Implications of Structures in Unoriented Cores of Utica Black Shale

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ABSTRACT

We performed detailed structural analyses on 713.5 m (2341 ft) of Ordovician Utica black shale core from 7 boreholes in the Mohawk Valley region of NYS. We documented 1148 veins and 3 clean fractures, including 58 veins and fractures with slip described in the table below. Sense of slip was deduced from releasing bends (rhombochasms) in calcite-filled fractures, bedding offsets, and slickenside/fiber orientation. That normal, thrust, and oblique slips are observed on fractures are consistent with foreland basin and escape tectonics.

Factors affecting downhole fracture frequency include distance to fault, fault throw, lithology, and the presence of fault splays. Cores in this study are generally too far (>250 m) from major NNE/NE striking Taconic faults for fracture frequency to be affected by the main faults according studies by Agle et al. (2006) and O'Hara et al. (2015), even for faults with large throw. Five cores have % total organic carbon (TOC) x-ray fluorescence (XRF), and/or % sand data. Of the 17 clusters of high fracture frequency (fracture intensification domains, FIDs), 7 correlate with higher values of brittleness indices. A combination of the factors above and the possible presence of subsurface fault splays could explain the location of FIDs in the cores. Fracture clusters in 74NY10 at the Trenton-Utica contact were omitted because they may represent complications associated with karst collapse and subsequent sediment infilling. In cores with TOC data, possible beef structures correspond to higher TOC intervals, which could indicate overpressure from gas generation was approximately contemporaneous with calcite veining. These relationships provide a check of possible gas/vein ages when coupled with subsidence curves.

CORE LOCATIONS

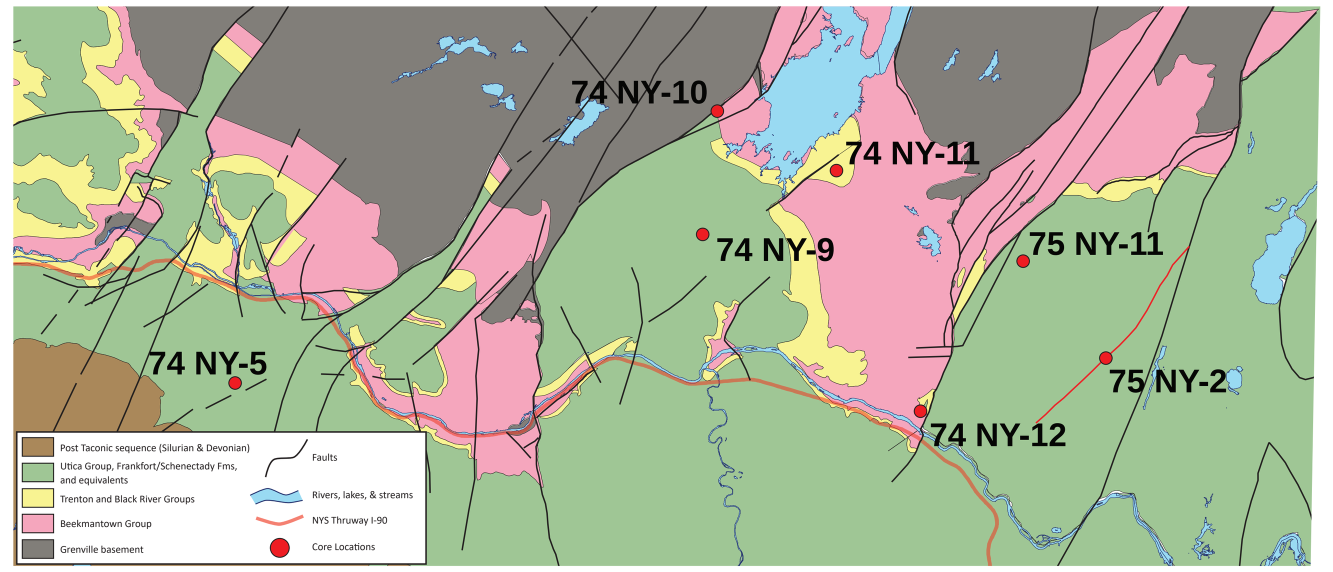


Figure 1. Geology of the Mohawk Valley region with major fault systems and core locations. The "Taconic" Mohawk Valley faults were generally thought to be normal faults related to plate flexure and plate subsidence as the Laurentian plate entered the subduction zone (Figure 4A) followed by possible reverse motion during Late Taconic contraction (e.g., Jacobi, 2003). However, the Macdonald et al. (2014) model suggests that the Taconic plate tectonic model is more complex and that the Mohawk Valley faults may be the result of retroarc thrust loading (Figure 4B).

