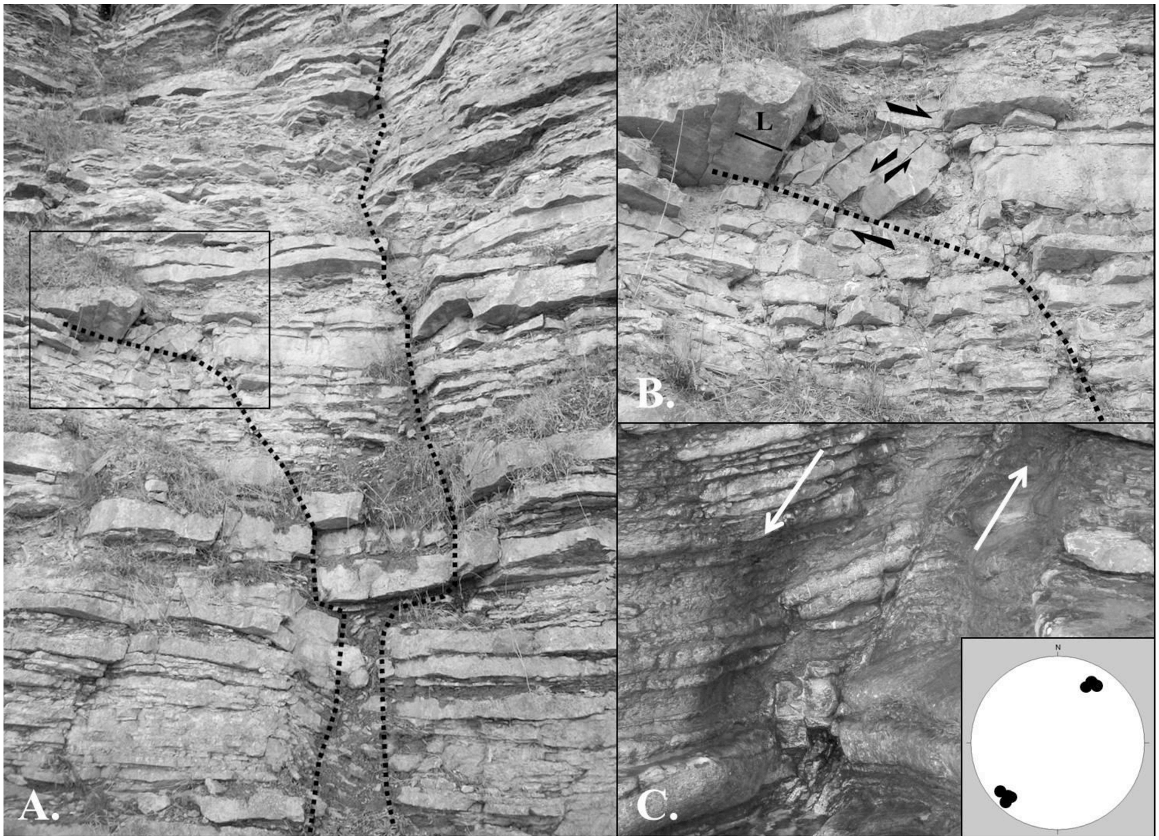


Figure 5 - Photographs of faults in Trenton Group limestone at Stony Point, New York. A. Complex fault with breccia zone, splays and no apparent dip-slip displacement. B. Close up of a domino structure where the fault merges with bedding. C. Example of a normal fault with several decimeters of displacement. The inset stereogram is the poles to fault planes.

*Utica Shale***.**

Continuing upward in the strata, the Utica black shale directly overlies the Trenton limestone. Four different fracture sets, with the highest density occur within the shale. Because shale is highly susceptible to weathering, there are few outcrops of the Utica shale away from the deep gulfs that occur in the flanks of the plateau. Within the gulfs, pavement style exposures provided an opportunity for detailed digital joint analysis. High resolution photo mosaics were collected and scaled using a computer program, so that total joint density could be quantified. In the example of Figure 6, once the different joint sets were identified (four in this case), the total joint length was summed for the outcrop surface. A plot of the results as vectors (total joint length/outcrop area verses azimuth), provides a visual representation for the joint set that is most abundant relative to geographic coordinates. The southeast striking joint set has a density that is three times greater than the east-northeast and northeast striking joint sets.

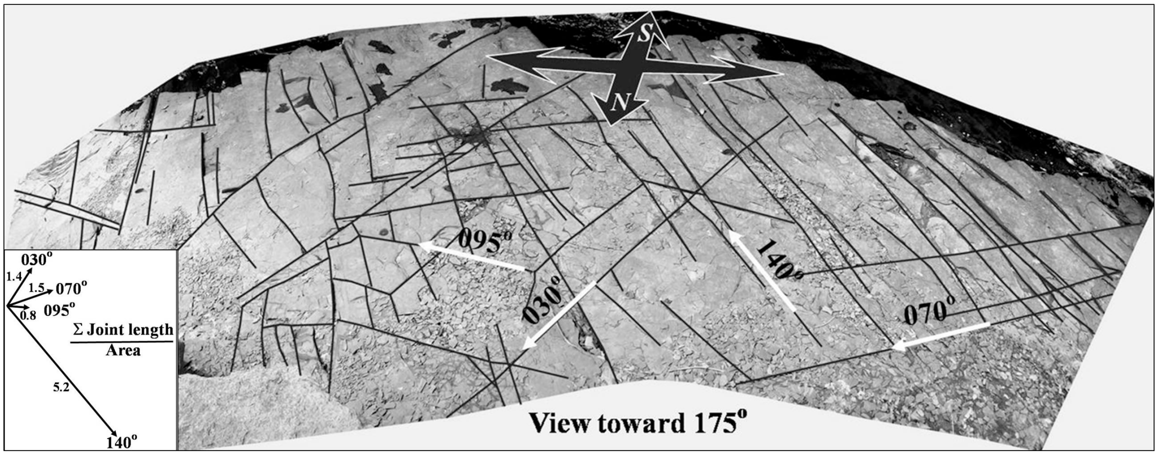


Figure 6 - Outcrop photograph of the Utica Formation with joint traces. The white arrows on the photograph show four joint sets with the average strike. The vector diagram in the lower left represents the total joint length per joint set divided by the outcrop area. See the text for details.

Whetstone Gulf Shale-Siltstone.

The Whetstone Gulf Formation consists of a sequence of black and gray shale that contains siltstone beds. The occurrence and thickness of siltstone beds increases stratigraphically upward. As well, there are thin sandstone layers that occur near the top of the formation. Northeast and southeast striking joint sets occur within the shale and siltstone beds, with rare occurrence of north-south striking joints in the sandstone beds (Figure 7). The regional consistency of the northeast and southeast striking joints can be seen in Figure 8, where the joints are shown to be consistent over an area of several square kilometers between Mooney Gulf and Totman Gulf on the western flank of the Tug Hill plateau. This is pattern of map-scale joint consistency is typical of the Whetstone Gulf Formation.

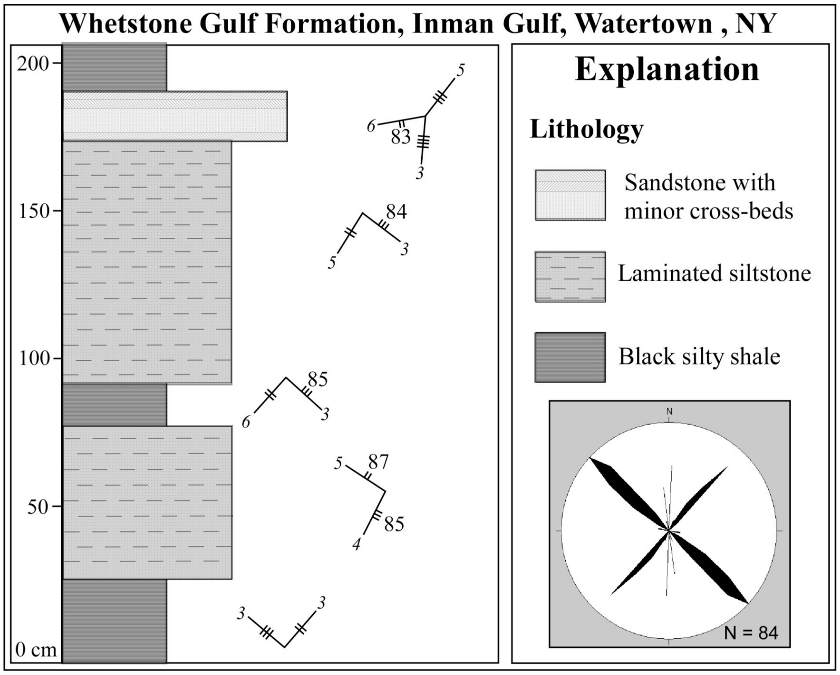


Figure 7 - Representative stratigraphic column for the Whetstone Gulf Formation at Inman Gulf. See text for details.

