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FAULTS AND FRACTURE SYSTEMS IN THE BASEMENT ROCKS OF THE ADIRONDACK MOUNTAINS, NEW YORK

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INTRODUCTION

While significant progress has been made in our understanding of the Mesoproterozic geologic history of the Adirondack Mountains (Figure 1) and the entire Grenville Province (Chiarenzelli et al. 2011; McLelland et al. 2010; Rivers 2008), relatively little research has been completed on the late, brittle geologic structures since the 1980s (Isachsen and McKendree 1977; Isachsen et al. 1983; Isachsen 1985; Weiner and Isachsen 1987). The Adirondack Mountains (Figure 1) have a distinct, north-northeast and east-northeast trending topographic grain (Figure 2) related to this later brittle history. These fracture systems and faults overprint a region largely shaped by deep-crustal, ductile processes (Gates et al. 2004; McLelland 1984). Fundamental questions regarding the age, origin, and kinematic history of these fracture systems and faults, their influence on the adjacent Paleozoic basins, and their potential for generating earthquakes remain largely unknown and/or loosely constrained. This article is a general introduction to the types of brittle geologic structures found in the Adirondack Mountains rather than a complete summary of all brittle features in the region.
Most of the examples described in this article are in areas that are readily accessible.

FAULTS, FRACTURE SYSTEMS, AND GRABEN

Lineaments

The landscape of the Adirondacks is dominated by long (10s of kilometers [km]) northeast trending linear valleys (e.g., the valleys containing Long Lake, Indian Lake, Piseco Lake, and the northeast arm of the Great Sacandaga Reservoir; Figure 2). The northeast trending lineaments cross cut geologic (rock type) contacts, and it has been argued that the linear persistence of these valleys is due to differential erosion along prominent fracture systems and fault zones (Isachsen and McKendree 1977; Isachsen et al. 1983). These prominent northeast trending topographic features (Figure 2) are dissected by several other lineament sets that trend east-northeast, northwest, east-west, and a minor north-south trending population. The northwest trending lineaments are persistent in the southeastern and northwestern regions of the Adirondacks, where they are nearly parallel to (southeast trending) and cross cut (northwest trending) the Proterozoic geologic structures defined by bedrock mapping. The east-northeast and east-west lineaments are parallel to Proterozoic structure in the southern Adirondacks (south of Piseco Lake), where they form broad arcuate geomorphic discontinuities (Fakundiny 1986), but they also cross cut Proterozoic structures in the central Adirondacks. The minor north-south trending lineaments are significantly shorter than the others and are most likely associated with the Pleistocene glacial history of the Adirondacks.

Figure 1: *Map showing the location of the Adirondack Mountains with respect to the northeast U.S. and Canada.*

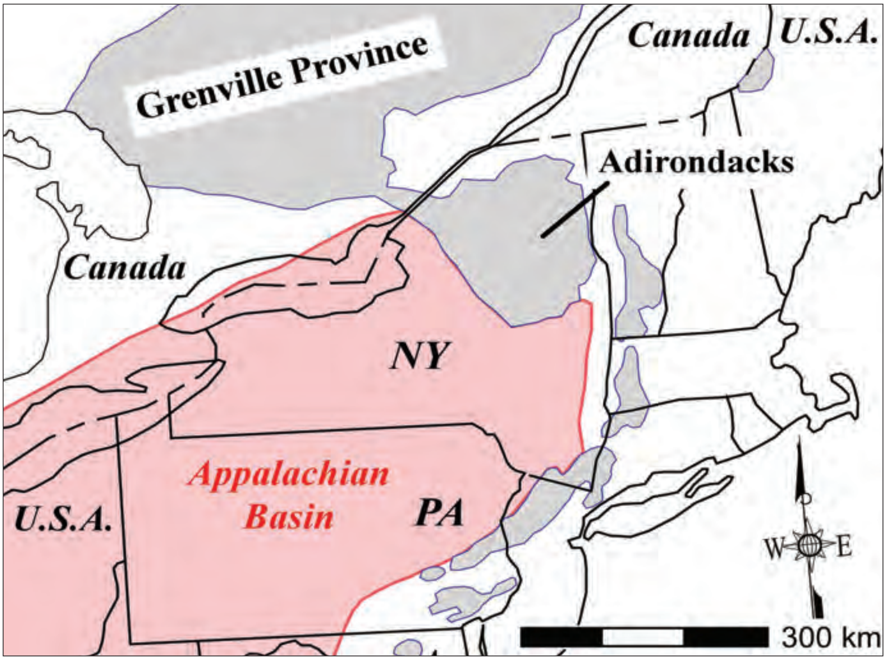
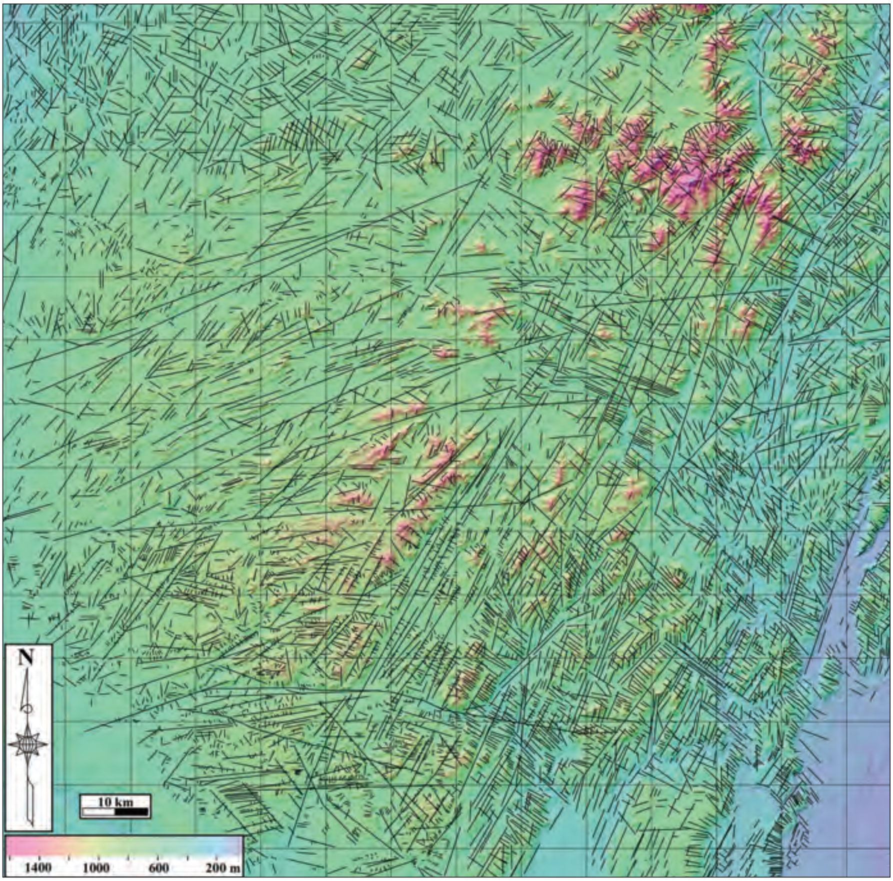


