Faulting and Mineralization in the Cambro-Ordovician Section of the Mohawk Valley

Saturday Field Trip A1

Guidebook for the field trip held October 7th, 2006
in conjunction with the 35th Eastern Section AAPG Meeting
and 78th NYSGA Field Trips
held in Buffalo, NY

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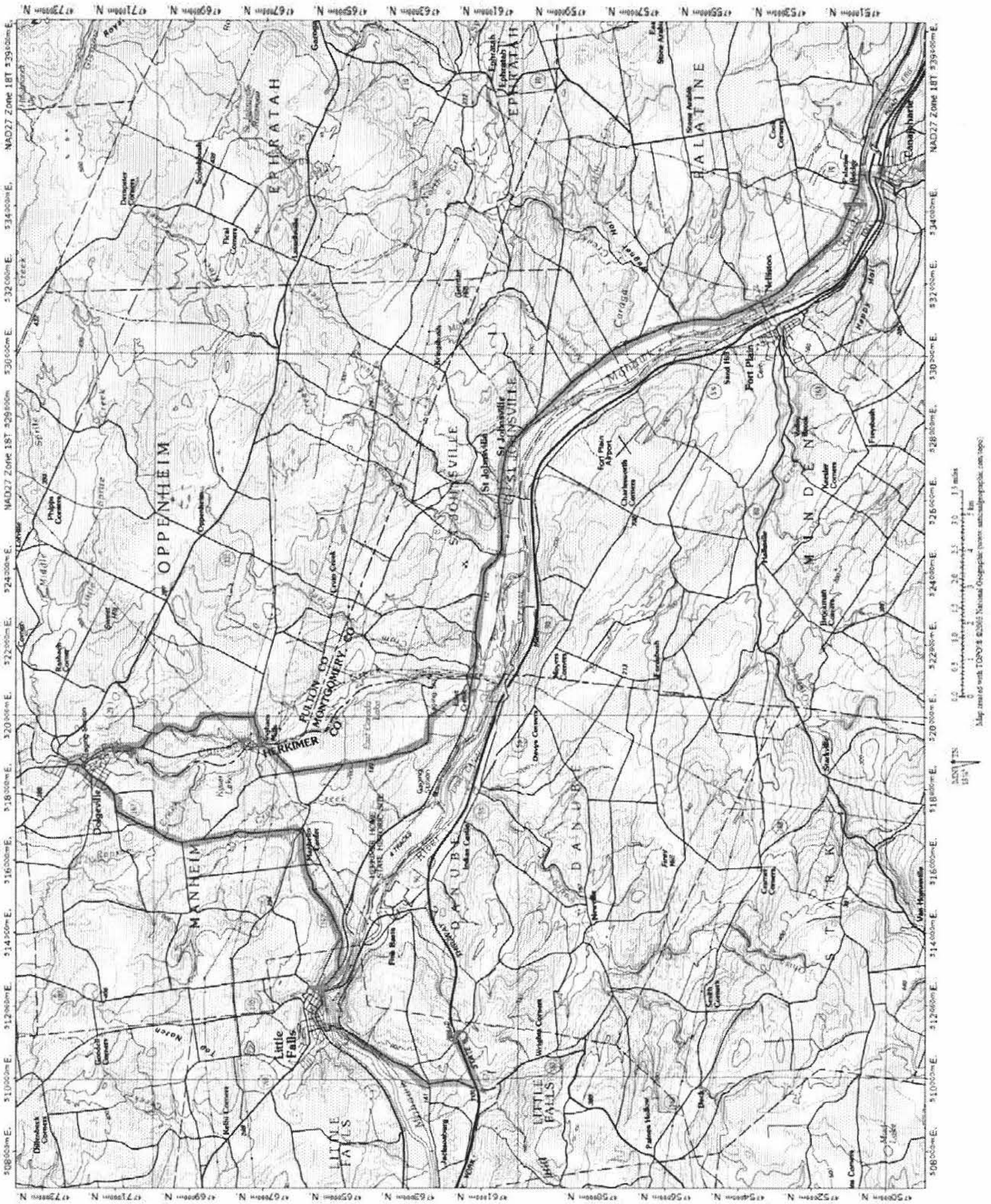


STOP 1: Palatine Bridge Quarry
STOP 2: Ingham Mills
STOP 3: Dolgeville Dam
STOP 4: Outcrop at Rts 5&169
STOP 5: Thruway Cut
Optional Stops also included

INTRODUCTION

The Cambro-Ordovician section in the Mohawk Valley region is one of the most well known and longest studied Cambro-Ordovician sections in the world. From Amos Eaton in the 1820s (e.g., 1824) to Vanuxem (1834, 1838, 1843) to Emmons (1842), Schuchert (e.g., Clarke and Schuchert, 1899) to Ruedemann (1897, 1925) to Cushing (1905) to Kay (1937, 1968) to the more recent geologists (e.g., Bird and Dewey, 1970; Fisher, 1977, 1979; Fisher et al., 1970; Landing et al., 1996; Jacobi 1981, 2002; Bradley and Kidd 1991; Bradley and Kusky, 1986; Cisne and Rabe, 1978; Cisne et al, 1982; Mitchell et al., 1994; Goldman et al, 1994; Lehmann et al, 1995; Brett and Baird 2002; Baird and Brett 2002), and many, many more (see review in Jacobi and Mitchell, 2002), the Cambro-Ordovician geology in the Mohawk Valley (Fig. 1) has provided critical data for understanding Cambro-Ordovician stratigraphy (Fig. 2) and the inferences that can be drawn from the stratigraphy and structure. For example, the original application of plate tectonics to land geology utilized the Mohawk Valley geology (Bird and Dewey, 1970; Fig. 3A), as have revisions to the original model (e.g., Jacobi, 1981; Fig. 3B; Bradley and Kidd, 1991; Fig. 3C). More recently, the Mohawk Valley section has functioned as the test case for detailed volcanic ash geochronology (tephrachronology) and graptolite correlations (e.g., Mitchell et al., 1994), and for gauging the relative importance of tectonic versus eustatic sea level signals on the apparent sequence stratigraphy in the basin (e.g., Mitchell et al., 1994; Lehmann, 1994; Joy et al., 2000; Jacobi and Mitchell, 2002; Brett and Baird, 2002; Baird and Brett, 2002).

