Bedrock fracture control on surface and subsurface hydrogeology in the Tug Hill plateau and the environmental implications
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Abstract
With sufficient density and aperture, bedrock fractures play a very important role in groundwater infiltration and migration, in addition to the transport of contaminants. During this investigation, the bedrock fractures of Paleozoic formations of the Tug Hill plateau were studied in the context of their relationship with surface drainage and possibly subsurface flow. Understanding the drainage of surface water and the percolation of surface water into groundwater systems, is essential for water quality monitoring and protection. Considering that all of the major drainages that flow from the Tug Hill plateau eventually enter the eastern Lake Ontario basin, and that these drainages carry pollutants from agriculture and from atmospheric deposition, understanding controls on the drainage is fundamental. Therefore, a geographic and geometric analysis of drainage patterns using digital elevation models was examined for the Salmon River watershed (largest drainage basin on the plateau) in conjunction with the detailed fracture analysis for the plateau. A strong correlation exists between fractures in the Oswego Formation and the surface drainage across the formation, but correlations are questionable for other formations in the plateau region. A surface and subsurface hydrologic model was developed that involves rapid transport by fracture controlled drainage that also receives groundwater from inter-basin regions through vertical and horizontal migration through tectonic and bed-parallel fractures.

Introduction
Agricultural and industrial pollutant contamination is a continuing concern for the environmental health of the basins of the Great Lakes, including New York State's contribution to Lake Ontario. Surface and subsurface water from the Tug Hill plateau region is a major contributor to the eastern region of Lake Ontario, and water quality issues have been raised during in a recent report of the Salmon River watershed (McGee, 2008). The Salmon River watershed alone covers upward of 50% of the plateau region (Figure 1). In that report, one of the priority issues is to maintain clean freshwater as a resource as it relates to atmospheric deposition of acid, nitrogen and mercury, and management of the watershed must include the identification of point and non-point pollution sources, sources of sediment influx and contributions from septic systems in the rural regions. Overall, McGee (2008) summarized that current agricultural and forestry activities in the watershed are not in-line with best management practices, and there may be negative impact on water quality. Understanding the flow path of surface water and the migration of surface water into complex groundwater subsurface systems, is essential for water quality protection strategies (Eslinger et al., 1994). Although the transport of contaminants on a regional basis may be primarily by surface streams, influx through the subsurface may play a significant role in some basins (Fetter, 2001). This is especially the case in watersheds underlain by fractured bedrock formations (Engelder et al., 2006; 2007; Jacobi, 2002; Twiss and Moores,
A bedrock fracture investigation in the Tug Hill plateau region of northern New York has demonstrated a correlation between fracture orientations and the various rock types that outcrop on the flanks of the plateau (Stilwell et al., 2005; Valentino et al., 2008; Valentino, 2009; O’Hara et al., 2010). As an estimation how the bedrock fractures contribute to subsurface transport of groundwater (and pollutants in the water), one of the objectives of the current investigation, was to document the degree of interconnectivity between different sets of bedrock fractures, and to examine how the different fracture sets correlate with surface drainage through the use of digital elevation models and drainage maps.

**Figure 1.** Map of the Salmon River watershed showing the drainage pattern for major and minor tributaries (from McGee, 2008).

**Methods**

**Field.** Thousands of bedrock fracture orientations were collected using standard geologic tools (compass) at locations within the limestone, shale and sandstone formations that are exposed in the flanks of the Tug Hill plateau, and along the Lake Ontario shore in Oswego County, NY. Transect mapping was completed in the gulls and gorges that occur are down-cut into the flank of the plateau, while individual outcrops were mapped along the lake shore and in some case at road-cut bedrock exposures (Stilwell et al., 2005; Valentino et al., 2008; Valentino et al., 2009; O’Hara et al., 2010).