Figure 2: *Digital elevation model of the Adirondack Mountains region with topographic lineaments showing the strong correlation between the landscape and geologic structures.*



Fault Map

The Preliminary Brittle Structures Map of New York (Isachsen and McKendree 1977) illustrates the distribution and general attitude of faults in the Adirondack Mountains (Figure 3). With the exception of a few faults that trace east-west across the central and southern Adirondacks, the region is dominated by northeast striking faults that displace geologic contacts. These northeast-striking faults are mainly normal faults. There are numerous northeast striking normal faults in the eastern half of the Adirondacks Mountains. Within this region, two fault networks cross the entire dome from northeast-southwest. An anastomosing network of normal faults traces more than 150 km from area of Dolgeville, north through Piseco and Indian Lakes, and the high peaks area of Lake Placid. A parallel network of faults trace from Gloversville in the southwest through North Creek and Schroon Lake in the northeast.

Detailed geologic mapping in the vicinity of Indian Lake (de Waard and Romey 1969; Gates et al. 2004; Valentino et al. 2004), paired with documentation of fracture systems and magnetic anomaly profile modeling (Kush et al. 2006; Mantaro and Valentino 2007), shows that the contacts between metaplutonic and metasedimentary rocks, and metamorphic foliation in the Proterozoic rocks, are truncated by a normal fault system. However, magnetic anomalies mapped on Indian Lake suggest a component of sinistral (left-lateral, near-horizontal) offset (Valentino et al. 2012). Farther south, the axis of the Proterozoic Piseco antiform is similarly displaced by sinistral offset at Piseco Lake (Valentino et al. 2012).

Fault and fracture system characteristics

As recognized by earlier researchers, there are few places in the Adirondack Mountains where brittle faults are exposed due to concealment in deep valleys filled with glacial sediments and colluvium, and lakes. Adirondack fault systems are made up of many small faults and fracture zones, which weather to weak, easily eroded rock, and thus hamper our ability to find natural exposures. However, there are some excellent locations where faults, related features, and fracture systems can be examined in the field, specifically on water washed and ice polished rock islands in lakes and the abundant cuts that were made during the construction of the roads in the Adirondacks. Three example locations will be described here: 1) small (<20 m) rock islands at Indian Lake; 2) the Piseco Lake area; and 3) road cuts on Route 8 near Hoffmeister, NY.

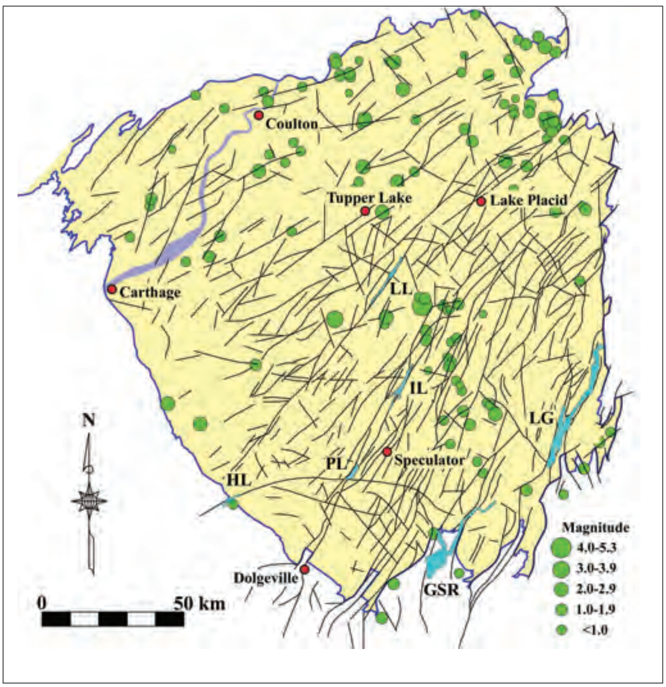


Figure 3: *Fault map for the Adirondack Mountains (after Isachsen and McKendree 1997). GSR-Great Scandaga Reservoir; HL-Hinkley Lake; IL- Indian Lake; LG-Lake George; LL- Long Lake; PL-Piseco Lake. Earthquake epicenters are represented by the green circles with size depicting the magnitude (data compiled from the USGS Earthquake Archive 2016).*