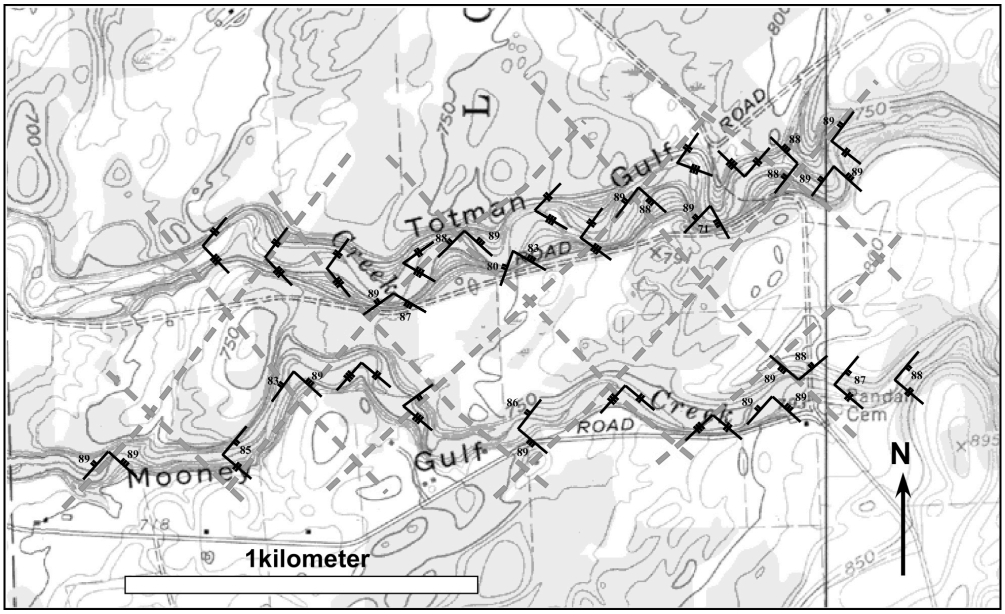


Figure 8 - Joint map for Totman and Mooney Gulfs, west flank of the Tug Hill plateau. The heavy dashed lines show the consistency in the strike of two joint sets in the Whetstone Gulf Formation over several kilometers.

Pulaski Shale-Siltstone-Sandstone.

Within the Pulaski Formation there are joints with strike variation on a bed-by-bed scale, where the shale, siltstone, and sandstone beds exhibit different joints sets and joint densities (Figure 9). Overall, there are northeast, east-northeast, southeast and south-southeast striking joint sets that appear to be tied to specific lithologies. This is the only formation in the Tug Hill plateau that exhibits both joint sets that appear to be associated with the Appalachian basin (J1 & J2) and with the crystalline basement. In addition, the shale units in the Pulaski Formation have extensive tightly spaced fracture cleavage ranging from 2 to 5 fractures per centimeter (Figure 10).

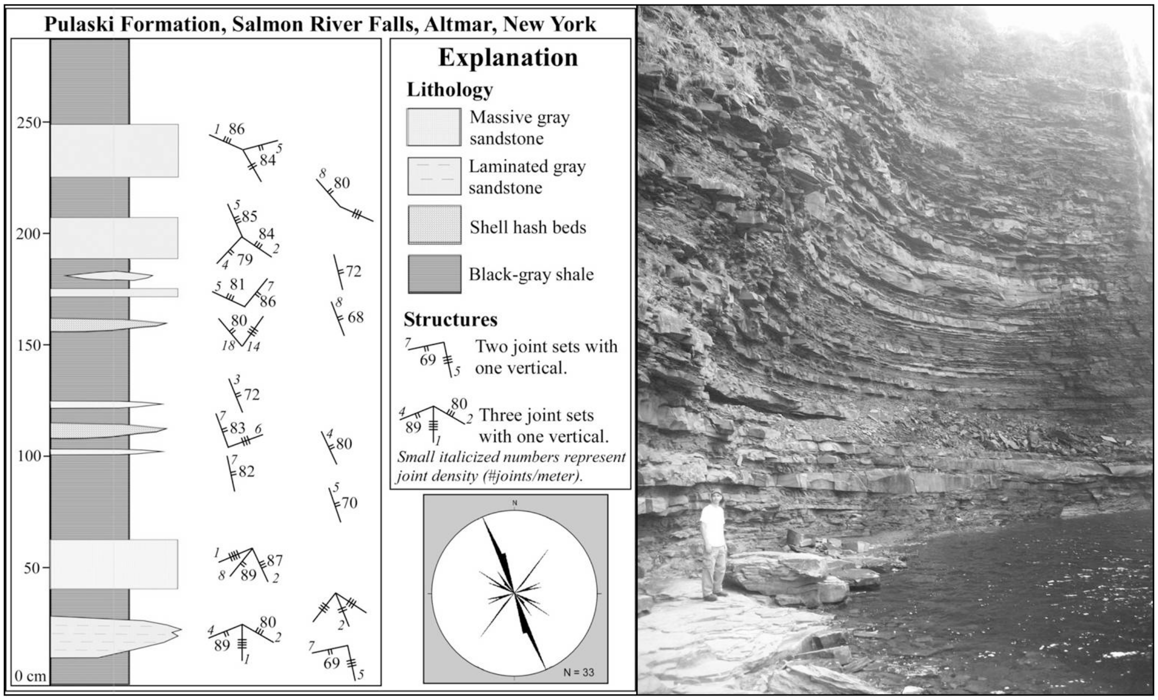
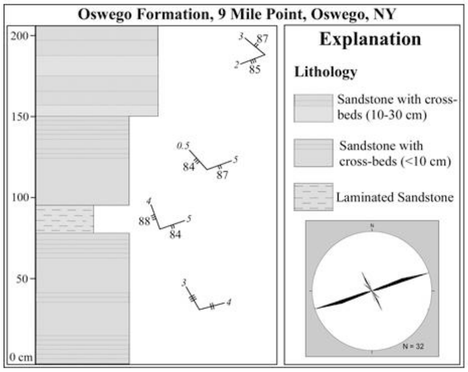


Figure 9 - Representative stratigraphic column for the Pulaski Formation at Salmon River Falls, Oswego County. The photograph shows the lithologic variability within the upper Pulaski Formation.

Figure 10 - Photograph of a shale bed that is sandwiched between two sandstone beds in the Pulaski Formation. Note that the shale contains fracture cleavage. The shale bed is about 10 cm thick in the photo.

Oswego Sandstone.

Finally, within the Oswego Formation, there are dominant east-northeast and southeast striking joint sets that persist from the region of Lake Ontario to the fringe of the Tug Hill plateau (Figures 11 and 12). These joint sets are consistent throughout the sandstone and only vary in strike where beds are either very thick (> 40 cm) or very thin (<2 cm). There is evidence for minor left lateral shear (2 – 20 cm) on the east-northeast striking joint set, where the southeast striking joints have been displaced horizontally. Small en-echelon fracture zones with left lateral geometry have a consistent strike with the individual fractures (Stilwell et al., 2005).