Table 1. Core Information. Cores listed from east to west.

core #	Fault Name	core dist. to fault (km)	throw (m)	Distance to thrust front (km)	Utica recovered in core (m)	Total Veins+	Slip: Normal	Slip: Thrust	Slip: Oblique/ Strike Slip	Slip: Bedding Plane Slip	Slip: Dip Slip unresolved motion
75-NY-2	Saratoga-McGregor	0*	137	8	137.4	328	11	16	0	0	0
75-NY-11	Hoffmans	1.73	381	23	113.7**	46	2	1	1	0	4
74-NY-12	Hoffmans	0.55	381	23	53.6	412	0	0	1	0	1
74-NY-11	Fonda	0.87	>40	45	3.7	142	0	0	0	0	0
74-NY-9	Fonda	2.54	>40	45	101.5	134	1	0	6	1	0
74-NY-10	E. Stone Arabia	1.46	24	58	83.2	74	4	4	0	0	0
74-NY-5	Mother Creek	3.97	137	68	220.4	12	0	0	0	0	0

* Core is on a fault splay (Isachsen 1980; Tice, 1993); ** Represents core examined. Total Utica recovered is 163.19 m; + No veins are dated.

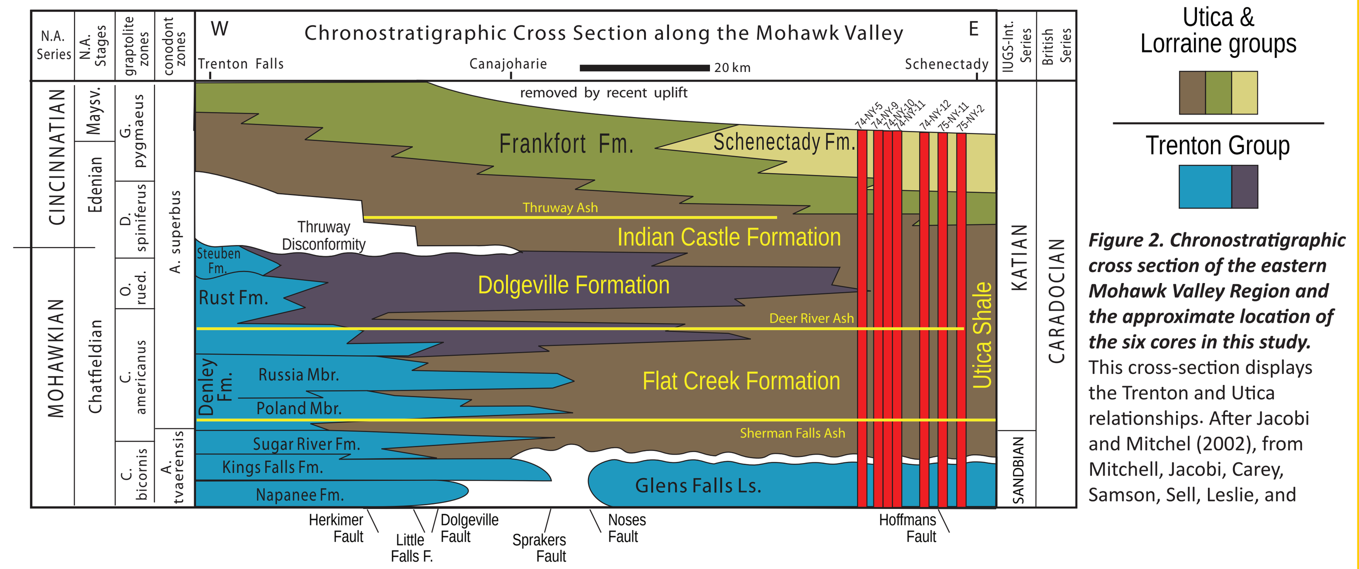


Figure 2. Chronostratigraphic cross section of the eastern Mohawk Valley Region and the approximate location of the six cores in this study. This cross-section displays the Trenton and Utica relationships. After Jacobi and Mitchell (2002), from Mitchell, Jacobi, Carey, Samson, Sell, Leslie, and Brett (2005).