Indian Lake fault zone

A Proterozoic structural dome occurs in the region of Snowy Mountain, immediately west of Indian Lake (de Waard and Romey 1969; Gates et al. 2004; Valentino and Chiarenzelli 2008). The dome is defined by penetrative S-L tectonite developed in gabbroic- and charnockitic-gneisses that surround a core of moderately deformed megacrystic anorthosite. The dome is flanked by metasedimentary belt of rock containing interlayered quartzite, marble, calc-silicate, and pelitic gneiss (deWaard and Romey 1969; Gates et al. 2004). This dome is truncated by the fault zone that occurs beneath Indian Lake (Figure 4), and displacement estimates based on modeling magnetic anomaly data suggest oblique displacement with the vertical component of about 1 km and the horizontal sinistral component of about 2 km (Mantaro and Valentino 2007; Valentino et al. 2012). Well-developed meter-scale zones containing northeast striking, subvertical anastomosing shear fracture (spacing <10 centimeters [cm]) occur in the rock islands at Indian Lake (Kush et al. 2006) composed of charnockitic gneiss (Figure 5A). Faulted, ground up rock (gouge) within these zones consists of broken grains of plagioclase, K-feldspar, quartz, and gash fractures filled with quartz and chlorite (Figure 5B). Detailed fracture maps reveal a network of nearly orthogonal fracture systems south of Indian Lake, where it appears that the main fault zone splays and underlies the southern arms of the lake. Northeast striking shear fractures are most prevalent, and where there are adequate markers, they appear to have experienced sinistral slip. On the contrary, the northwest striking fracture set is less developed and they display dextral (right-lateral, near-horizontal) shear. Based on this information, Valentino et al. (2012) conclude that the northwest striking fractures accommodated counter-clockwise rotation of blocks between two fault splays that experienced sinistral offset (Figure 6).

The Indian Lake fault zone can be traced using lineaments for many kilometers to the northeast and to the southwest of the lake region. Following the lineaments to the southwest, it appears that the fault zone has displaced formation contacts in the area north of Speculator, NY. Continuing farther southwest, the fault zone enters the broad valley of Piseco Lake (Figure 7). Cannon (1937) mapped several steep dipping normal faults in this region based on the offset of geologic contacts and correlation with lineaments. At Piseco Lake, the axis of a Proterozoic antiform defined by metamorphic foliation is clearly offset about 2 km, with the shear sense sinistral but most likely also having a normal component. Fractures were mapped in the regions adjacent to Piseco Lake, and they have a similar orientation to those observed to the northeast (Valentino et al. 2012). It is rare to find natural exposures of the fault rocks in the back country of the Adirondack Mountains because they readily weather due to abundant fracture porosity. However, excellent road cuts immediately south of Piseco Lake display zones of intense fracturing that may represent minor splays off of the main fault zone. One such exposure is a fine example of the variability of developed fractures (Figure 8). Most commonly, the bedrock within and near the fault zones has a fracture spacing ranging from 0.5 to 1 m, but within the fracture zones, the frequency of fractures can be greater than 25 over a distance of less than a meter (spacing <4 cm). Typically, these fracture zones range from a few meters to more than 10 m wide, with transition zones on either side where fracture density gradually increases when traversing from outside to inside the zone.

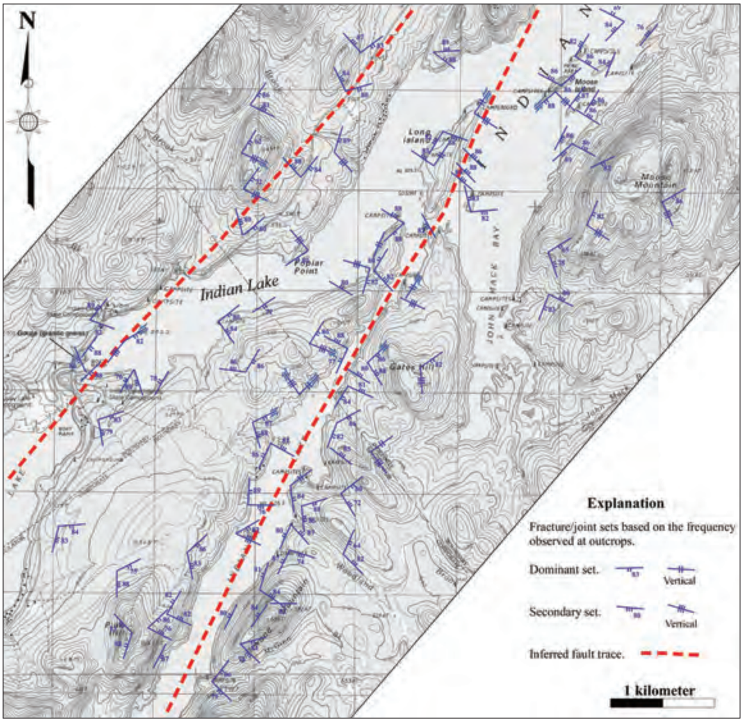


Figure 4: *Fault and fracture map for the southern Indian Lake region.*

Piseco Lake – Propect fault zone

The Indian Lake fault zone intersects the Prospect fault zone in the area immediately southwest of Piseco Lake. Unlike most major faults in the Adirondacks, the Prospect fault cuts across the region with a generally east-west strike, forming a broad arcuate trace, essentially following the ductile structure of the region (Figure 2). Like the other faults, there are few places where the Prospect fault can be observed in outcrop. But it does occur in the bed of the West Canada Creek in the lower reaches of the Ohio Gorge and can be directly observed during times of very low discharge. Within the gorge, the fault is characterized by roughly east-west striking anastomosing shear fractures with narrow (<1 m) breccia and gouge domains developed from the local granitic gneiss. Rare brittle shear sense indicators suggest complex displacement on the Prospect fault with some showing normal shear and other exhibiting strike-slip. A prevalent fracture set that is subparallel to the fault occurs throughout the region of the fault but also in the western Adirondacks in general (Figure 9). The Prospect fault zone is shown on the New York State geologic map to trace westward through Hinkley Lake, where it exits the Adirondack basement and has displaced the Ordovician carbonates of the Trenton Group. A strong linear magnetic anomaly that occurs at Hinkley Lake was interpreted to be the trace of the fault (Hewitt et al. 2009; Valentino et al. 2012).