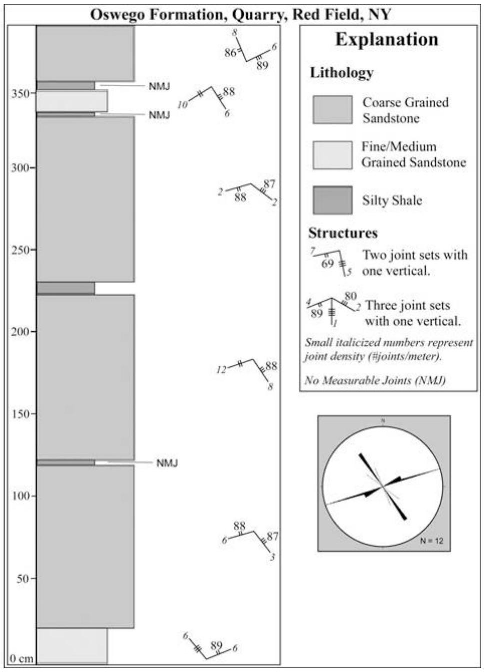


Figure 11 – Representative stratigraphic columns for the Oswego Formation at Nine Mile Point and Redfield, Oswego County, New York.

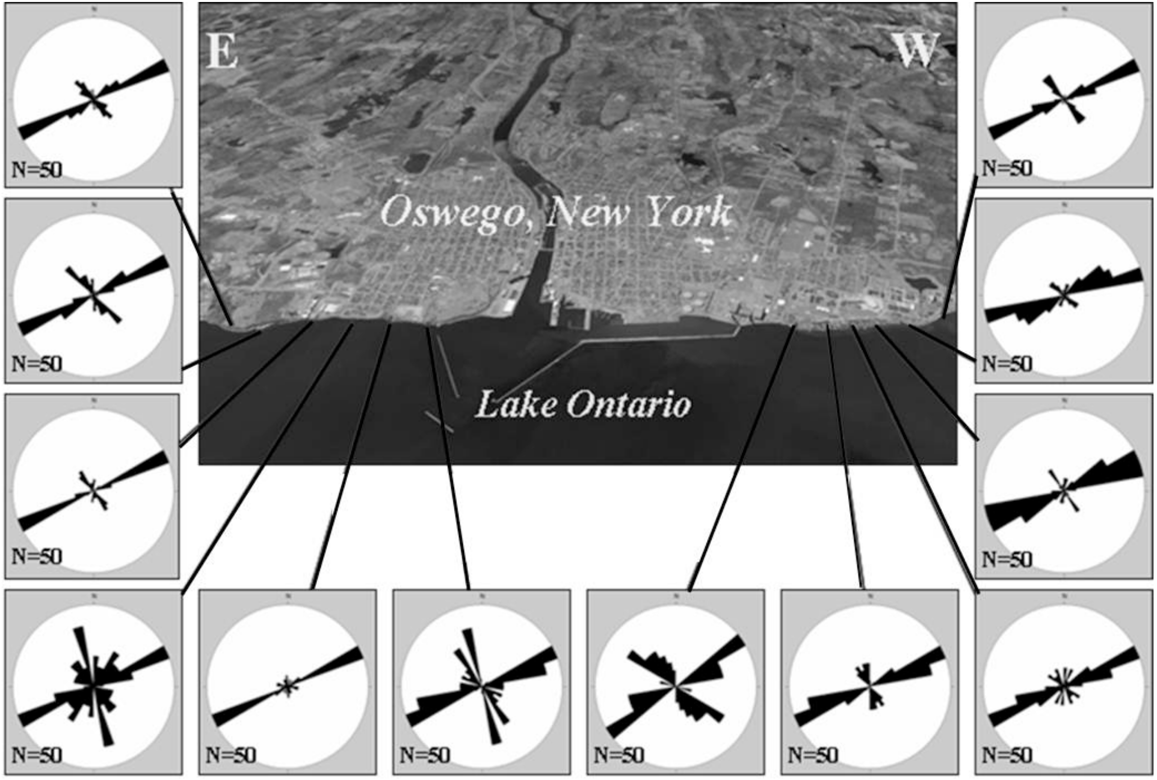


Figure 12 - Rose diagrams for the Oswego Formation at the type section in Oswego, New York. Each rose diagram is tied to the location along the Lake Ontario shore.

Regional fracture analysis

Joint density (joints/meter) is the inverse of joint spacing. For example, a joint density of 5 joints per meter is equivalent to a rock with average joint spacing of 20 cm. Joint spacing was plotted using box-and-whisker (Mcgill et al., 1978) diagrams (Figure 13) for comparison within rock formations across the region, and for comparison between the different formations. Two integrated box-and-whisker diagrams were plotted to portray variation in the strike direction of the joint sets against the variation in the joint spacing. This type of plot allowed for visual and quantitative comparison within and across rock formations.

Within the carbonate rocks of the Black River Group there are southeast, east-northeast and northeast striking joint sets that all have a mean joint spacing of about 30 cm. The limestone of the Trenton Group contains southeast, east-northeast, northeast and north-south striking joint sets with mean spacing of about 50 cm. Black shale of the Utica Formation has very tight joint spacing ranging from 5-10 cm for the east-northeast and northeast striking joint sets, however, east-northeast striking joints are spaced about 50 cm. Within the Whetstone Gulf Formation, there are southeast, east-northeast, northeast and north-south striking joint sets that exhibit tight 15 cm spacing in the eastern flank of the plateau, and wider 40 cm spacing in the western flank of the plateau. Mean joint spacing of 10 cm is consistent throughout much of the Pulaski Formation, where the southeast, east-northeast and northeast striking joint sets are dominant. Finally, within the sandstone of the Oswego Formation, there are only southeast and east-northeast striking joint sets with mean spacing of 25 cm. The Oswego Formation contains by far the most consistent joint-set occurrence, strike and spacing, probably reflecting the relatively homogenous lithology of the formation.

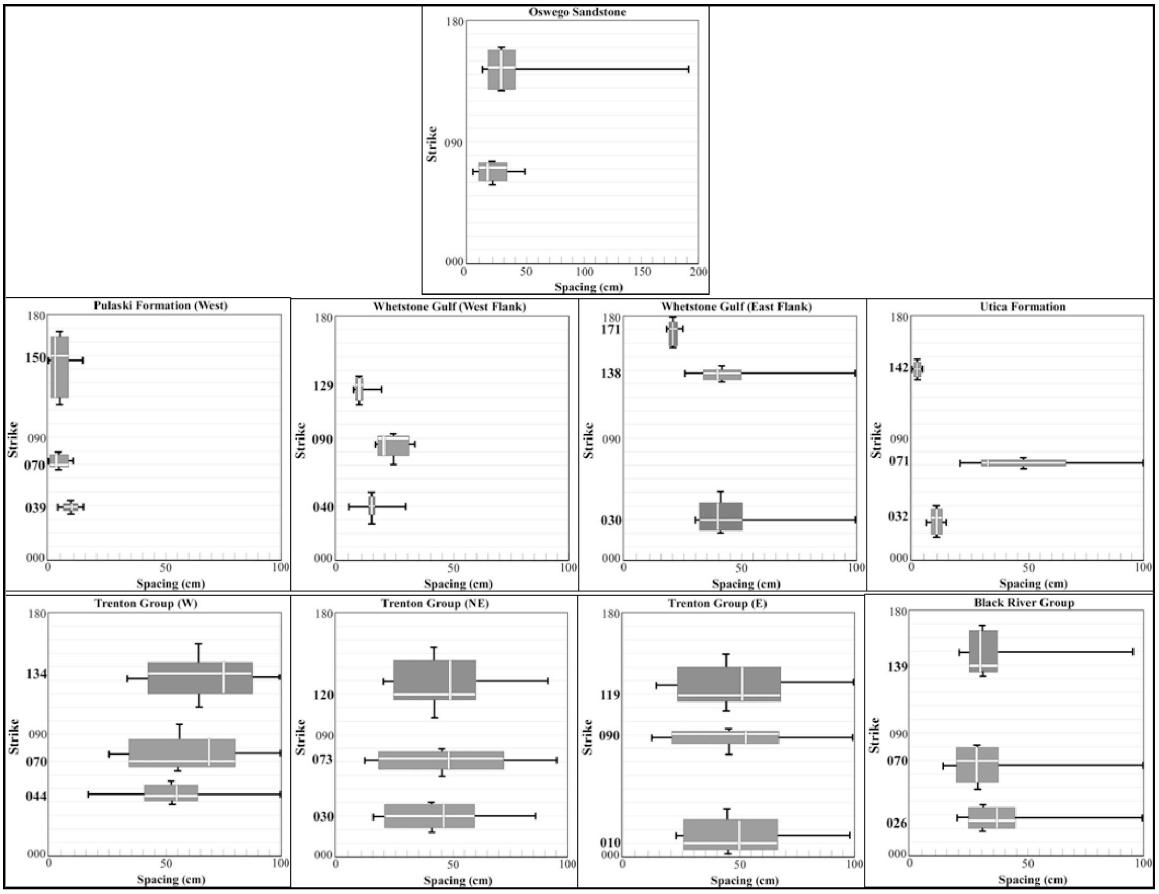


Figure 13 - Box and whisker plots of joint orientations and spacing for the Tug Hill plateau. The bottom row includes the carbonates of the Black River and Trenton Groups. The middle row includes the shale-bearing units of the Utica, Whetstone Gulf and Pulaski Formations. Note that the spacing scale for the Oswego sandstone is two times the other plots.