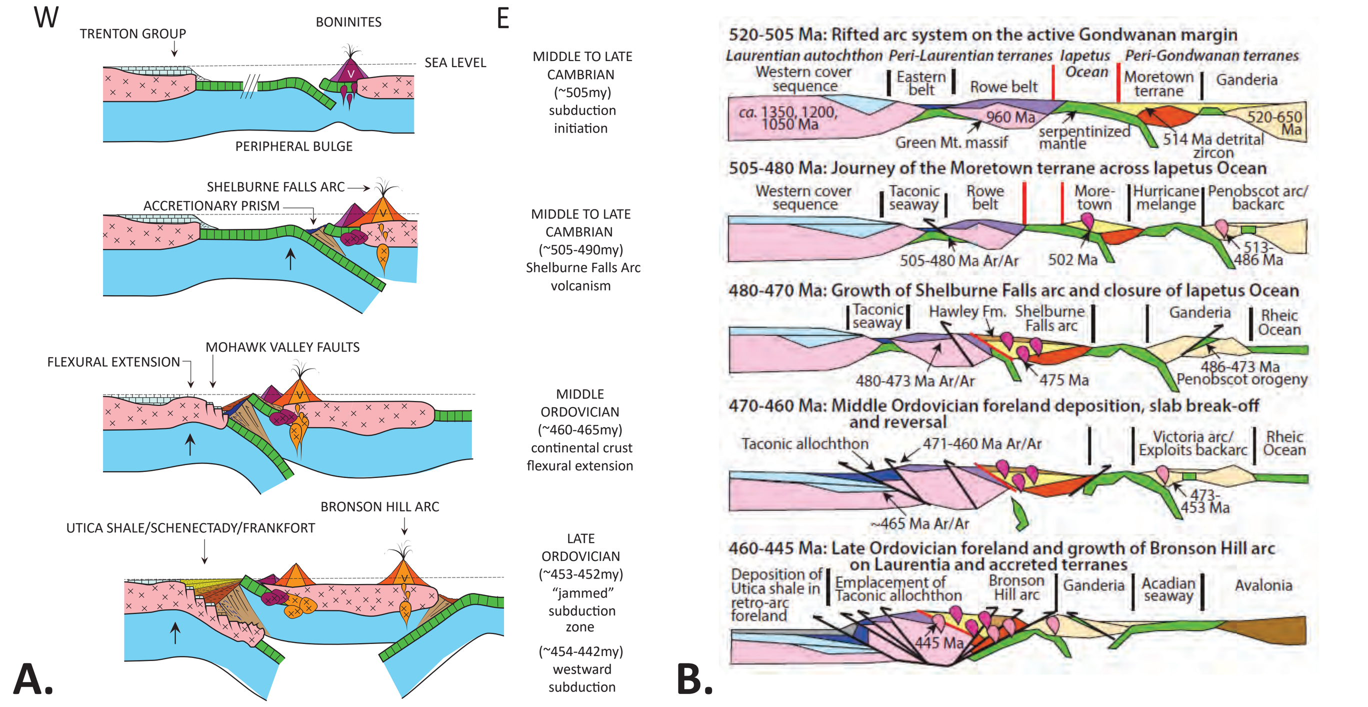


Figure 3A. The older Taconic subduction model includes normal faults created by flexural extension and eastward subduction of Laurentia. From O'Hara and Jacobi (2014), after Jacobi (1981), Stanley and Ratcliffe (1985), Bradley and Kidd (1991), Kim and Jacobi (1996, 2002), Karabinos et al. (1998).
Figure 3B. Model by Macdonald et al. (2014). In contrast to the older models, this more recent model), based primarily on detrital zircon provenance, suggests a much more complicated scenario.