Hoffmeister area

Outcrops along Route 8 in the west-central Adirondacks contain well developed fault breccia derived from the local granitic gneiss. One of the best examples occurs in an exposure located east of Hoffmeister, NY. At this location the breccia occurs in irregular domains that are upward of 5 m wide. The breccia is defined by variable sized fragments of grantic gneiss with a fine-grained matrix of green chlorite and grains of quartz and feldspar (Figure 10). This breccia occurs where the Prospect Fault appears to be intersected by one of the northeast striking splays associated with the Indian Lake Fault. The lack of breccia exposure beyond the road cut makes it difficult to determine if it is developed in one or both faults. Regardless, this breccia has the typical texture and secondary mineralogy that is observed in most Adirondack faults.

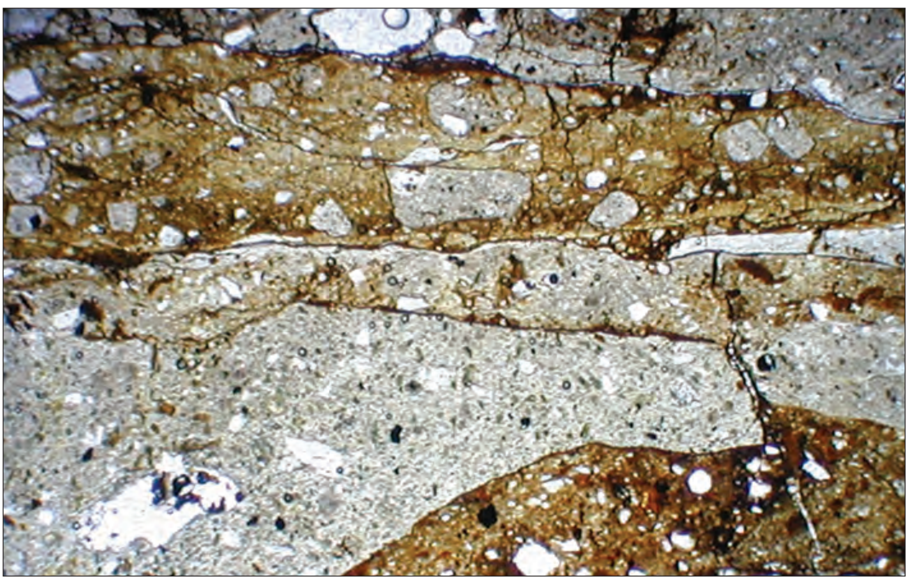
Graben Structures

There are several graben associated with the northeast striking faults. Some of these graben contain Paleozoic strata, indicating that the Adirondack basement was once overlain by Cambrian and Ordovician sedimentary rocks (Isachsen and Fisher 1970; Isachsen and McKendree 1977). Some grabens are filled with Quaternary sedimentary deposits, and others appear to be concealed by modern wetlands and lakes. The graben at Wells, NY (Figure 11) is one of the best exposed and well-known structures in the south-central Adirondacks. The Wells Outlier contains Cambrian sandstones and dolomites, as well as upper Ordovician carbonates and shale, in a down-faulted block approximately 2 km wide and 7 km long, with minimum normal displacement of 1000 m (Miller 1916). The western border fault is projected to the southwest, where it ends in the Mohawk River valley. The northeastern extension of the fault follows the East Branch Sacandaga River and cuts across the Orogen dome. Breccia that is several tens of meters wide is well developed in this fault, and local fractures are subparallel to the zone of fault breccia.

The valley of Piseco Lake was proposed to be a graben (Cannon 1937) bordered by fault splays linked to the Indian Lake fault zone. An integrated structural geology and magnetic gradiometry analysis was completed to develop a geometric and kinematic model for a proposed graben (Valentino et al. 2012). A series of linear magnetic anomalies in Piseco Lake are parallel to the local topographic northeast trending lineaments and subparallel to the dominant fractures that occur in the bedrock immediately west of the lake. As reported by Valentino et al. (2012), magnetic model solutions require the addition of a rock body with a low negative susceptibility, indicating a rock body under the lake that is rich in either quartz or calcite, with Paleozoic carbonate strata as found in other Adirondack graben being the best candidate. It was concluded that Piseco Lake resides over a graben that developed as an oblique-sinistral pull-apart basin (Figure 7) with a throw large enough to preserve Paleozoic strata that once covered the Adirondack basement.

Figure 5A: *Outcrop photograph of charnockitic gneiss at Indian Lake, with thin breccia and gouge zones. Minor drag fold shows sinistral shear on northeast striking fracture.*

Figure 5B: *Photomicrograph of fault breccia from the Indian Lake fault zone at Indian Lake consisting of fragments of granitic gneiss in a fine grained matrix of chloritized granite gneiss gouge.*



TECTONIC IMPLICATIONS

Jacobi and Mitchell (2002) proposed that the deposition of upper Ordovician strata in the Mohawk Valley, south of the Adirondack massif, was controlled by fault bounded structural blocks, demonstrating basement fault activity during Late Ordovician foreland basin development. These faults are the southern extension of major basement faults, such as the Indian Lake Fault Zone. On the western side of the Adirondack Mountains, Wallach and Rheault (2010) suggested that the gentle southwestern incline of the Ordovician strata is directly the result of basement faulting and uplift of the Adirondack dome. They further suggested that reactivation of a major basement shear zone (Carthage-Colton shear zone) and movement on other proposed basement faults based on lineament analysis contributed to the formation of the Tug Hill plateau. The eastern margin of the Adirondacks is bordered by major grabens that host Lake George and Lake Champlain. North of the Adirondacks there is a major fault system in the St. Lawrence River valley (Wallach 2002). Isachsen (1981) described the graben associated with the northeast striking Adirondack fault zones, clearly demonstrating that the Adirondack basement was once covered by Cambrian-Ordovician sedimentary rocks of the Appalachian basin. These basement faults likely served to accommodate the differential uplift of the region from 163 to 183 million years ago (Roden-Tice et al. 2000) – uplift that is largely responsible for the current dome-shaped topographic outline of the Adirondack Mountains region (Isachsen 1985). Taking into account the kinematic information recently documented for several Adirondack faults and the related fractures, it is possible that uplift was accommodated by both normal and sinistral (Figure 12) displacement (Valentino et al. 2012). Additionally, Isachsen (1975, 1981) proposed that Adirondack crust continues to rise, 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).