Adirondack region

Numerous northeast trending, long, narrow valleys and elongate lakes dominate the landscape of the Adirondack Mountains and define major topographic lineaments (Figure 2) that are interpreted as fault zone (Isachsen, 1975; Isachsen, 1981; Daneshfar and Ben, 2002). A few of these faults define the borders for small graben that contain Paleozoic carbonates (Isachsen, 1975; Isachsen, 1981). Although the fault lineaments are pronounced, the direct observation of the basement faults is obscured by glacial and lake cover, and mature forests, and the problem is compounded by intense weathering. In effect, there are few places where the faults can be directly studied and sampled without drilling. During this investigation, we examined joints and fracture zones at three locations within the Adirondack Mountains as a representative data set to compare with the joint data for the overlying Paleozoic rocks in the Tug Hill plateau. Joint orientation data was collected in the Moose River basin immediately east of the Tug Hill plateau. As well, joint data was collected in the regions of Piseco and Indian Lakes with the objective of demonstrating regional joint patterns in the basement. Figure 14 is a digital elevation model for the southern Adirondacks with pronounced topographic lineaments. Composite rose diagrams (several hundred joint strikes per diagram) of joint strikes for the three locations show a strong correlation between northeast trending lineaments and the dominant joint set. A second joint set generally strikes east-west to southeast.

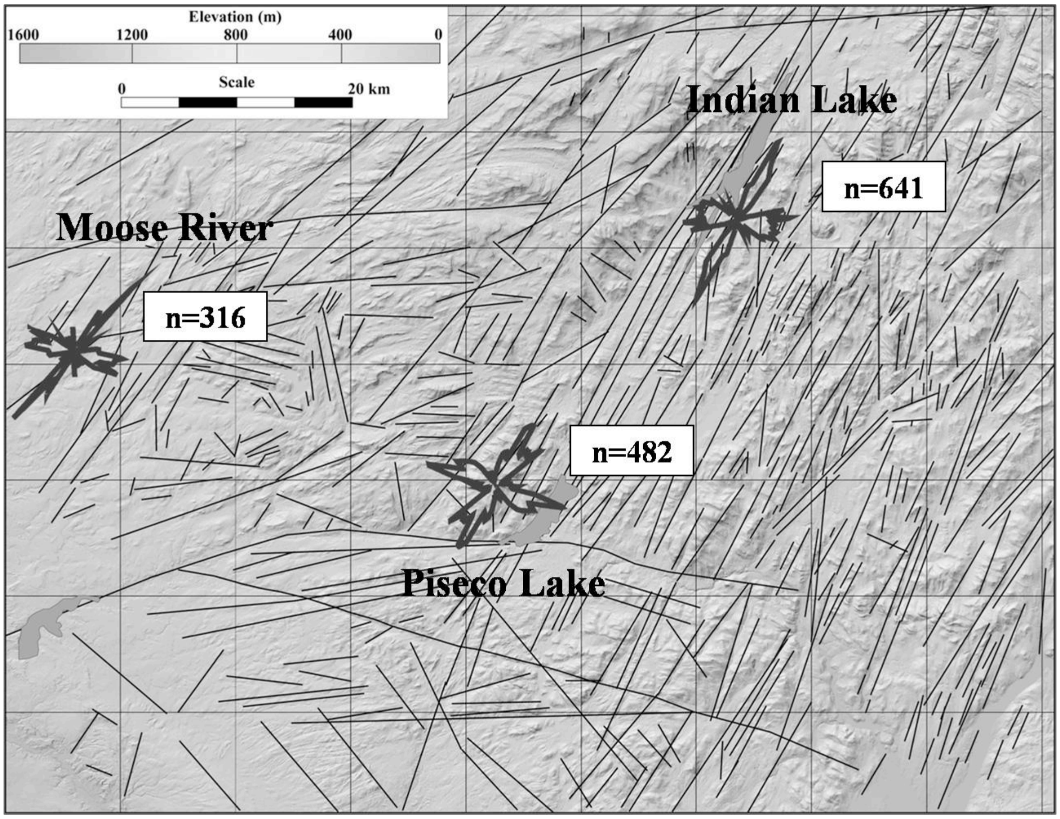


Figure 14 - Digital elevation model for the southern Adirondacks. The black lines highlight major topographic lineaments. The composite rose diagrams represent the distribution of the strikes for joints at three locations. See text for details.

DISCUSSION AND CONCLUSIONS

From the field observations during this study, it is apparent that joint density and strike are variable at the outcrop scale. However, at the regional scale, it is also apparent that joint variability is related to the proximity to the crystalline basement both laterally and stratigraphically, and related to the variation in rock type with mechanical characteristic control on the joint and fault formation (Figure 7). Starting at the base of the plateau, the limestone units have the most variability in joint strike with all sets that are present. The joint densities are relatively moderate with ~5 joints/meter in the rocks of the eastern flank of the plateau, and 2-3 joints/meter in the rocks of the western flank. In addition, the limestone units contain the highest number of southeast striking normal faults (Figure 15), and they are roughly parallel with the Black River fault (Figure 2) that was proposed by (Wallach and Rheault, 2010; Wallach, 2002). Within the shale-bearing rock formations, faults do not occur, but the fracture density is high in all of the sets that are present, with density values that exceed 20 joints/meter. There are dominant northeast, east-northeast and southeat striking joint sets with only a minor occurrence of the north-south striking cross fold joints. Finally, in the sandstone that caps the plateau, the joint sets have a generally low density of <1-4 joints/meter, and only the east-northeast and southeast striking fracture sets are present. The east-northeast striking joint set has evidence for left lateral reactivation (Stilwell et al., 2005), which is evident in the offset of southeast striking joints and discrete en-echelon fracture zones.

Figure 15 summarizes the occurrences of the four joint orientations and faults. The lower limestone groups contain the highest number of faults. These faults exhibit normal displacement, some terminate by merging with bedding plane fractures, and they strike northwest-southeast, a direction that is roughly parallel to the Black River Fault of Wallach and Reault (2010). The limestone groups also contain all four joints to some extent with the northeast, southeast and east-northeast striking sets being dominant. No faults were observed in the shale bearing formations of the Utica, Whetstone Gulf and Pulaski. However, these formations have the highest joint densities regardless of the joint set. All three formations contain well developed northeast, southeast and east-northeast striking joints, and only minor occurrences of N-S striking cross-fold joints. Overall the Oswego sandstone contains the least number of joints, with the east-northeast and southeast striking sets occurring in every outcrop. Minor occurrences of north-south striking joints were observed, and none of the northeast striking joints. The northeast striking joint set in the basement also occurs in the Paleozoic rocks, except that this set was not observed in the Oswego formation.