During the past decade, the Mohawk Valley section has been used as an analogue for subsurface hydrocarbon reservoirs in the Cambro-Ordovician section. The major gas discoveries in the Trenton/Black River in central NYS (and elsewhere) have driven a renewed interest in the exposed Mohawk Valley Cambro-Ordovician section. The present attention involves determining and understanding the factors that controlled the development of the Cambro-Ordovician gas reservoirs.

The present field trip examines a spectacular quarry floor that is a probable analog for the dolomitized Trenton/Black River reservoirs in central NYS. Trenches, cores, GPR, and waterblasting of the outcrop led to an integrated, very comprehensive picture of how secondary porosity and dolomitization develop. The field trip also visits faults that may have been the pathways for the fluids that dissolved the limestone, resulting in vuggy porosity, and that precipitated hydrothermal dolomite and other minerals in the void space. The trip includes several optional outcrops that display the stratigraphy and the characteristic porosities in various units. Finally, the trip stops at the well-known NYS Thruway locality where the Thruway Disconformity is exposed, separating ribbon limestones of the Dolgeville Formation from the overlying black shale of the Utica (Indian Castle Member). This last stop is particularly interesting for those who have an interest in the black shales of the Utica. Because of severe time constrains, the trip cannot stop at all the localities, but we have included the optional stops for geologists to visit at a later date. Here we can examine in outcrop the stratigraphy, faults, fluid migration along these faults, and tectonics in the Mohawk Valley.

This field trip is the outgrowth of the work of two research groups, the NYS Museum Reservoir Characterization Group (e.g., Smith and Nyahay, 2005), and the UB Rock Fracture Group (e.g., Jacobi and Mitchell, 2002). Each group has worked for some time in the Mohawk Valley; the

NYS Museum Reservoir Characterization Group has investigated a hydrothermal dolomite reservoir analog in the Palatine Bridge Quarry (STOP 1); their integrated technologies yielded a significant understanding of the hydrothermal systems. The Reservoir Characterization Group led a workshop and field trip to this site, (Smith and Nyahay, 2005). The UB Rock Fracture Group and iTAS (Integrated Tectonics and Stratigraphy Group at UB) have been working on stratigraphy and structure farther west in the western part of the Mohawk Valley sequence for 25 years (albeit sporadically; e.g., Ritter, 1983; Mitchell et al., 1994; Jacobi and Mitchell, 2002).

Below we first review the Mohawk Valley Cambro-Ordovician stratigraphy that incorporates the units and structures we will inspect on this field trip. Overall, the Cambro-Ordovician sequence in the Mohawk Valley records a Laurentian passive margin carbonate bank that is overstepped by black shales and later coarser clastics. The overstep resulted primarily from a continent/island arc collision wherein the Laurentian continental passive margin first passed over the peripheral bulge and then dropped down into an east-dipping subduction zone (e.g., Jacobi, 1981; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). A eustatic sea level rise may have been superimposed upon the tectonic signal (e.g., Brett and Baird, 2002). We also review the structure of the region, and the concepts involved in the dolomitization and development of the porosity typical of the Cambro-Ordovician carbonate section. A key component of the trip will be the link between faulting, fluid flow and reservoir development.

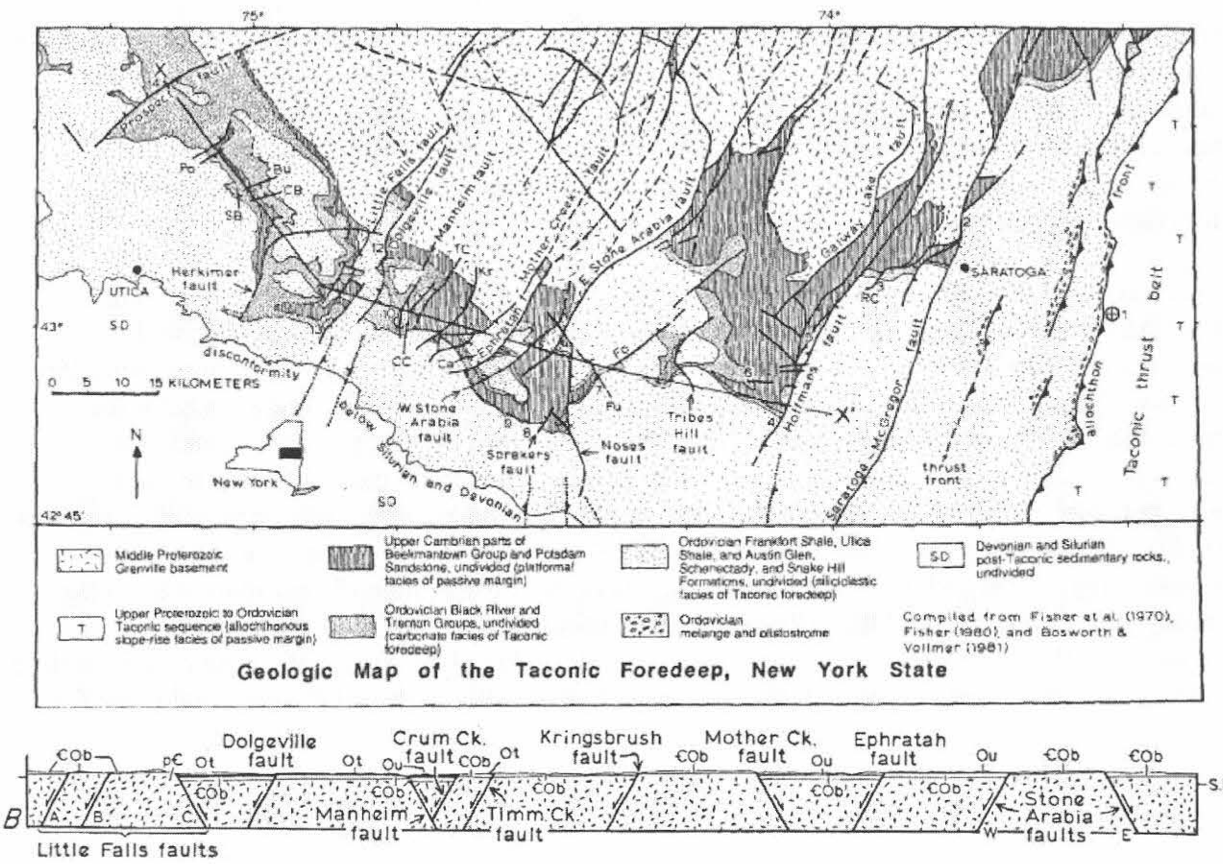


Figure 1. Geologic Map of the Mohawk Valley Region, New York State and Cross-Section across Field Trip Area. From Bradley and Kidd (1991).