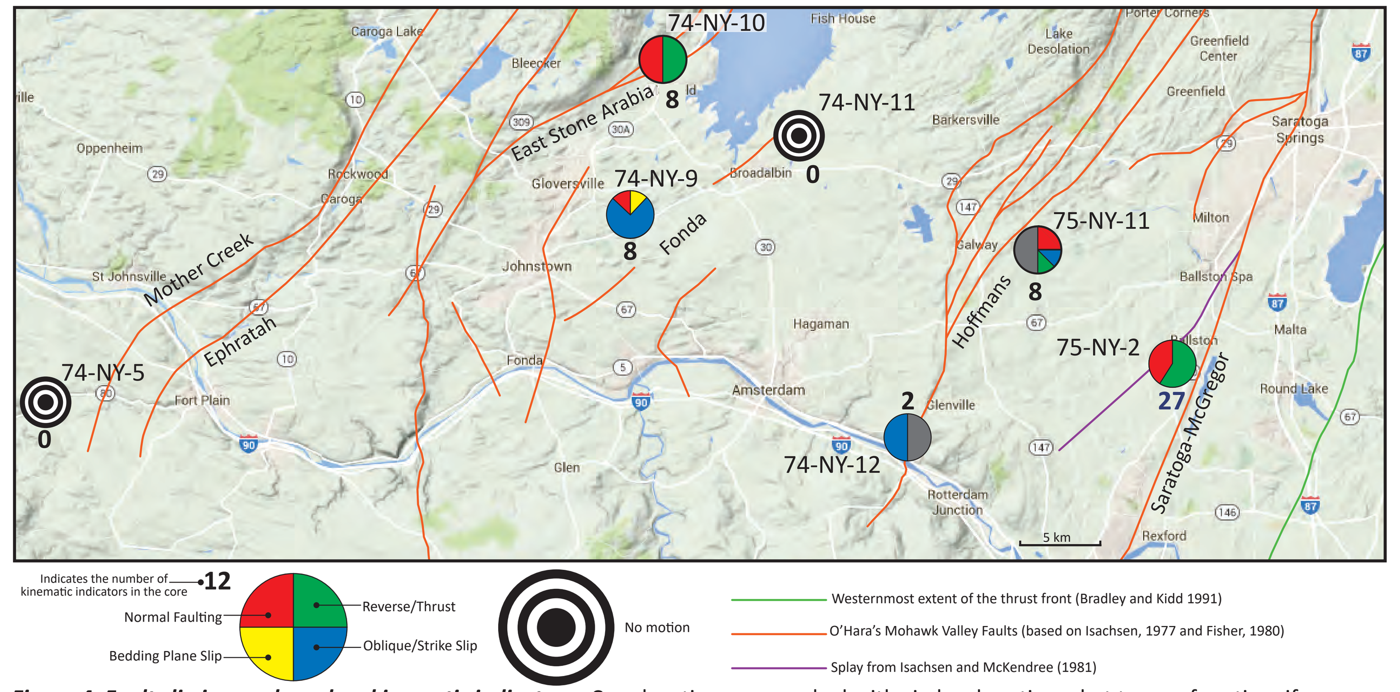


Figure 4. Fault slip in core based on kinematic indicators. Core locations are marked with circles denoting what types of motion, if any, are inferred from kinematic indicators. The size of the pie slice corresponds to the relative number of features with each type of sense of slip. The sense of slip is inferred from releasing bends (rhombochasms) and restraining bends in calcite-filled fractures, bedding offsets, and slickenside/fiber orientations.

FAULTING and KARST COLLAPSE IN 74-NY-10

Figure 5. Photos A-D are from the damage zone at the contact of the Utica and Trenton Groups in 74-NY-10. The damage zone is interpreted as a fault zone in photos A and B, and a karst collapse feature in photos C and D. ***A. Normal fault along a non-planar calcite vein.*** Motion was determined from the offset of a pyrite-rich layer. ***B. Shear in the fault zone. C. Brittle calcite deformation.*** Shale filled the gaps between calcite crystals. The shale was not yet completely lithified at the time of karst collapse. ***D. Karst collapse breccia.*** The red line indicates the wall of calcite crystals (dogtooth spar) and the wall of the karst. (See inset for conceptual diagram of dogtooth spar). Photos A, C, and D by Jacobi.