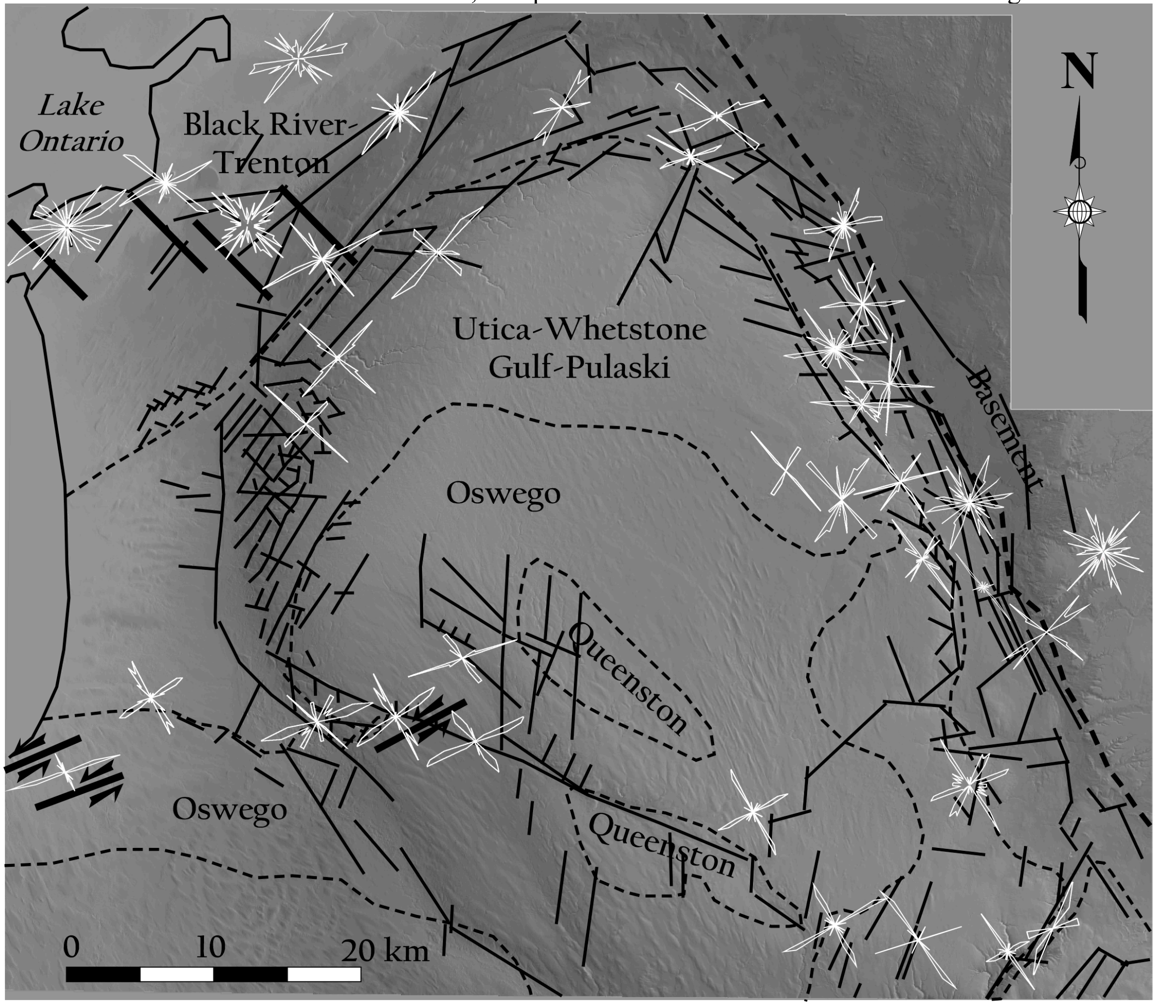
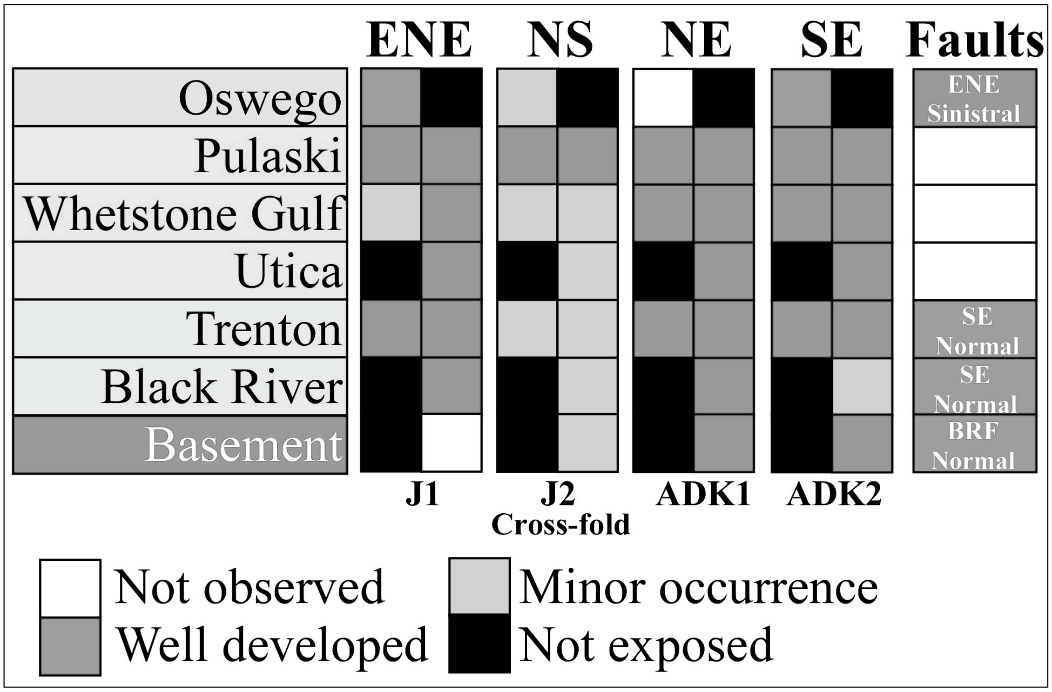


Figure 15 - Digital elevation model for the Tug Hill plateau with geologic formations, joint rose diagrams, and faults. The Black River fault is from Wallach and Rheault (2010). Minor faults are represented by short heavy lines represent observed faults. Those faults exhibit normal displacement in the northwest region and sinistral displacement in the Oswego Formation. The lighter weight black lines are interpreted topographic lineaments.

Four systematic joint sets were documented in the Tug Hill plateau. As before, Lash and Engelder (2009) demonstrated that the regional joint sets (J1 and J2) in the Appalachian basin Devonian strata are the result of hydrocarbon maturation fluid pressure during the Alleghanian orogeny. The east-northeast striking (J1) joints are well developed within all of the Ordovician rock units of the Tug Hill plateau (Figure - chart of joint sets), and there may also be some occurrences in the underlying basement. It is possible that maturation fluid pressure associated with the black shale of the Utica, Whetstone Gulf and Pulaski Formations was similar to the Devonian shale as explained by Lash and Engelder (2009). However, one should note that J1 is well developed in the underlying Trenton and Black River Group carbonates, suggesting that a mechanism other than maturation fluid pressure must also be responsible. Considering the persistence of these joints in all of the Ordovician strata, then perhaps they reflect the general east-west subhorizontal compression associated with the Alleghanian orogeny in the northern Appalachians, and the impact of that event on the underlying basement. On the contrary, the north-south striking cross-fold joints (J2) are only of minor occurrence, most likely due to the distal location relative to the Alleghanian thrust and fold belt.

The northeast and southeast striking joints (ADK 1 and ADK 2) that dominate the crystalline basement (Figure 16) are also developed in the overlying Ordovician strata of the Tug Hill plateau, but the occurrence is variable. The northeast striking joints have direct correlation with a suite of steeply dipping northeast striking normal faults in the southern Adirondacks (Roden-Tice, 2000; Valentino et al., 2011), however, no dip-slip deformation has been documented for the northeast striking joints in the Tug Hill plateau. Barosh (1990, 1992) proposed the northwest trace of oceanic fracture zones into eastern North America, showing several possible extensions into the Adirondack and Tug Hill regions. These proposed fracture zones are the likely cause of the southeast striking (ADK2) joint set, in addition to the southeast striking faults that occur within the Trenton Group. In the statistical analysis of Adirondack faults, Deneshfar and Ben (2002) also concluded that the northwest striking faults to be candidates for seismic activity. Wallach and Reault (2010) demonstrated that southeast striking faults account for the southwestern regional tilt of the Ordovician strata and accommodated the vertical rise of the crystalline basement during formation of the Adirondack dome. During this investigation, it was demonstrated that the east-northeast striking sinistral faults in the Oswego Formation cross-cut the southeast striking joints. This relative timing suggests that the sinistral deformation post-dates, or is synchronous with uplift of the Adirondack dome. This is most likely reactivation of the earlier developed J1 Appalachian joints as the result of differential uplift of the Adirondacks. These faults were only observed in the Oswego Formation, suggesting that the underlying shale units accommodated strain through partial plastic deformation. Note the development of cleavage in the Pulaski Formation and the lack of intense joints in some of the sections of the Whetstone Gulf formation.