With a few exceptions, earthquakes that have occurred in the Adirondack Mountains were generally low magnitude (<4.0) and shallow (<5 km). Figure 3 shows the distribution of earthquake epicenters and magnitudes from 1973 to 2016 (data compiled from USGS Earthquake Archive). About 58% of the quakes had a magnitude of less than 2.0, with 40% ranging from 2.0 to less than 4.0 magnitude. Most earthquakes occurred in a broad north-south trending zone that extends from the central Adirondacks toward the St. Lawrence River. Despite the persistence of northeast striking lineaments and fault zones in the Adirondacks, Deneshfar and Ben (2002) concluded that northwest striking faults in the Adirondack Mountains are more likely to exhibit seismic activity. The largest recorded earthquakes in the Adirondack region occurred near Massena in 1944 (magnitude of 5.8), in the Plattsburgh area in 2002 (magnitude 5.3), and in the central Adirondacks in 1983 (magnitude 5.1). Using the first motion of the earthquake P-waves, the fault plane orientations (nodal planes) for the 1983 and 2002 earthquakes were resolved. Both earthquakes appear to be associated with shallowly dipping (<25 degrees), north-northwest striking faults that do not break the earth's surface, suggesting that both of these earthquakes developed under the current east-west directed intraplate tectonic stress.

Figure 6: *Fracture trace map for the Indian Lake fault zone and the kinematic model based on shear fractures associated with the faults (after Valentino et al. 2012).*

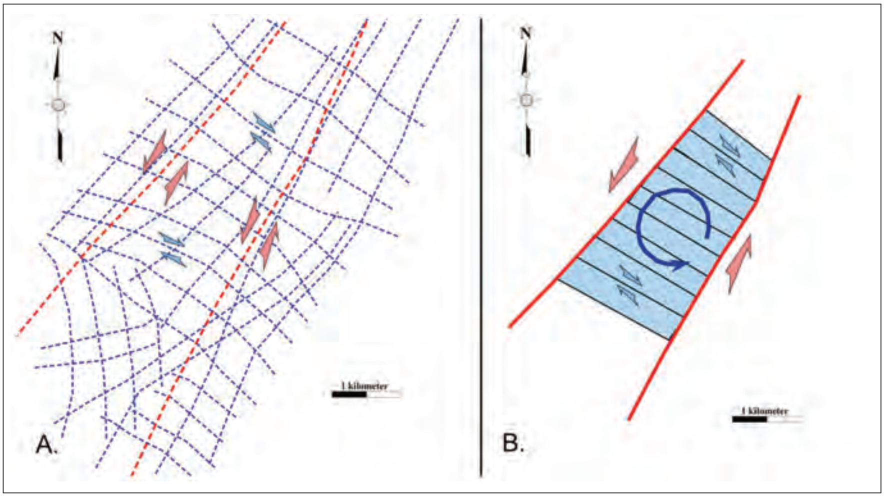


Figure 7: *Magnetic anomaly map that as used to interpret faults under Piseco Lake. The inset rose diagram is a histogram depicting the strike of fracture data that was collected in the area immediately west of Piseco Lake (after Valentino et al. 2012).*

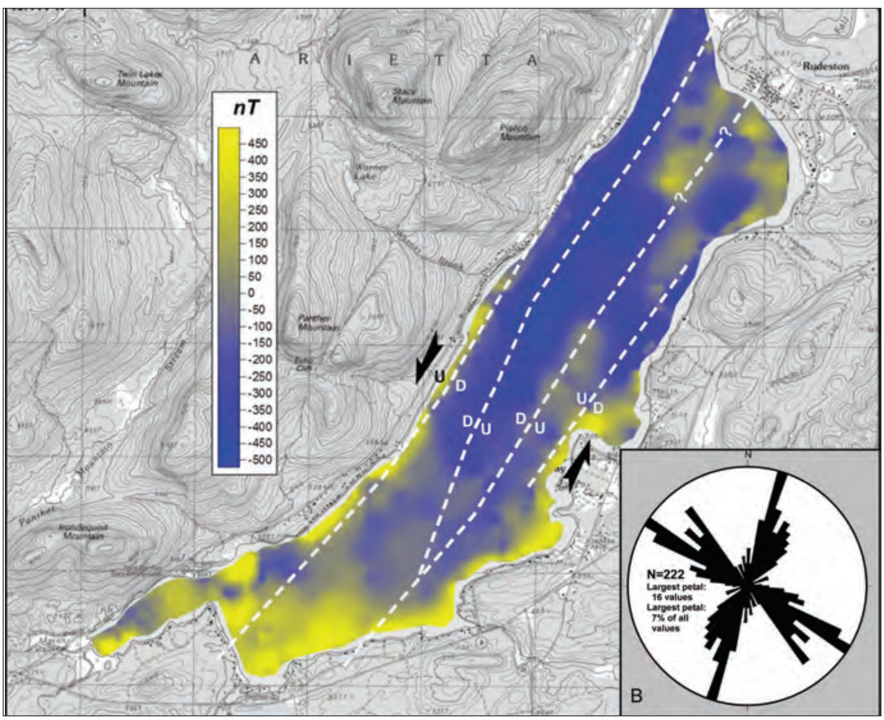


Figure 8: *Outcrop photograph of a fracture zone located west of Piseco Lake. Fracture spacing in the fracture zone is about 4 cm, while the spacing is 50-100 cm for the remainder of the outcrop.*

Figure 9: *Digital elevation model for the central and southern Adirondacks and the transition into the Tug Hill plateau to the west. The contours depict the subsurface elevation for the top of the Trenton Group based on depths obtained from drilled wells. The contours show the gentle southwest tilt of the Paleozoic strata as the result of uplift in the Adirondack dome. Composite rose diagrams for five regions (A-E) in the basement show the strike of subvertical fracture systems.*