EXAMPLES OF STRUCTURE IN THE CORES

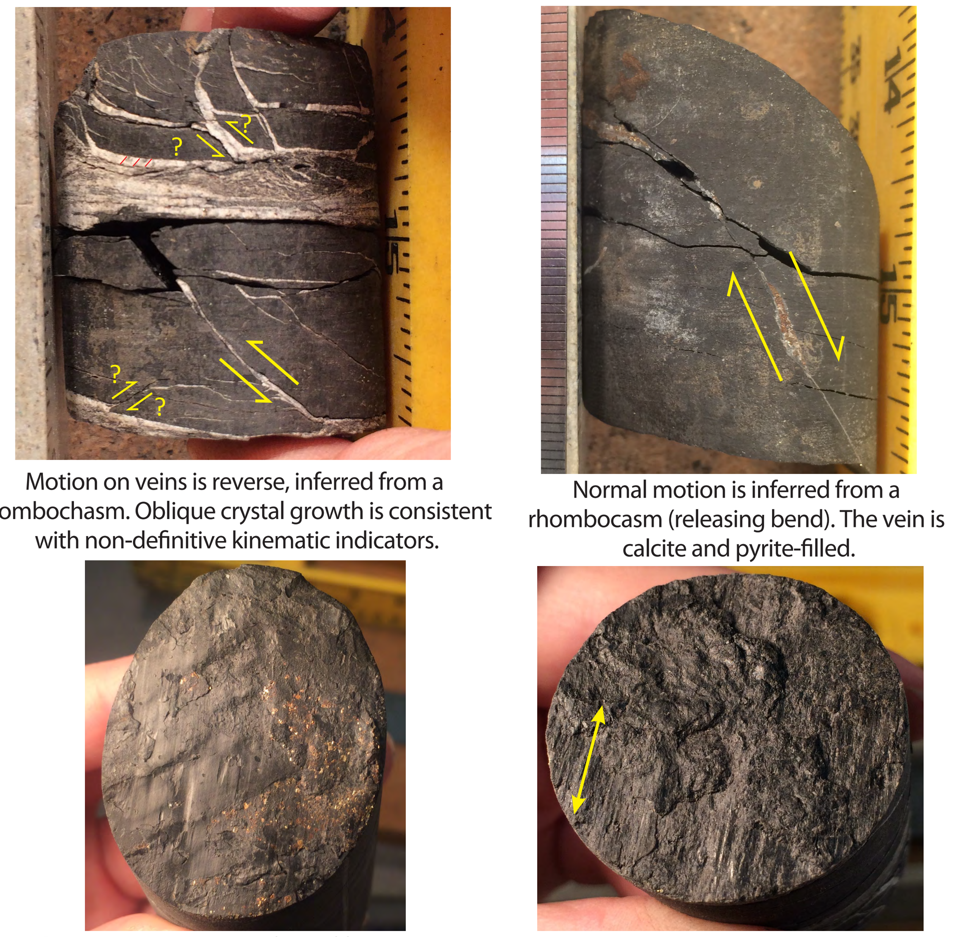
74-NY-9

Slickensides with rake of 19 degrees indicate oblique slip.

Sub-horizontal slickenfibers (parallel to bedding) indicate strike slip motion.

Bedding-parallel polished/worked surface.

75-NY-11



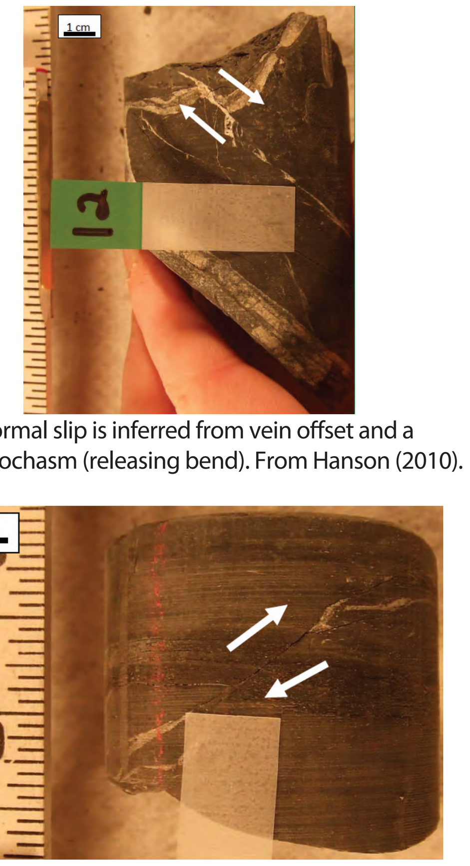
Motion on veins is reverse, inferred from a rhombochasm. Oblique crystal growth is consistent with non-definitive kinematic indicators.

Normal motion is inferred from a rhombocasm (releasing bend). The vein is calcite and pyrite-filled.

Striations along the surface of fracture 11.

Slickensides indicate bedding-parallel slip.