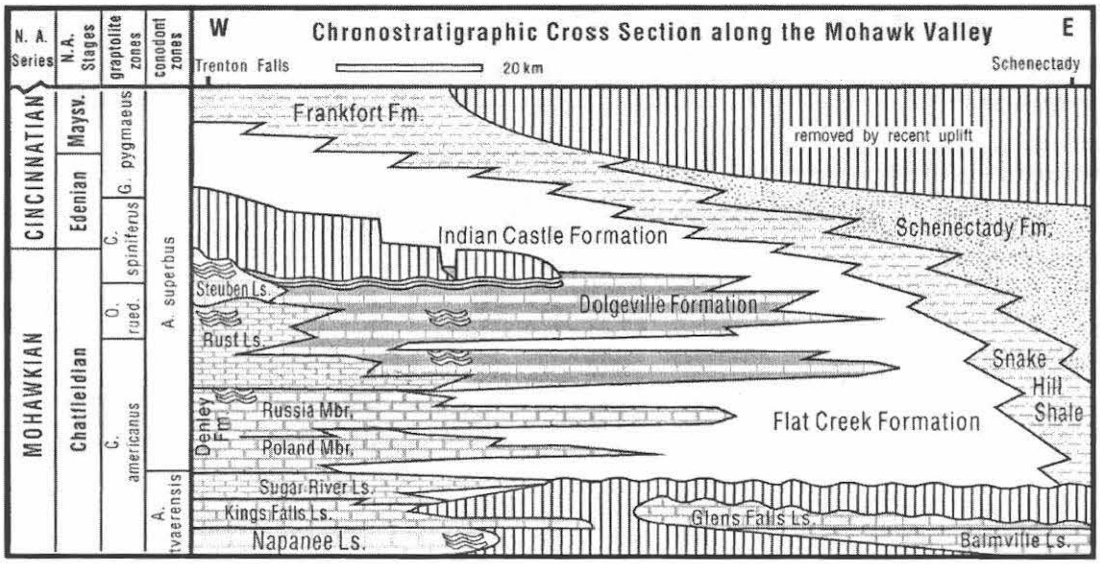


Figure 2. Chronostratigraphy of the Western Mohawk Valley, NYS. Modified from Jacobi and Mitchell (2002).

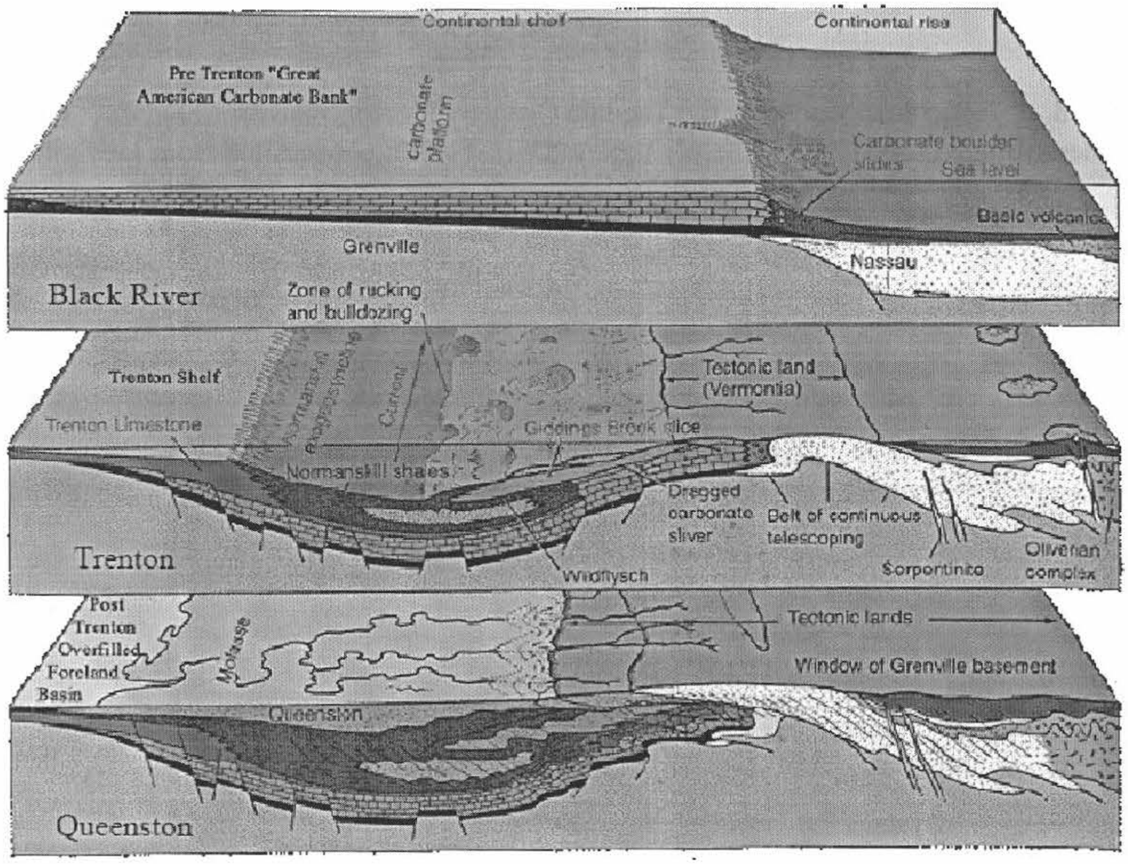


Figure 3. (A) Tectonic Model for the Taconic Orogeny that Involved Westward Subduction Located East of the Model. Modified from Bird and Dewey (1970).