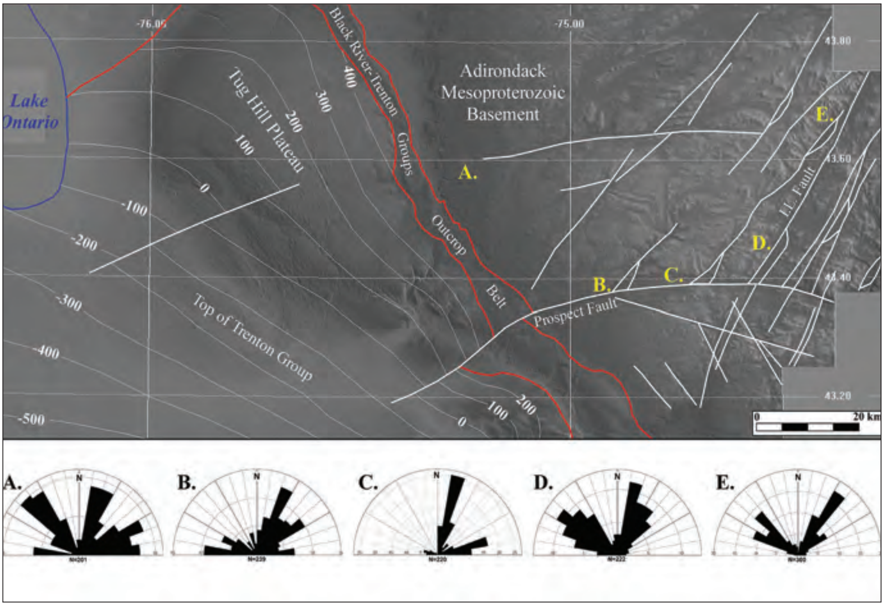
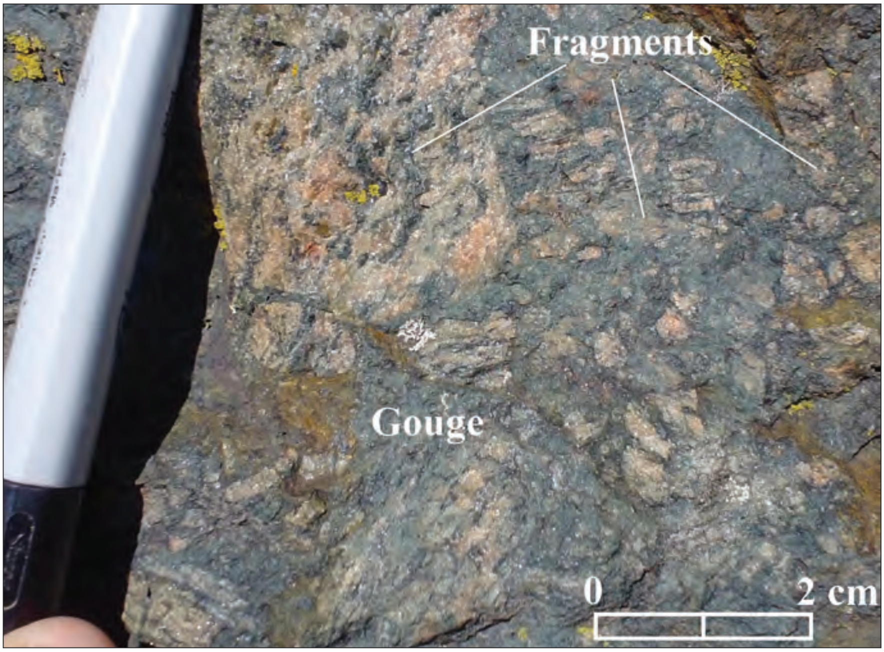


Figure 10: *Outcrop photograph of brecciated granitic gneiss associated with the Prospect fault.*



CONCLUSIONS

1. There are three general groups of topographic lineaments in the Adirondack Mountains with the major northeast trending lineaments being valleys that are underlain by fault zones.

2. The Indian Lake fault zone is one of the most extensive in the Adirondack Mountains, and it extends well beyond the Adirondacks into the Mohawk valley to the south and through the High Peaks region to the north. This fault zone consists of many splays with the total displacement that includes both normal and transcurrent displacement.

3. There are few fault zones that strike east-west in the central and southern Adirondack Mountains, but those that exist, such as the Prospect fault, are well-developed. These faults appear to cross-cut northeast striking faults, as in the area of Piseco Lake, where the Indian Lake fault zone intersects the Prospect fault. The Prospect Fault closely follows the trend of Mesoproterozoic ductile structure across the Adirondack Dome.

4. There are three major steeply dipping fracture systems in the Adirondack Mountains associated with faulting. Northeast striking fractures are linked to the major northeast striking fault zones. Northwest striking fractures occur in structural blocks located between northeast striking faults. East-west striking faults have steeply dipping subparallel fractures.

5. The major northeast striking fault zones locally have associated graben structures, such as the grabens at Wells and Piseco Lake. These fault basins contain Paleozoic strata, providing firm evidence that the Adirondack dome was once covered by younger sedimentary rocks before uplift and erosion in the Mesozoic. As well, there is evidence that these graben developed as pull-apart basins during sinistral-normal shear.