75-NY-2



Normal slip is inferred from vein offset and a rhombochasm (releasing bend). From Hanson (2010).

Reverse slip is inferred from bedding offset and a restraining bend along the fault. From Hanson (2010).

Figure 6.

BEEF STRUCTURES and BURIAL HISTORY

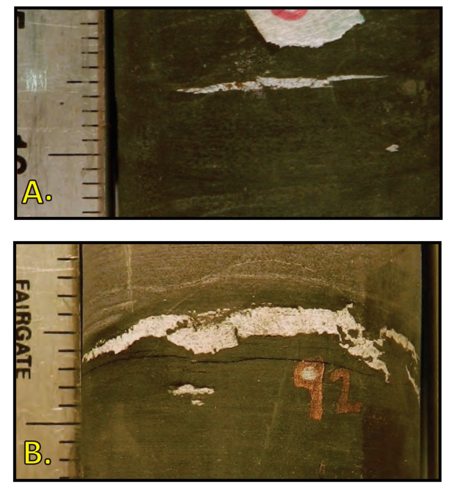


Figure 7: Examples of potential beef structures from 74-NY-9. Beef structures are bedding-parallel calcite-filled fractures formed at sites of opportunity created by the overpressure during gas generation. Zones of beef fracturing correspond to intervals with high TOC (Al Duhailan et al., 2015). Potential beef structures identified in the cores do correspond with high TOC intervals. Based on Figure 8, these structures most likely developed in the Alleghanian, or late (neo) Acadian when peak gas generation occurred.

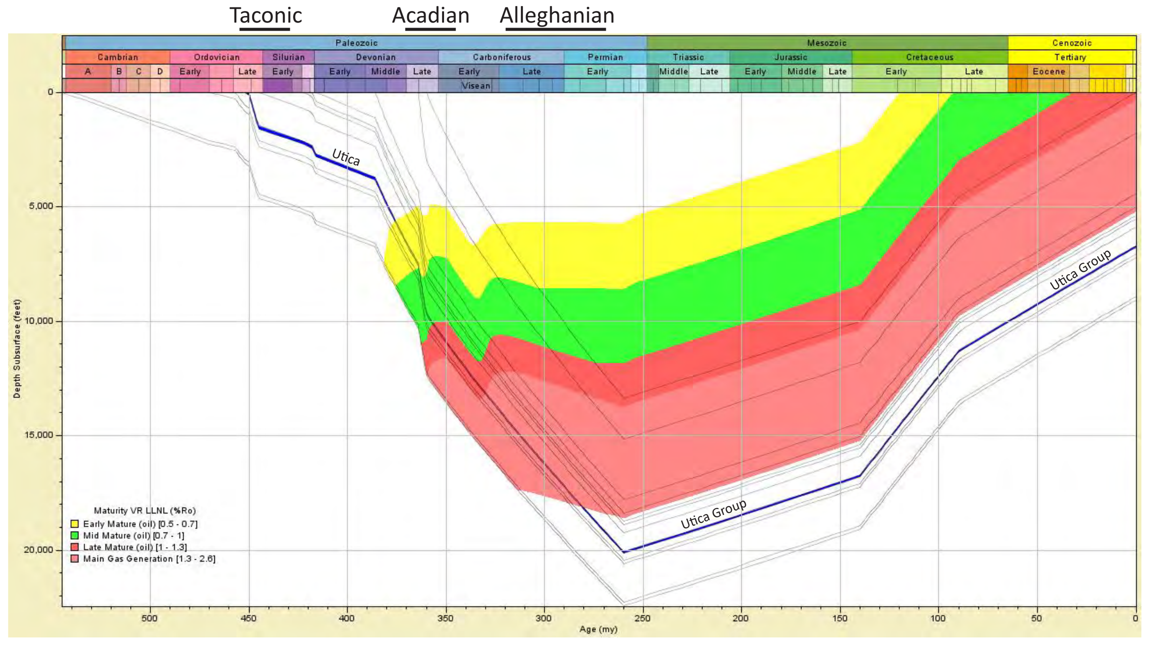
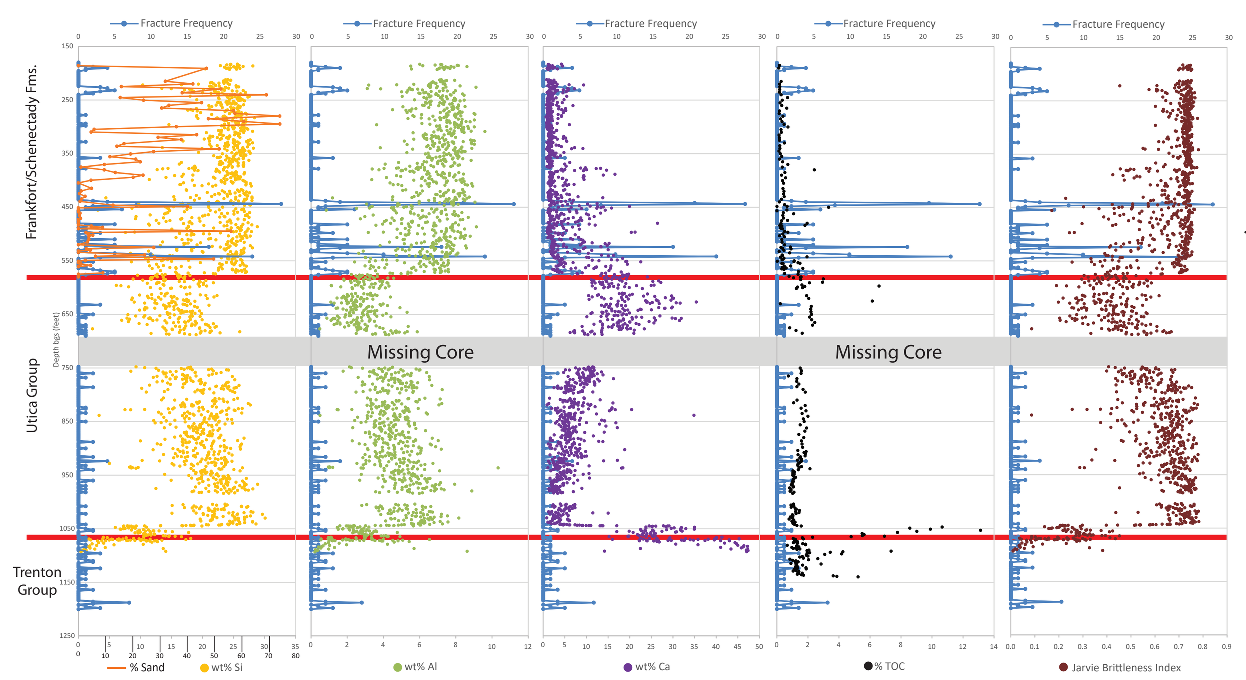