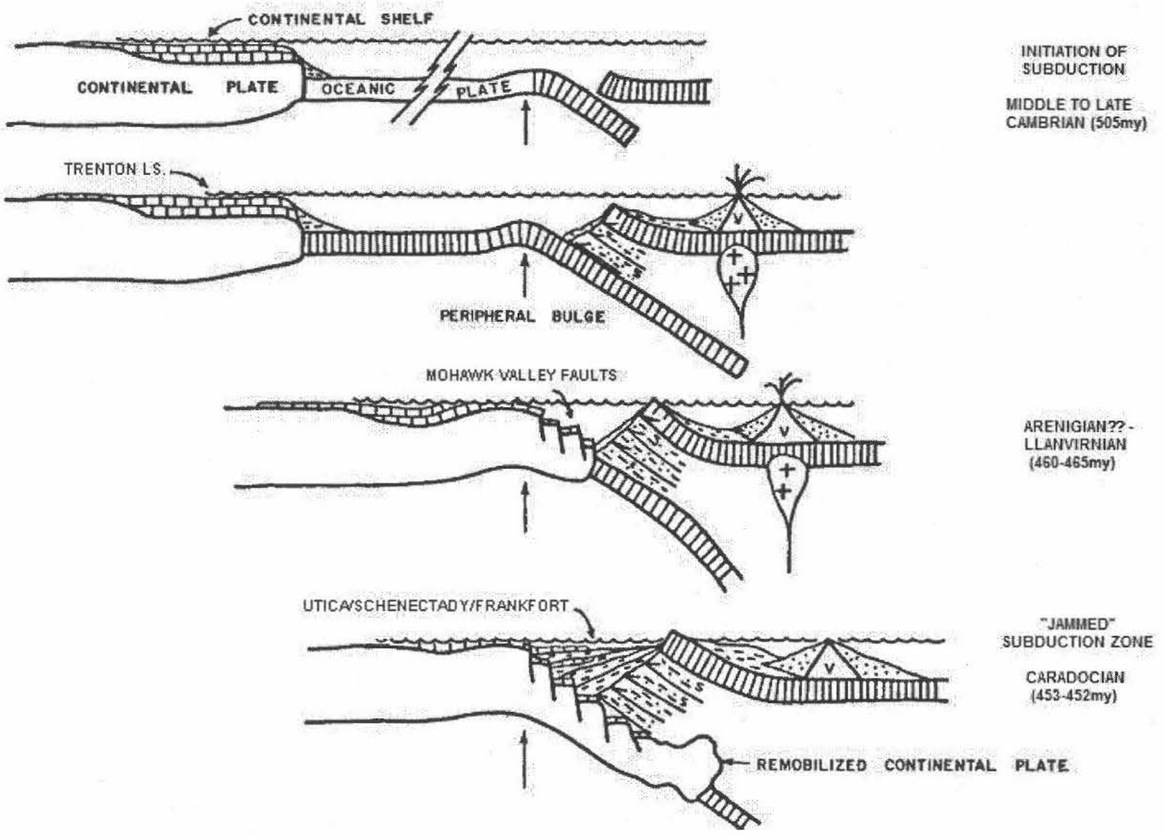


Figure 3. (B) Tectonic Model for the Taconic Orogeny Showing Eastward Subduction, Peripheral Bulge Effects, and Mohawk Valley Block-Faulting. Modified from Jacobi (1981).

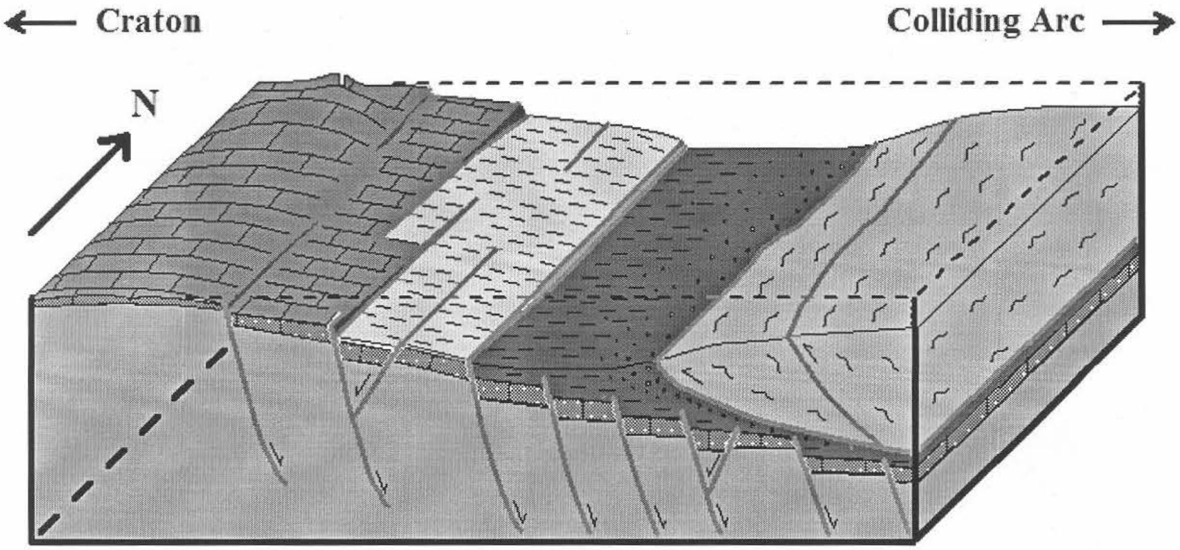


Figure 3. (C) Tectonic Cross-Section for the Taconic Orogeny Showing Eastward Subduction, Facies Distribution, and Mohawk Valley Block-Faulting. From Bradley and Kidd (1991).

CAMBRO-ORDOVICIAN STRATIGRAPHY IN THE LITTLE FALLS AREA, MOHAWK VALLEY

Little Falls Formation (Beekmantown Group)

The Cambro-Ordovician section of the Mohawk Valley (Fig. 4) has been studied for over 180 years (Fig. 5). The first formal study of the rocks now comprising the Little Falls Formation was conducted by Amos Eaton in 1824. He assigned the rocks the name "Calciferous Sandrock". The unit held this informal lithologic designation until Clarke (1899) assigned the name Beekmantown for the exposures in Clinton County, NY. Clarke (1903) was later the first to apply the informal moniker "Little Falls Dolomite" to the rocks comprising the cliff face at Little Falls, NY. The first detailed geologic map of the Little Falls, NY area was produced by Cushing (1905), where he mapped the extent of the Beekmantown Formation (including, but not limited to the rocks now comprising the Little Falls Formation). Five years later, Ulrich and Cushing (1910) were the first to observe the age disparity between the upper and lower units of the Beekmantown Formation in the Mohawk Valley. They split the lower unit and named it the Little Falls Dolomite, while the upper unit retained the Beekmantown designation. The name Little Falls Dolomite remained in informal use until the formal designation of a type section by Zenger (1976). Since no single locality exposes the Little Falls Formation in its entirety, he described a composite type section consisting of several of the better exposures within the Little Falls 7.5' Quadrangle. Zenger (1981) provided an in-depth examination of the stratigraphy and petrology of the Little Falls Formation in its type area, in addition to a comprehensive review of previous work.