Figure 11: *Simplified map of the graben at Wells, NY (after Isachsen and Fisher 1970).*

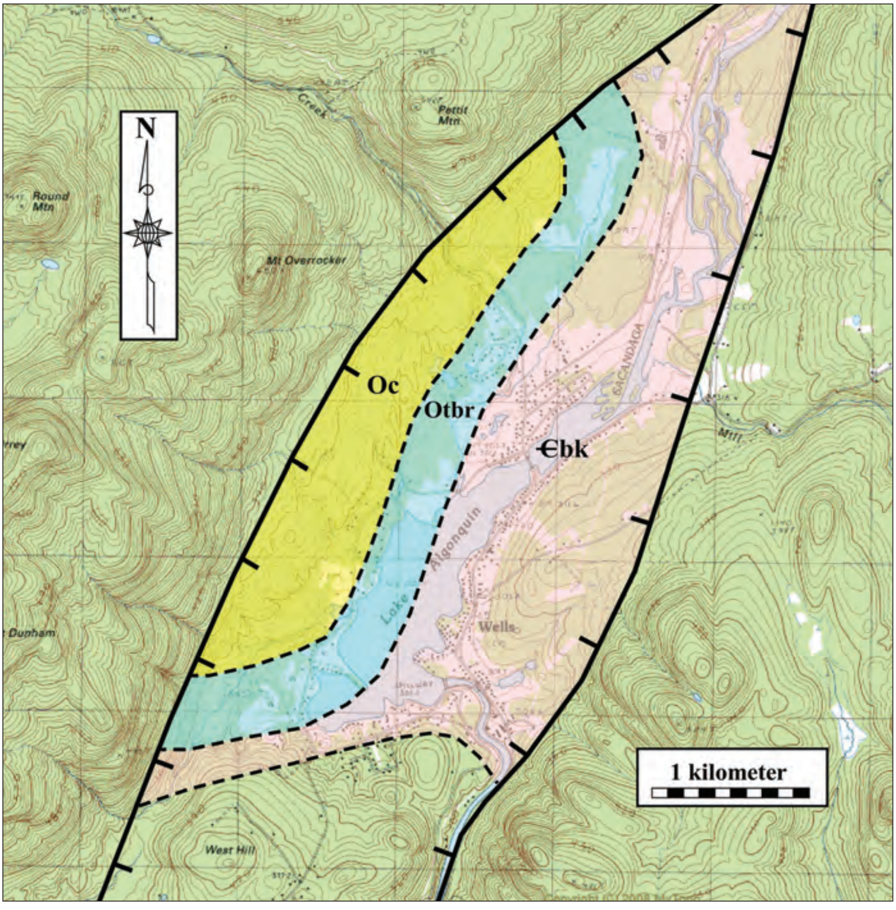
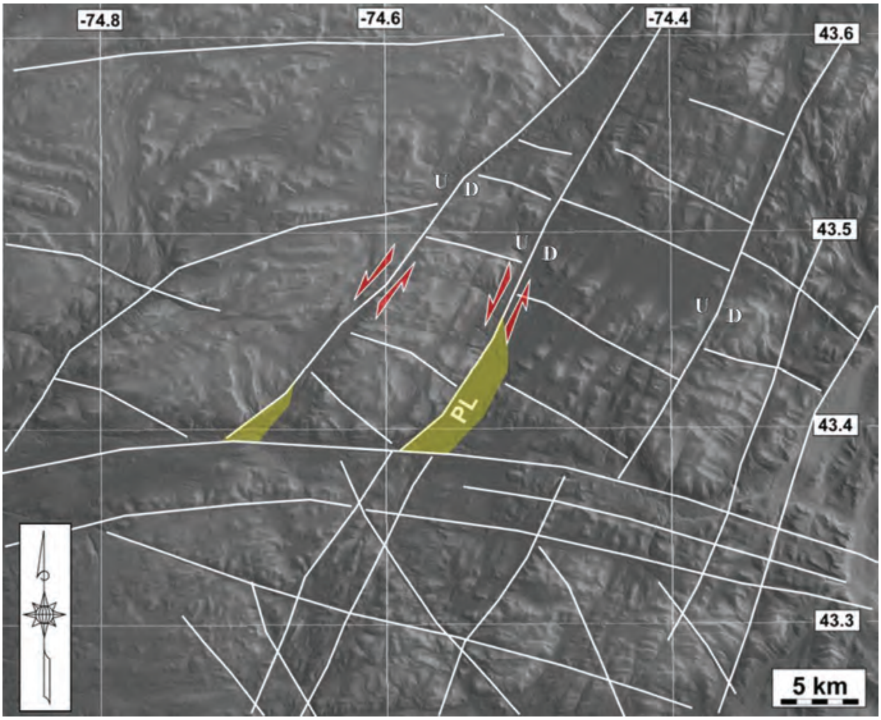


Figure 12: *Structural model for the Adirondack basement to explain the occurrence of faults and three major fracture systems. PL denotes the location of the Piseco Lake graben.*



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LITERATURE CITED

Barosh, P.J. 1986. "Neotectonic movement, earthquakes and stress state in the eastern United States," *Tectonophysics*, 132: 117-152.

Barosh, P.J. 1990. "Neotectonic movement and earthquake assessment in the Eastern United States," *Reviews in Engineering Geology*, 8: 77-109.

Barosh, P.J. 1992. "Northwest-trending basement fracture zones in the Eastern United States and their role in controlling neotectonic movement and earthquakes," *Proceedings of the International Conference on Basement Tectonics*, 7: 409.

Cannon Jr., R.S. 1937. "Geology of the Piseco Lake Quadrangle," *NYS Museum Bulletin*, 312, 107 pp.

Chiarenzelli, J., D. Valentino, M. Lupulescu, E. Thern, S. Johnston. 2011. "Differentiating Shawinigan and Ottawan orogenesis in the Central Adirondacks," *Geosphere*, 7: 2-22.

DeWaard, D. and W. Romey. 1969. "Petrogenetic relationships in the anorthosite–charnockite series of the Snowy Mountain dome, south central Adirondacks. Origin of anorthosites and related rocks," in Y.W. Isachsen (Ed.), *NYS Science, Service Memoir*, 18: 307-315.

Daneshfar, B. and K. Benn. 2002. "Spatial relationships between natural seismicity and faults, southeastern Ontario and north-central New York state," *Tectonophysics*, 353: 31-44.

Fakundiny, R. H. 1986. "Trans-Adirondack Mountains structural discontinuities," in Aldrich, M. J. and Laughlin, A. W. (Eds.), *Proceedings of the Sixth International Conference on Basement Tectonics*, Salt Lake City, International Basement Tectonics Association, 64-75.

Fakundiny, R.H., J. Yang, N.K. Grant. 1994. "Tectonic subdivisions of the Mid-Proterozoic Adirondack Highlands in Northeastern New York," *Northeastern Geology*, 16: 82-93.