Figure 8. Subsidence/maturation curve for a well in northeast Delaware County, NY. Based on the subsidence curve, veined fractures with bitumen are likely to be Acadian or later, (assuming no hydrothermal circulation) not Taconic. The late age of the veins agrees with conclusions by O'Reilly and Parnell (1999) and Pommer (2013). (Planned Re-Os dating of sulfides and perhaps the bitumen in the veins hopefully will provide an age for these veins). Plot by C. Willan of EQT.

BRITTLENESS

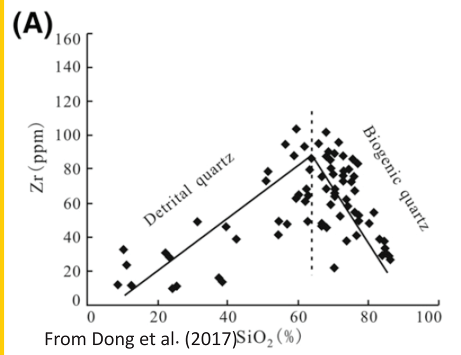


$$BI = \frac{V_{quartz}}{V_{quartz} + V_{calcite} + V_{clay}}$$

BI = brittleness index
V = volume
Jarvie et al. 2007

Figure 9. Fracture frequency vs. geochemistry and brittleness index. The X-ray diffraction data above are used as proxies for mineralogy of 75-NY-2. Aluminum is a proxy for clay (e.g., Lash and Blood, 2014), silicon a proxy for quartz (Dong et al., 2017), and calcium a proxy for calcite (Liu et al., 2013). Also shown are TOC and the brittleness index (BI) using Jarvie et al.'s (2007) formula shown on upper right. XRF data from Sabota (2015).