	ENE		NS		NE		SE		Faults
	J1		J2 Cross-fold		ADK1		ADK2		
Oswego	▒	■	░	■	☐	■	▒	■	ENE Sinistral
Pulaski	▒	▒	▒	▒	▒	▒	▒	▒	☐
Whetstone Gulf	░	▒	░	░	▒	▒	▒	▒	☐
Utica	■	▒	■	░	■	▒	■	▒	☐
Trenton	▒	▒	░	░	▒	▒	▒	▒	SE Normal
Black River	■	▒	■	░	■	▒	■	░	SE Normal
Basement	■	☐	■	░	■	▒	■	▒	BRF Normal

☐ Not observed
▒ Well developed
░ Minor occurrence
■ Not exposed

Figure 16 – Summary of joint occurrence and development in the Tug Hill plateau region. For each joint set there are two columns. The left and right columns are for the western and eastern flank of the plateau respectively.

As the Adirondack dome uplifted in the Late Jurassic to Cretaceous (Roden-Tice et al., 2000) the Paleozoic strata of the plateau underwent deformation (Figure 9), resulting in the regional 2^o-5^o southwestern tilt of the plateau strata, displacement on minor faults, and development of joints. This investigation demonstrates that there is a geometric and most likely genetic relationship between the southeast striking joint sets of the Adirondacks, the parallel Black River fault and the smaller faults found in the lower limestone units of the Tug Hill plateau. With the uplift of the Adirondack dome, the stratigraphic units of the plateau had different responses depending on structural competency and position, and thus had control on the development of joints and their intensity (Figure 17). The limestone layers responded to the uplift by developing southeast striking normal faults and high joint density closer to the basement. Within the shale bearing rock units, the response was development of high density joints in addition to local fracture cleavage consistent with a less competent rock body. Finally, the Oswego sandstone was not as severely affected by the uplift but instead there was reactivation of the east-northeast striking joints as minor left lateral faults. Considering the relative strength of a thick sandstone body, the Oswego sandstone should exhibit more variability in joints. However, the thick underlying shale formations probably absorbed much of the joint forming stress through development of fracture cleavage and low-temperature plastic flow. Even in the lithified state, the clay that makes up the shale formations would have experienced some degree of grain-boundary sliding in conjunction with fracture cleavage formation resulting in plastic deformation.

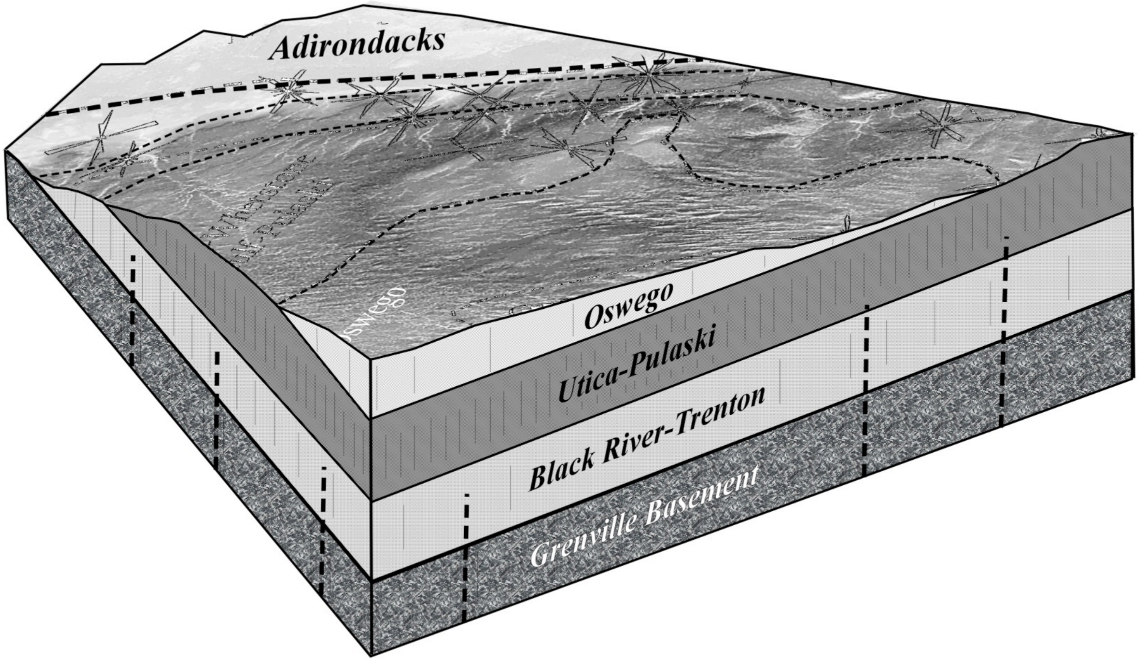


Figure 17 – Conceptual model for joint and fault distribution in the Tug Hill plateau.

Road log and field guide

This field trip circumnavigates the Tug Hill plateau starting in Oswego, New York, on Lake Ontario, traversing up the west side of the plateau at the Salmon River, Mooney Gulf and Stony Point, followed by a traverse down the eastern flank stopping at Whetstone Gulf and Wells Creek.

Stop 1: Lake Ontario at SUNY Oswego

The field trip begins at the parking-lot for Mary Walker Health Center on the campus of SUNY Oswego. From the parking-lot, follow the path along the lake shore toward the east to the first metal stair case. The outcrop of interest is at the bottom and to the west of the stair case.

A. Thick to medium bedded Oswego sandstone.
B. Two prominent joint sets (east-northeast and southeast striking).
C. Sinistral fault in the pavement outcrop.
D. Evidence for minor sinistral displacement on individual east-northeast striking joints.
E. East-northeast striking en-echelon fracture zones with sinistral geometry.

Road log:

At the entrance to the parking-lot, turn left on Rudolph Road.
0 – 0.5 miles to Sheldon Ave., turn right.
0.5-0.7 miles to Washington Blvd., turn left.
0.7-1.0 miles to Bridge Street, continue straight through traffic light.
1.0-2.5 miles to 7th Street, turn left.
2.5-2.7 miles to Schuyler Street, turn right.
2.7-3.0 miles to Helen Street, turn left.
3.0-3.4 miles to Stop 2.

Stop 2: Lake Ontario in East Oswego

From the parking-lot, walk east along the lake shore to the first large exposure of the Oswego sandstone.

A. Thick bedded Oswego sandstone.
B. Two prominent joint sets (east-northeast and southeast striking)
C. Fracture zone about 1 meter wide.

Road log:

3.4-3.6 miles Back-track on Helen Street to the intersection with Mitchel Street and turn left.
3.6-4.9 miles to Middle Road on Mitchel Street, proceed straight across the intersection.
4.9-10.9 miles on Middle Road to State Route 104, turn left.
10.9-26.6 miles to Co. Rt. 22, turn left.
26.6-31.0 miles to Co. Rt. 13, turn right.
31.0-31.2 miles to Cemetery Street (Co. Rt. 22 again), turn left.
31.2-35.7 miles to Falls road, turn right.
35.7-37.0 miles to Stop 3 (Salmon River Falls parking-lot)

Stop 3: Salmon River Falls

From the parking-lot, follow the trail northeast to the top of the falls, and then follow the trail back toward the parking-lot to the entrance to the gorge trail.

A. Oswego sandstone at the top of the falls.
B. Pulaski formation in the gorge.
C. Joints and fracture zones in the Oswego sandstone.
D. Fracture cleavage in the shale beds of the Pulaski formation.
E. Normal fault on the southeast side of the base of the falls.