The unit consists largely of medium to dark gray, thick-bedded, medium to coarse-grained dolostone. The unit weathers to a buff color and often exhibits a "sucrosic" texture. Some beds, especially in the lower parts of the formation, contain abundant quartz grains and even feldspars. Beds near the top of the formation often have a reddish hue. In several outcrops on the fault blocks west of Little Falls Fault B (north of the city of Little Falls) the upper Little Falls Formation contains a few horizons of sediment slide (debrite/slumped) material, which average 2m in thickness. Fossils are exceedingly rare within the Little Falls Formation. Near faults, circulating hydrothermal fluids have created open vuggy porosity in susceptible layers. These vugs are variably filled with calcite, dolomite, anthraxolite, and quartz ("Herkimer Diamonds"). In the field trip area, the Little Falls Formation non-conformably overlies the Grenvillian basement and disconformably underlies the Tribes Hill Formation. The lower contact is abrupt and the upper contact, although it represents a significant time gap, can be difficult to recognize and locally appears gradational, such as at the type locality, the "Roll Away" at Little Falls (east of Little Falls Fault B). Our working definition of the "gradational contact", following Zenger (1976), is the presence of reddish staining and a distinct upsection increase in fucoidal texture (burrowing).

Tribes Hill Formation (Beekmantown Group)

The earliest studies of this unit lumped it in with the Little Falls Formation as "Calciferous Sandrock" and later Beekmantown formation, as described above. The name Tribes Hill Formation was first used by Ulrich and Cushing (1910) when they split this unit from the older

Little Falls Dolomite. The unit is named for exposures in and around Tribes Hill, NY. Fisher (1954) formally divided the formation into six distinct members. These member divisions were redefined by Landing and others (1996) in order to more easily recognize the divisions outside of the type area, although these new divisions are still difficult to recognize in the Little Falls region.

The formation consists largely of light to medium gray, thin to medium-bedded, fine to medium-grained mottled dolostones and limestones with rare shale laminations. In contrast to the underlying Little Falls Formation, fossils and bioturbation are quite common within this unit. In the field area, the Tribes Hill Formation disconformably overlies the Little Falls Formation and disconformably underlies the Lowville Formation. The upper contact is an abrupt change from limestone and dolostone to the easily recognizable limestones above.

In the eastern Mohawk Valley, the Tribes Hill Formation is variably dolomitized. At some locations it is completely dolomitized from top to bottom whereas in other locations it has very little dolomite (Landing, 1996). In some locations, it is possible to link the dolomitization to faults and fractures and this dolomitization is thought to be of a hydrothermal origin. The Tribes Hill Formation is the host of the hydrothermal dolomite reservoir analog at the quarry in Palatine Bridge (STOP1).

Lowville Formation (Black River Group)

This unit was informally referred to as the "Birdseye limestone" be early workers. Clarke and Schuchert (1899) were the first to refer to the unit as Lowville Limestone for the exposures at the railroad bridge in Lowville, NY. This formation is the only representative of the Black River Group consistently present in the field trip area. The Pamelia Formation, which underlies the Lowville Formation to the northeast is entirely absent, whereas the Watertown Formation, which overlies the Lowville Formation, appears only in a thin horizon at Ingham Mills. The Lowville Formation is perhaps the easiest to recognize in the area. It is an excellent building stone and is used in many foundations, fences, and bridges of the region, as well as many historic structures including Ingham Mills Church and Palatine Church.

The unit is a dove gray, thin to thick-bedded, very fine-grained limestone commonly exhibiting "birdseye" texture. The unit's diagnostic feature, aside from its characteristic color, is the near ubiquitous presence of the sub-vertical burrows of *Phytopsis tubulosum.* In the field area, the Lowville Formation disconformably overlies the Tribes Hill Formation and disconformably underlies the Sugar River Formation. The upper contact is readily identified by an abrupt switch in the color and texture of the limestones.

The Black River thickens to the southwest where it hosts prolific natural gas reservoirs in structurally-controlled hydrothermal dolomite. The tight shallow marine limestone facies form lateral seals around the vuggy, brecciated dolomite. A paper is included for field trip attendees by Langhorne Smith on the Black River hydrothermal dolomite reservoirs of New York.

Kings Falls and Sugar River Formations (Trenton Group)

Vanuxem (1838) was the first to formally work on the Trenton limestone at the type section of Trenton Falls. Kay (1937) was the first to divide the Trenton into smaller stratigraphic units. The rocks now comprising the Kings Falls Formation were named the Kirkfield Limestone, while the rocks of the Sugar River Formation were named the Shoreham Limestone. Later, Kay (1968) revised his stratigraphy and adopted the terms Kings Falls and Sugar River limestones to denote this part of the Trenton Group. He established the type section of the Kings Falls Formation at Kings Falls along the Deer River near Copenhagen, NY. The type section of the Sugar River was established at the excellent exposures along the Sugar River in Lewis County, NY. Both the Kings Falls Formation and Sugar River Formation outcrop in the field area, but their lithology is so similar, the outcrops so "patchy", and the section so thin that it is impractical to map at the formation level within the Little Falls area. The other limestone formations of the Trenton Group are wholly absent from the field trip area, with the exception of the section at Ingham Mills, which includes the underlying Napanee Formation.

The Kings Falls Formation consists of gray to dark gray, medium to thick-bedded, very coarsely fossiliferous limestone with calcareous shaly interbeds. This formation also commonly displays surfaces marked by large-scale ripples. The Sugar River Formation is a very similar lithology, although the beds tend to be thinner and more irregular and the grain size tends to be less coarse. Additionally, the high-energy sedimentary structures typical of the Kings Falls are largely absent in the Sugar River. In the field area, these formations lie disconformably on the Lowville Formation and conformably underlie the Flat Creek Member of the Utica Formation/Group. The upper contact is a rather abrupt switch from coarse-grained limestone to black shale.

The Trenton Limestone has produced gas from numerous shallow fields around Lake Ontario for more than a century. This gas play is very different than the hydrothermal dolomite play. Wells commonly encounter extremely high pressure gas that flows at a very high rate for a few hours or days and then decreases to almost nothing. It is the opinion of co-leaders Smith and Nyahay that this overpressured gas comes from bedding planes in the interbedded shale and limestone of the Trenton Group. The high pressure of the gas may be enough to open the bedding plane until it starts producing at which point the bedding planes close, cutting off the flow of gas.