Faure, S., A. Tremblay, and J. Angelier. 1996. "State of intraplate stress and tectonism of northeastern America since Cretaceous times, with particular emphasis on the New England-Quebec igneous province," *Tectonophysics*, 255: 111-134.

Gates, A.E., D.W. Valentino, J.R. Chiarenzelli, G.S. Solar, M.A. Hamilton. 2004. "Exhumed Himalayan-type syntaxis in the Grenville orogen, northeast Laurentia," *Journal of Geodynamics*, 37: 337-359.

Hewitt, E., D. Valentino, J. Chiarenzelli. 2009. "Magnetic anomaly mapping and subsurface modeling of Hinckley reservoir, Hinckley, New York," *Geological Society of America, Abstracts with Programs*, 41(3): 31.

Isachsen, Y.W. 1975. "Possible evidence for contemporary doming of the Adirondack Mountains, New York, and suggested implications for regional tectonics and seismicity," *Tectonophysics*, 29: 169-181.

Isachsen, Y.W. 1981. "Contemporary doming of the Adirondack mountains: further evidence from releveling," *Tectonophysics*, 71: 95-96.

Isachsen, Y.W. and D.W. Fisher. 1970. "Geologic map of New York: Mohawk sheet," *New York State Museum, Map and Chart Series*, 15, scale 1:250000.

Isachsen, Y.W., E.P. Geraghty, and R.W. Wiener. 1983. "Fracture domains associated with a neotectonic, basement-cored dome: the Adirondack Mountains, New York," in R.H. Gabrielsen et al. (Eds.), *Proceedings for the Fourth International Conference on Basement Tectonics*, International Basement Tectonics Association, 287-306.

Isachsen, Y.W., E. Landing, J.M. Lauber, L.V. Rickard, and W.B. Rogers. 1991. *Geology of New York, A simplified account*. New York State Museum/Geological Survey, The University of the State of New York, The State Education Department, Educational Leaflet (28).

Isachsen, Y.W. and W.G. McKendree. 1977. "Preliminary brittle structures map of New York," *New York State Museum Map and Chart Series*, 31, Scale 1:125,000.

Jacobi, R. 2002. "Basement faults and seismicity in the Appalachian Basin of New York State," *Tectonophysics*, 353: 75-133.

Jacobi, R. and C. Mitchell. 2002. "Geodynamical interpretation of a major unconformity in the Taconic Foredeep: slide scar or onlap unconformity?" *Physics and Chemistry of the Earth*, 27: 169-201.

Kush, E., N. Mantaro, and D. Valentino. 2006. "The Indian Lake faut zone and Snowy Mountain dome, central Adirondack Mountains, New York," *Geological Society of America, Abstracts with Programs*, 38(2): 37.

Mantaro, N. and D. Valentino. 2007. "Magnetic modeling of the Snowy Mountain dome and the Indian Lake fault zone," *Geological Society of America, Abstracts with Programs*, 39(1): 79.

Mareschal, J.C. and P.D. Zhu. 1989. "Focal mechanisms of small earthquakes and the stress field in western Quebec Adirondack region," *Tectonophysics*, 166: 163-174.

McLelland, J. 1984. "Origin of ribbon lineation within the southern Adirondacks, U.S.A." *Journal of Structural Geology*, 6: 147-157.

McLelland, J., 1985. Structure and Rock Fabric Within the Central and Southern Adirondacks , New York State Geological Association, 57th Guidebook, p. 186-210.

McLelland, J.M., B.W. Selleck, and M.E. Bickford. 2010. "Review of the Proterozoic evolution of the Grenville Province, its Adirondack outlier, and the Mesoproterozoic inliers of the Appalachians," in R. Tollo et al. (Eds.), *From Rodinia to Pangaea*: The lithotectonic record of the Appalachian region. *Geological Society of America Memoir*, 206, p. 21-29.

Miller, W.J. 1916. "Geology of the Lake Pleasant quadrangle," *New York State Museum Bulletin*, 182, 75 pp.

Rivers, T. 2008. "Assembly and preservation of upper, middle, and lower orogenic crust in the Grenville Province-Implication for the evolution of large, hot, long-duration orogens," *Precambrian Research*, 67: 237-259.

Roden-Tice, M. and S. Tice. 2009. "Regional-scale mid-Jurassic to Late CretaceousUnroofing from the Adirondack Mountains through central New England based on apatite fission-track thermochronology," *Journal of Geology*, 113: 535-552.

Roden-Tice, M.K., S.J. Tice, and I.S. Shofield. 2000. “Evidence for differential unroofing in the Adirondack Mountains, New York State, determined by apatite fission track termochronology,” *Journal of Geology*, 8: 155-169.

United State Geological Survey, Earthquake Archive. Accessed 2016 from http://earthquake.usgs.gov/earthquakes/search.

Valentino, D., J. Chiarenzelli, E. Hewitt, and D. Valentino. 2012. “Applications of water-based magnetic gradiometry to assess the geometry and displacement for concealed faults in the southern Adirondack Mountains, New York, U.S.A.,” *Journal of Applied Geophysics*, 76: 109-126.

Valentino, D. and J. Chiarenzelli. 2008. “The southern Adirondack sinistral transpressive shear system,” *Field trip guidebook* of the Friends of the Grenville 37th Annual field meeting, 1-56.

Wallach, J. 2002. “The presence, characteristics and earthquake implications of the St. Lawrence fault zone within and near Lake Ontario (Canada–USA),” *Tectonophysics*, 353: 45-74.

Wallach, J. and M. Rheault. 2010. “Uplift of the Tug Hill Plateau in northern New York State,” *Canadian Journal of Earth Science*, 47: 1055-1077.

Weiner, R.W. and Isachsen, Y.W. 1987. “Detailed studies of selected well-exposed fracture zones in the Adirondack Mountains dome,” *New York, US Nuclear Regulatory Commission Technical Report (NUREG/CR-3232),* 82 pp.

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