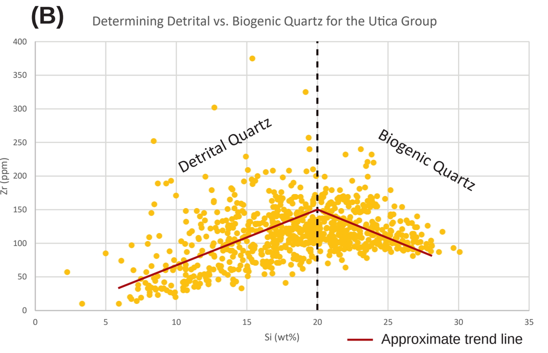
Figure 9 (continued). A study by Dong and others (2017) found clay content to be the most important mineralogical factor in determining the brittleness of shale. Quartz and carbonate increase brittleness, whereas TOC and clay reduce brittleness. Intervals of high fracture frequency in the Frankfort/Schenectady Formation have a higher concentration of quartz and low TOC, which is intuitively correct, but also have high clay and low calcite, which is counter to expectations. The low fracture frequency Utica section has similar percentages of quartz, clay, and calcite as the high fracture frequency clusters in the Frankfort/Schenectady interval. It is clear that a multivariate function strongly influences the fracture frequency, not just one.



From Dong et al. (2017)

Figure 10A (left). Silica versus zircon plot for samples from Horn River Fm core. Detrital versus biogenic quartz is determined by the slope of the trend line: positive slope indicates detrital quartz, negative slope indicates biogenic quartz.

10B (right). Silicon versus zircon for the Utica Group of 75-NY-2. Values greater than 20% indicate biogenic silica, which enhances brittleness. (Dong et al., 2017). Figure 9 indicates that much of the lower section of the Utica contains biogenic silica (wt% Si >20%). The increasing concentration of Si downsection in the Utica interval suggests that tthe lower section of the Utica is more brittle than the upper section.



CONCLUSIONS

1. Cores 74-NY-9 and 74-NY-12, and 75-NY-11, associated with the Fonda and the Hoffmans faults display kinematic indicators consistent with strike slip and oblique slip. In 74-NY-9, 75% of the kinematic indicators express oblique or strike slip. Strike slip motion has been proposed for NNE and NE striking faults by Jacobi et al. (2013, 2014, 2015) based on 3D seismic, map patterns, and field studies where releasing and restraining bends have been observed.

2. The presence of normal, thrust, and oblique/strike slip motion is consistent with foreland basin and escape tectonics during the Taconic Orogeny as well as reactivation of the Mohawk Valley faults during subsequent orogenies and rifting. Depending upon the age of the vein-filled fractures, normal motion could be from basin subsidence resulting from Taconic or Acadian thrust loading, thrust motion from Taconic/Salinic retroarc thrusting or Alleghanian tectonics, and oblique and strike slip motion related to Taconic/Acadian escape tectonics or Alleghanian slip of Africa past Laurentia.

3. Clusters of high fracture frequency in 75-NY-2 correspond to peaks in the percentage of sand. The high fracture frequency interval has high quartz and low TOC, but high clay and low carbonate. Quartz and calcite are generally considered to increase the brittleness of a rock, TOC and clay to decrease it. The low and high fracture frequency intervals have similar values for quartz, clay, calcite, and TOC, which indicates that mineralogy alone may not predict where fractures will form in regions where local fault splays may affect areas away from the master faults.

4. Subsidence/maturation curves strongly suggest that at least two types of vein-filled fractures did NOT form during the Taconic unless hydrothermal fluid migration occurred. Rather, the veins with bitumen probably developed in the Acadian/Alleghanian, and the gas-generated beef structures developed in the Alleghanian.

5. Cores in this study are generally too far from major Mohawk Valley faults (>250 m) for fracture frequency and aperture in the cores to be affected by the faults according to a study by O'Hara et al. (2015). This finding is consistent with previous field studies that showed the influence of Mohawk Valley faults on fracture frequency is generally less than 250 meters (Agle et al., 2006). Anomalous FIDs in the cores are likely due to unmapped faults or fault splays.

6. A damage zone at the Utica-Trenton contact in 74-NY-10 displays complex brittle and ductile deformation (Figure 5). There are vein kinematic indicators that suggest down dip (normal) motion in the fault zone above a deformed section interpreted as karst collapse with no apparent kinematic indicators. Karst collapse implies local uplift above the water table or subaerial exposure of the Trenton Group from a combination of sea level change and tectonic fault block motion.

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