**Image Analysis.** Air photographs of shallow-water region of Lake Ontario were obtained from the New York State G.I.S. consortium for macro-lineament analysis. In addition, the trace of
bedrock fractures from on-shore to off-shore was completed by correlating specific fractures, or fracture zones, in the photographs with those identified at the outcrops to “ground truth” the image analysis. At the regional scale, digital elevation model (DEM) data was compiled for the Tug Hill plateau and analyzed for regional fracture and fault zones by identifying major lineaments. Like the image analysis completed along the lake shore, correlation was attempted between major DEM lineaments and the on-ground data. Finally, the drainage pattern for the Salmon River watershed was assessed for possible geometric correlation with lineaments and fracture data.

Results

The bedrock stratigraphy of the western Tug Hill Plateau consists of Ordovician rocks that vary from limestone, sandstone, siltstone and shale (Figures 2 and 3). The structurally lower most rock formation is the Middle Ordovician limestone units of the Trenton Group. A sequence of black shale of the Utica and Whetstone Gulf Formations, overly the Trenton limestone. A gradual increase in siltstone and thin sandstone beds defines the transition into the Pulaski Formation. On the geologic map of New York State (Fisher et al., 1970 – NYS Museum), the Oswego Formation is overlain by red shale and sandstone of the Queenston Formation, however, the Oswego Formation forms the erosion resistant cap for the Tug Hill plateau.

![Figure 2. Bedrock geologic map of the Tug Hill plateau (left). The inset map shows the location relative to New York State (maps from the NYS Museum, Fisher et al., 1970).](image)

All of the bedrock formations of the Tug Hill plateau contain bedrock fracture sets that are subvertical and intersect bedding plane fractures (Figure 4). As well, all the formations have at least two major fracture sets. The Trenton limestone was studied in the region of Henderson Harbor and in the Black River valley. Although there were two dominant fracture sets, the limestone yields the most variable fracture orientations (Figure 5) and highest density (number of fractures per unit volume of rock). The shale of the Utica and Whetstone Gulf Formations contain two major fracture sets with low density (1 per 5 meters across strike). Although the fracture density is low, they are laterally continuous over outcrops that span 10’s of meters. The density of fractures increases (5 per meters across strike) within the inter-layered shale, siltstone and sandstone of the Pulaski Formation (Figures 4 and 5), and is especially well exposed in the Salmon River gorge. Finally, the thick sandstone beds of the Oswego Formation contain fracture sets that are regularly spaced (~1 per meter measured across strike).
Figure 3. General stratigraphy for the Ordovician strata of Tug Hill Plateau region.

Figure 4. Photograph of the Pulaski – Oswego Formation transition in the Salmon River gorge. Note the subvertical fracture sets that intersect the beds (after Stilwell et al., 2005).

The varying resistance and composition of the rock type controls the rate of erosion, and the glacial till serve as barriers and guides for rivers in some cases, but the dominant trends in the rivers appear to be consistent with the fracture orientations. The systematic fracture analysis was compared with the detailed drainage basin pattern from the Salmon River watershed (Figure 1). The length and trend direction of stream segments show a similar overall radial distribution to those of the fracture sets. Rose diagrams were plotted for the trend of stream segments and separated by each bedrock formation (Figures 6 and 7). To date, on the ground fracture data has not been collected in the interior of the Tug Hill plateau due to land access restrictions, however, the rose diagram for the Queenston Formation suggests that there may be north and northeast
striking fracture sets. The drainage pattern for the Oswego Formation has the best correlation with data collected in the field. The stream segments that cross the Oswego Formation have two dominant directions, northeast and northwest, and they are generally parallel to the two dominant fracture sets in the formation. Fractures in the Pulaski Formation do not appear to have much control on the surface drainage pattern. This result is not very surprising due to the lack of erosion resistance that shale and siltstone have relative to the overlying thick sandstone beds of the Oswego Formation.

Digital elevation model data for the Tug Hill plateau was downloaded from the USGS, assembled for lineament analysis. Much of the interior of the Tug Hill plateau is dominated by north-northwest short linear landforms that are recognized as drumlins, and not related to bedrock structure (Figure 8). However, the margins of the plateau are dominated by long (5-10 km) lineaments that trend northwest and north-northwest. Within the northwest region of the plateau where the bedrock is Trenton limestone, there is a regular occurrence of lineaments that mimic the fracture patterns that were observed at outcrops. The long lineaments reflect the steep candidates for fault zones, but field work needs to be completed to test this idea.