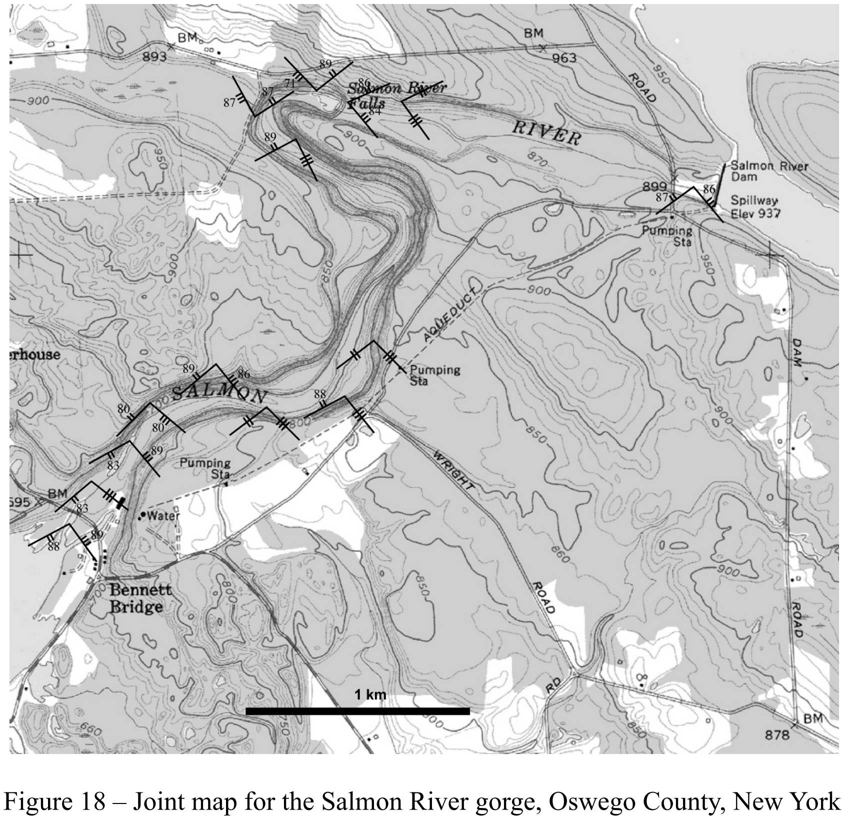


Figure 18 – Joint map for the Salmon River gorge, Oswego County, New York.

Road log:

37.0-38.3 miles on Falls Road to Co. Rt. 22, turn left.
38.3-42.8 miles on Co. Rt. 22 to Co. Rt. 13, turn right.

42.8-48.4 miles to Co. Rt. 2A, turn right.
48.4-50.5 miles to the entrance of I81 headed north.
50.5-62.7 miles on I81 north to Route 193, turn right.
62.7-63.4 miles to Route 11, turn left.
63.4-65.6 miles to Lemay Road, turn right.
65.6-67.7 miles on Lemay Road to a gravel pull-off on the left.

Stop 4: Mooney Gulf.

From the parking area, follow the gravel road into the gulf. There are excellent exposures on the north side of the gulf. See Figure 8 for a detailed joint map of Mooney and Totman Gulfs.

A. Whetstone Gulf formation.
B. East-northeast and southeast striking joints are present.
C. Some joints can be traced 10's of meters.

Road log:

67.7-69.8 miles on Lemay Road back to Route 11, turn right (north).
69.8-73.1 miles to Route 178, turn left.
73.1-85.9 miles on Route 178 to Military Road, proceed straight.
85.9-87.3 miles to North School House Road, turn right.
87.3-87.4 miles to Robert Wehle State Park entrance, turn left.
87.4-87.7 miles on the park road to the parking-lot.

Stop 5: Robert Wehle State Park at Stony Point.

From the parking-lot, walk northwest to the lake shore. There are several trails to the lake shore, but the closest is located behind the tennis court. Once on the lake shore trail, follow it toward the northeast and see the topographic map inset for reference. It will be necessary to traverse down the steep embankment to reach lake level. See Figure 19 for details.

A. Trenton Group limestone.
B. Minor normal faults with mineralized fractures.
C. Fault with no apparent displacement. The fault merges with bedding.
D. Large rock-fall that was controlled by two prominent joint sets.

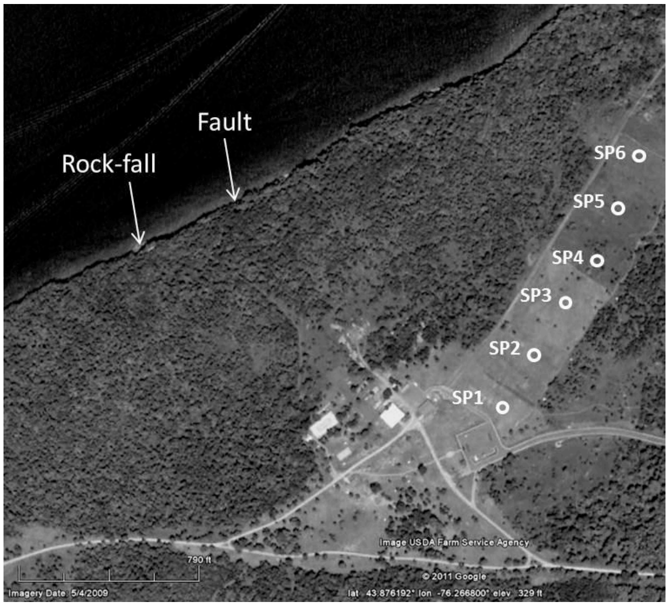


Figure 20 – Google Earth image for Stop 5 showing the locations of outcrops at the lake shore and the locations that azimuthal electrical resistivity surveys were run to reveal joint directions within the park.

Azimuthal Electrical Resistivity for Joint Analysis

Azimuthal ER (AER) involves a Wenner survey around a single point to look for directional variation, which can be impacted by the direction of groundwater-filled joints. The direction of the lowest ER values should correlate with the direction of the most prominent joints (Taylor and Flemming, 1988). At Stony Point, the limestone bedrock is very close to the surface with thin soil. In an attempt to locate joint patterns away from the lake shore, six azimuthal electrical resistivity (ARE) surveys were conducted (Figures 21 and 22). Each AER survey was completed with an automated 24 node system with the azimuthal increment of 30 degrees.

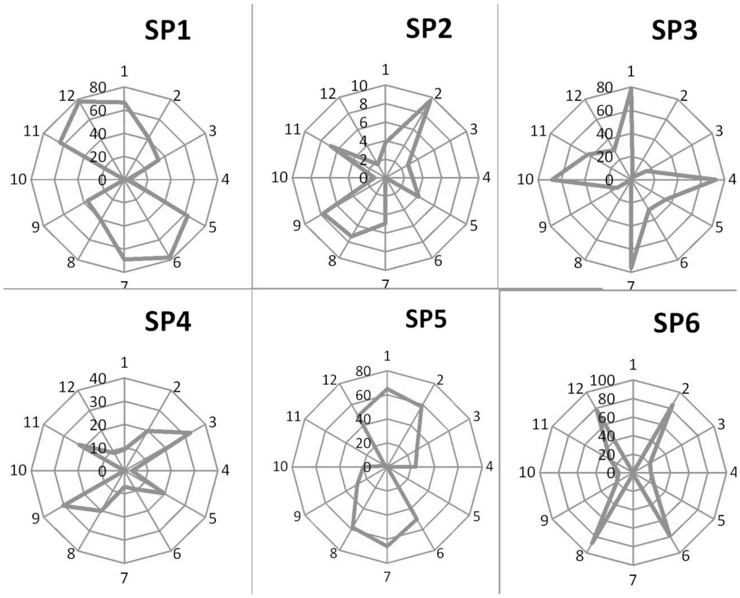


Figure 21 – Azimuthal electrical resistivity surveys that were collected at Stony Point. The ER scale is in ohm-meters. North is in the direction of #1 on each radial graph 30 degree increments for each ER reading.