Dolgeville Formation (Trenton Group)

The Dolgeville Formation was known as the "Trenton-Utica passage beds" by early workers. Cushing (1909) was the first to suggest that these beds be mapped as a distinct unit, not merely as the gradation between the Trenton and the Utica Groups. He established the type section as the well-exposed beds near Dolgeville, NY, in East Canada Creek. Goldman and others (1994) noted that this unit splits the Utica Group into two "tongues", a lower (Flat Creek Member) and an upper (Indian Castle Member). They stated that the Dolgeville is age equivalent to the Denley Formation (upper Trenton), younger than was previously believed. The Dolgeville is now believed to correlate with the Rust (which overlies the Denley; Jacobi and Mitchell, 2002; Brett and Baird, 2002; Baird and Brett, 2002). As its early moniker suggests, the Dolgeville Formation is intermediate between the limestones of the upper Trenton Group and the black shales of the Utica Group. A typical outcrop consists of "ribbon" limestones with rhythmic interbeds of black shale.

The ribbon limestones consist of dark gray to black, thin to medium-bedded, fine-grained limestone. Some of the limestones display graded bedding, planar laminae, climbing ripples, and striations on the sole of the beds, all consistent with a turbiditic origin for these ribbon limestones (e.g., Mehrtens, 1989; Jacobi and Mitchell, 2002). At several localities, including Nowadaga Creek, Crum Creek, and the Thruway road cut near Little Falls, the upper Dolgeville is dramatically folded and truncated by a surface termed the Thruway Discontinuity by Baird and others (1992). The significance of the Thruway Disconformity has been debated (Fischer, 1979; Baird and Brett, 2002; Brett and Baird, 2002; see review in Jacobi and Mitchell, 2002), but it is probable that the sharp erosive contact between the undisturbed black shale of the Indian Castle Member of the Utica Group and the underlying folded Dolgeville shales and ribbon limestones marks a slide scar. In the field area, the Dolgeville Formation conformably overlies the Flat Creek Member. The disconformable upper contact approaches a gradational conformity to the east and in the Dolgeville graben at Dolgeville, where a lack of sediment sliding apparently preserved the original gradational contact.

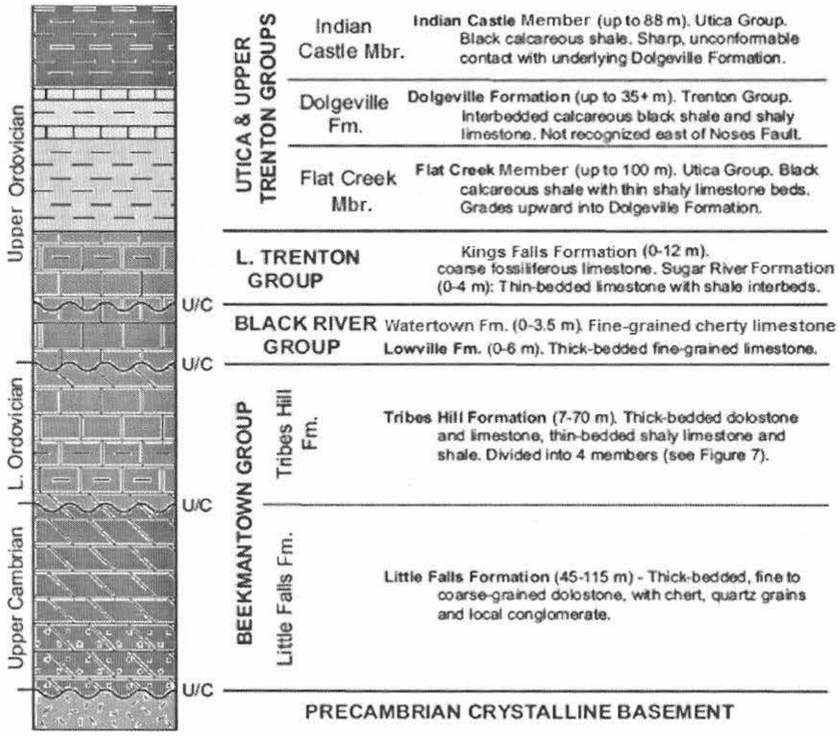
Flat Creek Member (Utica Group)

The rocks now comprising the Utica Group were first properly named by Emmons (1842). Attempts to subdivide the thick mass of black shale proved difficult because of the uniform lithology. Kay (1937) proposed divisions based on graptolite biostratigraphy, but these divisions were later abandoned by Fisher (1977) on the basis that they were not recognizable lithostratigraphic divisions. The unit now known as the Flat Creek Member is the stratigraphically lowest "tongue" of black shale that extends westward below the Dolgeville Formation. Fisher (1979) proposed a simple correlation whereby the carbonates of the Trenton Group grade eastward into the mixed carbonates and shales of the Dolgeville Formation and that this unit then grades into the black shale of the Utica Group. Using k-bentonite and biostratigraphic correlation, Goldman and others (1994) demonstrated that the Utica shale was both younger and older than the Dolgeville Formation. They proposed the name Flat Creek Member for the lower tongue of black shale below the Dolgeville Formation and established the type section at Flat Creek. This unit consists of calcareous black shale, indistinguishable lithologically from that of the Indian Castle Member, which lies above the Dolgeville Formation. In places, such as at Wintergreen Park, the unit consists of flaggy limestones and interbedded shales. In the field area, this unit conformably overlies the Sugar River Formation and conformably underlies the Dolgeville Formation. The upper contact is gradational and was defined by Goldman and others (1994) as the point where ribbon limestones comprise less than 20% of the unit.

Indian Castle Member (Utica Group)

When Goldman and others (1994) noted that the Dolgeville Formation divided the Utica into two tongues in the Little Falls area, the lower tongue was named the Flat Creek Member and the upper tongue was named the Indian Castle Member. Previously, the rocks of the Indian Castle Member were known simply as the Utica shale. The type section of this unit was established at

Nowadaga Creek (Goldman et al, 1994). The Indian Castle Member is lithologically indistinguishable from the Flat Creek Member, though it is younger and lies above the Dolgeville Formation. This unit consists of calcareous black shale with rare thin limestone beds. In the field area, this unit disconformably overlies the Dolgeville Formation and conformably underlies the Frankfort Formation. The upper contact is gradational and defined by the increasing silt content.