Figure 5. Composite air photograph for the eastern Lake Ontario region including Tug Hill plateau (Google Earth 2010). The colored rose diagrams and lines represent fracture data and traces from various bedrock formations. (Purple – Proterozoic crystalline basement in the Moose River region; Pale blue – Trenton limestone; Orange – Whetstone Gulf and Pulaski shale and inter-layered shale, siltstone and sandstone; Yellow – Oswego sandstone.)
**Figure 6.** Drainage pattern for the Salmon River watershed (map from McGee, 2008) superimposed by lineaments (red lines), showing the general direction of stream flow. These lineaments show strong correlation with fracture orientations within the Oswego and Pulaski Formations. Black dashed lines separate the bedrock formations.

**Figure 7.** Rose diagrams showing the trend of drainage segments for the Salmon River watershed. A. Queenston Formation; B. Oswego Formation; C. Pulaski Formation.
Figure 8. Digital elevation model for the Tug Hill plateau with interpreted lineaments that may represent concealed faults and fracture zones. The horizontal distance of the image is approximately 80 kilometers. North is toward the top of the image. DEM data from USGS.

escarpments of the plateau and mark the transition from the cap rock, Oswego sandstone, and the core rock, shale and siltstone of the Whetstone Gulf and Pulaski Formations. Some of the long lineaments and lineament zones (Figure 8) are most likely

Discussion and Conclusions

This investigation has demonstrated that the drainage in the Salmon River basin from the Tug Hill Plateau through agricultural regions of Oswego County into eastern Lake Ontario, is most likely controlled by bedrock fractures. In the subsurface, the subvertical fractures may serve as conduits for groundwater migration. Where these fractures intersect with bedding plane fractures, groundwater migration should continue laterally. Surface runoff will rapidly flush any agricultural or atmospherically deposited pollutants (McGee, 2008) into rivers, and ultimately into Lake Ontario. The time of this process may be days or even weeks during high-flow periods, and there is most likely continuous transport of residual contaminants during other flow conditions. However, contaminants that remain in the soil will slowly migrate into the groundwater system along the steeply inclined bedrock fracture zones described herein. Where
these fractures intersect abundant shallowly inclined bedding plane fractures, the pollutants will then migrate laterally to local tributaries and rivers that flow into the lake (Figure 9), and this process may explain continuous low levels of contaminants that occur in the surface water system (McGee, 2008). The residence time of contaminants is considerably longer in this type of subsurface system, but the time is controlled by the density, aperture and orientation of the fracture zones.

The Trenton limestone that outcrops at the base of the plateau and at lake-level in southern Jefferson County, has some of the highest fracture densities observed during this study. As well, the Trenton limestone has the greatest variability in fracture orientation (Figure 5). In addition to abundant fractures, natural dissolution of limestone leads to increase in fracture aperture which allows for more rapid surface water infiltration and groundwater migration. Within the plateau, the limestone is overlain by a thick sequence of relatively impermeable shale, but the shale beds contain some of the most continuous fractures observed. The calcite content of the shale is sufficiently high in some sections of the Whetstone Gulf formation, and fracture apertures of 1-2 cm were observed. Although the shale is generally impermeable, the presence of continuous open fractures makes it possible for groundwater to readily pass through the formation. Abundant fractures in the Pulaski and Oswego Formations must contribute to groundwater infiltration on the flanks and top of the plateau.

The surface imagery integrated with field work has demonstrated some reasonable correlations between the bedrock fractures and surface drainage, and leads to the conclusion that groundwater flow within the Tug Hill plateau must be equally influenced by fractures. Finally, an overall understanding of the bedrock fractures in the Tug Hill plateau is fundamental for developing a comprehensive model of contaminant transport, as well as for implementing an environmental management plan for the eastern Lake Ontario basin.
Figure 9. Schematic hydrogeologic model for the Tug Hill plateau that integrates both surface water flow and groundwater migration along bedrock fractures (ground surface in the model is a skewed image from Google Earth 2010).
References Cited