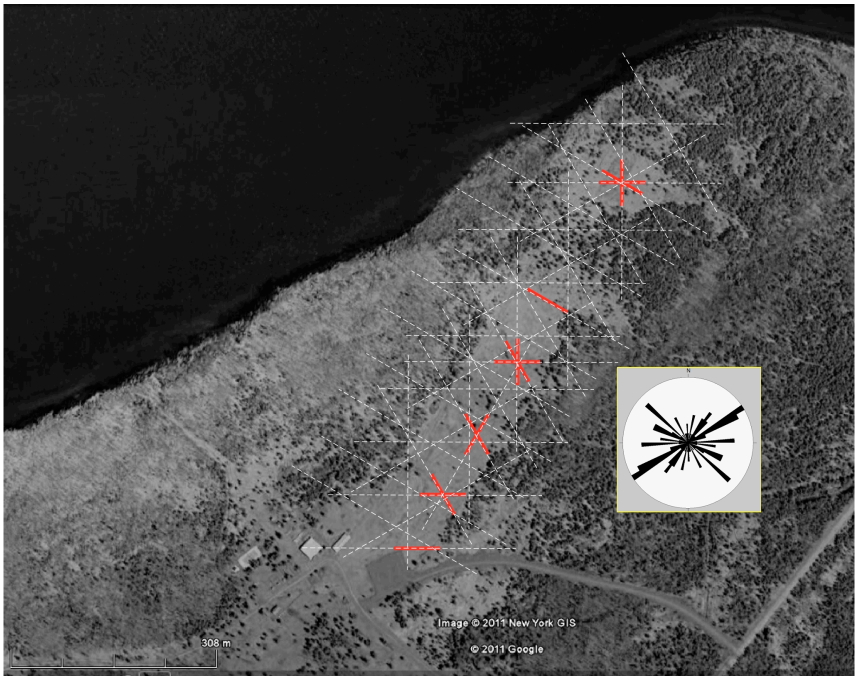


Figure 22 – Interpreted joint directions from the AER surveys at Stony Point. The inset rose diagram is for joint data that was collected at the outcrops on the lake sure (n = 244). The white dashed lines represent the inferred joint directions in the Trenton limestone from the AER results.

Road log:

87.7-88.0 miles Follow the park road back to North School House Road, turn right.
88.0-88.1 miles to Military Road, turn left.
88.1-89.5 miles to Route 178, proceed straight.
89.5-101.9 miles to the entrance of I81 on the left.
101.9-106.0 miles on I81 north to S. Harbor Road (one exit on high-way), turn right at end of exit ramp.
106.0-106.7 miles on S. Harbor Road to Route 177. Proceed straight through the intersection.
106.7-131.4 miles on Route 177 headed east across the Tug Hill plateau. Turn right on Co. Rt. 29.
131.4-139.1 miles on Co. Rt. 29 to the entrance of Whetstone Gulf State Park on the right.
139.1-139.5 miles on the park road to Stop 6.

Stop 6: Whetstone Gulf State Park.

Excellent exposures of Utica black shale occur in the bed of the creek that parallels the park road into the gulf. As well, the Whetstone Gulf formation is exposed in numerous high-walls that can be accessed along the road side farther up the gulf.

A. Utica black shale.
B. Whetstone gulf shale and siltstone beds.
C. Complex joint sets in the Utica formation (see text for details).
D. Follow the trail into the gulf to view the transition from Whetstone Gulf formation to Pulaski formation.
E. Follow the Rim Trail to the head of the gulf to view thick sandstone beds on the lower Pulaski formation.

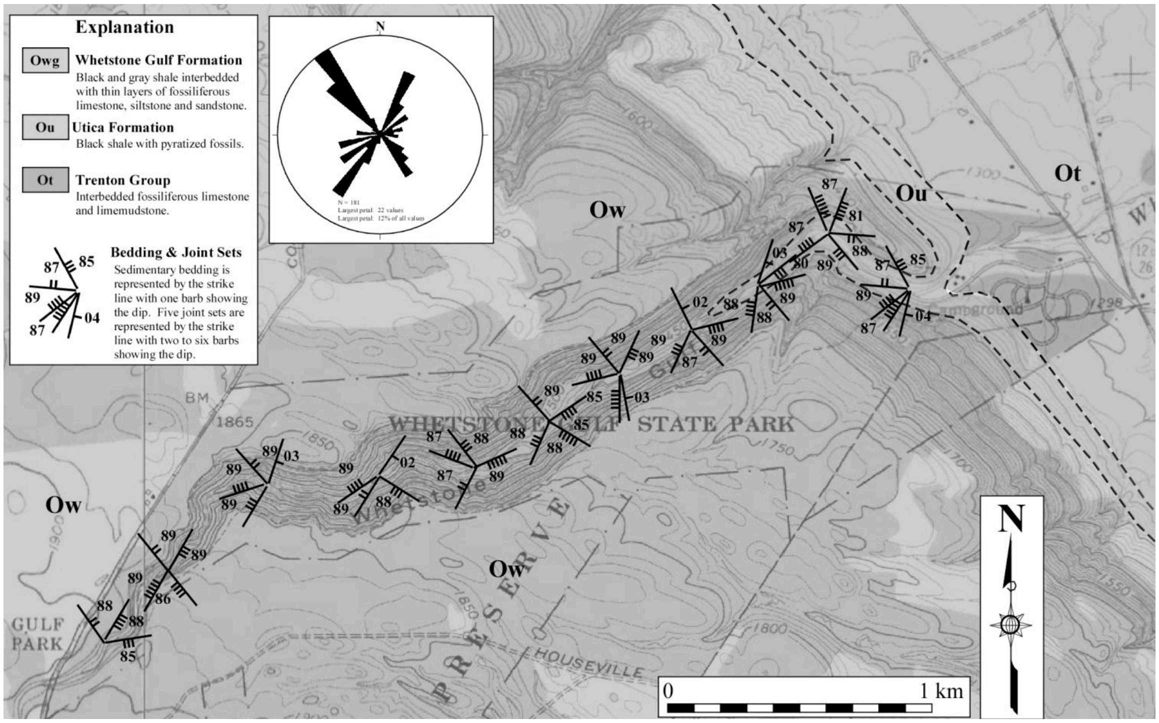


Figure 23. Geologic map of Whetstone Gulf, Lewis County, NY, with emphasis on joints. Mapping completed by A.P. O'Hara, 2009.

Road log:

139.5-139.9 miles on the park road back to the entrance. Turn right onto Co. Rt. 29.
139.9-140.0 miles on Co. Rt. 29 to Co. Rt. 26, turn right.
140.0-148.0 miles to Route 12D, proceed straight.
148.0-156.6 miles to Route 46 (Gorge Road), proceed straight.
156.6-171.2 miles on Route 46 to Wells Creek and Stop 7.

Stop 7: Wells Creek.

Walk along the road that parallels Wells Creek to view excellent exposures of the Utica black shale that directly overlies the Trenton limestone. The limestone is exposed in the bed of the creek.

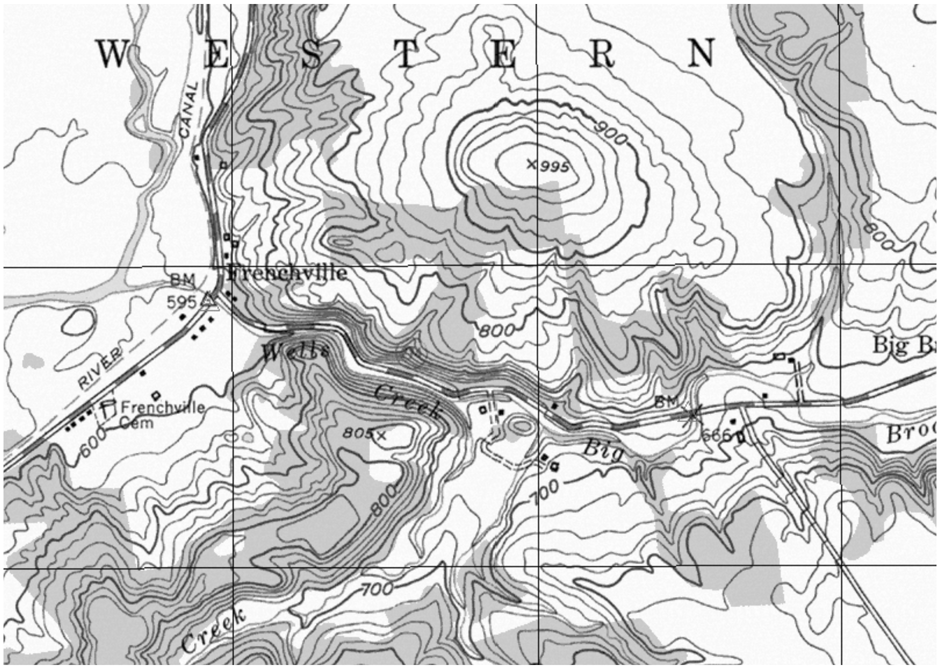


Figure 24 – Topographic map for the Wells Creek area, the location of Stop 7.

End of trip.

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