Indian Castle Member (up to 88 m). Utica Group. Black calcareous shale. Sharp, unconformable contact with underlying Dolgeville Formation.

Dolgeville Formation (up to 35+ m). Trenton Group. Interbedded calcareous black shale and shaly limestone. Not recognized east of Noses Fault.

Flat Creek Member (up to 100 m). Utica Group. Black calcareous shale with thin shaly limestone beds. Grades upward into Dolgeville Formation.

Kings Falls Formation (0-12 m). coarse fossiliferous limestone. Sugar River Formation (0-4 m): Thin-bedded limestone with shale interbeds.

Watertown Fm. (0-3.5 m). Fine-grained cherty limestone
Lowville Fm. (0-6 m). Thick-bedded fine-grained limestone.

Tribes Hill Formation (7-70 m). Thick-bedded dolostone and limestone, thin-bedded shaly limestone and shale. Divided into 4 members (see Figure 7).

Little Falls Formation (45-115 m) - Thick-bedded, fine to coarse-grained dolostone, with chert, quartz grains and local conglomerate.

Figure 4. Stratigraphic Section of the Western Mohawk Valley and Unit Descriptions. Modified from Cross (2004).

Eaton 1824	Vanuxem 1842	Cushing 1905	Ulrich and Cushing 1910	Kay 1937	Fisher 1954	Kay 1968	Zenger 1981	Goldman and others 1994	Landing and others 1996
Greywacke	Utica Slate	Utica Shale	Utica Shale Dolgeville	Utica Sh	Not Studied	Utica Sh	Not Studied	Indian Castle Dolgeville	Not Studied
			Utica Shale	Canajoharie Sh		Canajoharie Sh		Flat Creek	
Metalliferous Limerock	Trenton LS	Trenton LS	Trenton LS	Shoreham LS Kirkfield LS Rockland LS		Sugar River LS Kings Falls LS Napanee LS		Sugar River LS Kings Falls LS Napanee LS	
Sparry Limerock		Black River LS	Black River LS	Chaumont LS		Watertown LS		Not Studied	
	Birdseye LS	Lowville LS	Lowville LS	Lowville LS		Gull River LS			
Calciferous Sandrock	Fucoidal Layers	Beekmantown Formation	Tribes Hill LS and DT	Tribes Hill LS and DT	Chuctununda Fonda Mbr Wolf Hollow Cranesville Palatine Bridge FortJohnson	Not Studied			Canyon Road Wolf Hollow Van Wie Mbr Sprakers Mbr
	Calciferous Sandrock		Little Falls Dolomite	Little Falls Dolomite	Not Studied		Unit A Unit B Unit C Unit D		Not Studied
Primary	Primary	Precambrian	Precambrian	Precambrian			Precambrian		

Figure 5. Stratigraphic Nomenclature of the Rocks of the Mohawk Valley

FAULTING IN THE MOHAWK VALLEY

Introduction

Faults in the Mohawk Valley, were recognized by the earliest geologists in the region; the faults with the largest stratigraphic offset were mentioned in Vanuxem's report of the third geological district (1842). Later workers examined these faults in greater detail (Darton, 1895; Cushing, 1905; Megathlin, 1938; Dunn, 1954, Fisher, 1954; Fisher et al, 1970; Fisher, 1980; Bradley and Kidd, 1991, see review by Jacobi and Mitchell, 2002). The apparent stratigraphic offsets and dips on exposed faults suggested to the early geologists that the faults in the Mohawk Valley are, to the first approximation, normal faults (although kinematic indicators were, and continue to be, elusive). However, using primarily fault map patterns, Shaw (1993) proposed that similar faults to the north in Canada were strike slip faults. Jacobi and Mitchell (2002) provided evidence for dip-slip, as well as oblique slip, motion on faults in the Mohawk Valley (see discussion below). Further, the en echelon nature of the dolomitization "pods" (and other considerations) at the first stop of this trip, Palatine Bridge, suggested to Smith and Nyahay (2004, 2005) that WNW-striking faults were strike slip.

In the field trip area, the faults strike in three distinct orientations: NNE, N, and WNW. The NNE-striking faults parallel gravity anomalies and probably formed during Eocambrian Iapetan opening and/or Cambrian Rome Trough development (Jacobi, 2002; Jacobi et al, 2004, 2005). These faults were apparently reactivated during Taconic times, when the major motion on the faults occurred. Offset Ordovician contacts, Ordovician growth fault geometries, and stratigraphically-bound breccias from fault scarps indicate Taconic motion (see reviews in Bradley and Kidd, 1991; Jacobi and Mitchell, 2002). The NNE-striking faults experienced oblique slip, based on bedding dip, slickenlines (STOP 4), and tectonic model considerations (Jacobi and Mitchell, 2002; Jacobi et al., 2004, 2005). The WNW-trending faults are postulated to have formed as transfer zones between the NNE Iapetan faults (Jacobi, 2002), and follow older Precambrian trends (Jacobi and Smith, 2000). The WNW-striking faults were also reactivated during the Taconic. Jacobi (2002) showed that the N-trending faults cross gravity anomalies and are assumed to have initiated during Taconic time as a result of trench/peripheral bulge tectonics. The northerly-trending Dolgeville Fault (STOP 3) displays down-dip slickenlines and drag folds with horizontal plunges, all of which support a down-dip slip on this fault (Jacobi and Mitchell, 2002).

The Taconic extensional faulting resulted from continental plate flexure over the peripheral bulge and into the trench/subduction zone (e.g., Jacobi, 1981; Bradley and Kidd, 1991; Jacobi and Mitchell, 2002; Baird and Brett, 2002). As the Taconic collision continued, it is possible that some of these faults reversed motion (Jacobi et al., 2004, 2005).

History of Investigations on the Fault Timing

The debate on timing of initiation of faulting in the region has a long history (see reviews in Bradley and Kidd, 1991; and Jacobi and Mitchell, 2002). Cushing (1905) first suggested that the faults may be as old as the Taconic "disturbance". Megathlin (1938) stated that the normal offsets on the faults suggest a tensional stress regime and thus the faults cannot be associated with the compressive stages of any "revolution"; rather, they must have occurred during a subsequent relaxation phase making them post-Taconic. This apparent quandary is resolved by the peripheral bulge flexure models that have been advanced by more recent workers (Jacobi, 1981; Bradley and Kidd, 1991) that allow for the seemingly contradictory co-existence of regional extension (and normal faulting) in the upper crust and far-field tectonic compression.

A variety of evidence indicates that faulting was active during deposition of the Ordovician units. Fisher (1954) suggested that the "disturbance" may have initiated in early Tribes Hill time, citing folding in the Tribes Hill Formation and thinning of the Palatine Bridge Member (now called Sprakers Member) near major faults. Cisne et al. (1982) examined the distribution of graptolite biozones and facies in the fault blocked region and concluded that local tectonics had a major influence on local facies patterns and basin bathymetry. Fisher (1979) noted the westward vergence of folds within the Dolgeville Formation, rather than the expected eastward direction down the inferred paleoslope into the foreland basin. Jacobi and Mitchell (2002) also observed anomalous fold directions and paleoflow directions at several locations in the Mohawk Valley, and attributed the inferred anomalous paleoslopes to local fault block rotations and bathymetric reorganization. They also cited changes in stratigraphic thickness as evidence of the local significance of these faults during deposition. In contrast, Brett and Baird (2002) believed that the faults exerted only minor control, if any, on deposition. They proposed that the faults had no surface expression at the time of deposition, based on the persistence of marker beds and facies gradations. They suggested that broad tectonic warping and eustatic sea-level changes were the dominant influence on deposition.

There is some evidence for an earlier episode of faulting in the Late Cambrian/earliest Ordovician including the debrites at the top of the Little Falls Formation, the distinct chemistry of the vein and vug fills in the Little Falls Formation (Cross et al, 2004), and growth faults in the Little Falls Formation that die out up section (Smith and Nyahay, 2005). Jacobi et al. (2006) suggested that these deformation and fluid circulation events were related to the initiation of subduction.

Jacobi (2002) suggested that the NNE-striking faults initiated during Iapetan opening time (and/or Rome trough development time), based on map patterns of aeromagnetic, gravity, and satellite image lineaments. He traced NNE-striking Iapetan opening faults from Pennsylvania where they arc through the Pennsylvania Salient to the ENE-tending basement faults in central NYS. From there eastward, it is possible that the ENE-striking faults swing once again, this time more northerly into the NNE-tends of the Mohawk Valley faults. No Iapetan-opening sediments have been recognized in the fault basins of the Mohawk Valley. However, following Burke and Dewey (1973), Jacobi et al. (2005) proposed that an Iapetan-opening mantle plume was located southeast of the New York Promontory. Such a plume could account for the major bend in the Iapetan trends, and for the lack of Iapetan-opening fault basin sediments along the Mohawk Valley faults, since the Mohawk Valley region would have been near the center of the mantle plume dome, and so would experience primarily erosion, not deposition.

The youngest age of motion on the faults was assumed to be of Utica age. All the geological investigations recognized that the faults clearly offset the carbonate/black shale contact, but the lack of markers within the Utica, the lack of critical outcrop in the stratigraphically (and topographically) higher units to the south, and the lack of observed significant offset of younger units led to the assumption that motion on the faults ceased in Utica time (e.g., Fisher et al., 1970; Fisher, 1980; Bradley and Kidd, 1991). Indeed, on geology maps, the faults were portrayed as not offsetting the Ordovician/Silurian contact south of the Mohawk Valley; rather, the faults end in the Utica (e.g., Fisher et al., 1970; Fisher, 1980; Bradley and Kidd, 1991). However, to the south, Jacobi and Smith (2000) proposed that the NNE-trending faults were reactivated in Silurian time, and controlled the depositional limits of the Clinton Group, Vernon Formation, and Cobleskill Formation. Each of these units pinches out at a location that is on strike with particular Mohawk Valley faults to the north. Further, well logs south of the Mohawk Valley display anomalous thickness changes across the southward projection of the Mohawk Valley faults (Jacobi and Smith, 2000). Jacobi and Smith (2000) also found that the Devonian Onondaga Formation to the south was disposed in monoclines, and faulted, on strike with the NNE-striking Mohawk Valley faults. The conclusion is that these faults were reactivated in the Silurian and the Devonian (and perhaps in the Alleghanian) times. The minimum age of motion along the Mohawk Valley faults is provided by the age of an undeformed peridotite dike within the Manheim Fault zone (130 ±10 my; Fisher, 1980).

It is apparent that the faults of the Mohawk Valley have a long and complex history in which these zones of weakness were reactivated at many different intervals throughout the history of the basin. It is probable that their sense of motion would shift with changes in paleostress orientations.

MINERALIZATION OF THE MOHAWK VALLEY

Mineralization in and around fractures and faults is of great scientific and economic interest. Many carbonate hosted ore deposits occur around faults interpreted to be conduits for upward flowing hydrothermal fluids. Hydrothermal dolomite formed around faults and fractures hosts prolific oil and gas reservoirs in the Ordovician and Devonian carbonates of the Appalachian and Michigan Basins.

In the past decade, more than twenty new natural gas fields have been discovered in laterally discontinuous hydrothermal dolomites of the Upper Ordovician Black River Group in south-central New York. The dolomites form around basement-rooted wrench faults that are detectable on seismic data. Most fields occur in and around elongate fault-bounded structural lows interpreted to be negative flower structures (Smith, 2006). Away from these faults, the formation is composed of impermeable limestone and forms the lateral seal for the reservoirs. In most cases the faults die out within the overlying Trenton Limestone and Utica Shale. Most porosity occurs in saddle dolomite coated vugs, breccias and fractured zones. Matrix porosity is rare in the Black River cores in the New York State Museum collection.

The patchy distribution around basement-rooted faults and geochemical and fluid inclusion analyses support a fault-related hydrothermal origin for the saddle and matrix dolomites. This play went for many years without detection because of its unconventional structural setting (i.e. structural lows versus highs).

Hydrothermal fluid flow is thought to be most common while faults are active and much less common during periods of tectonic quiescence (Sibson, 1990, 2000; Davies, 2001; Knipe, 1993; Muir-Wood, 1994; Davies and Smith, 2006). The timing of hydrothermal alteration is closely linked to the timing of fault movement. In the case of the Black River hydrothermal dolomite reservoirs it appears that the faults primarily moved during the Late Ordovician Taconic Orogeny when the Trenton and Black River Groups were still buried to very shallow depths (less than a kilometer). This fits with the depth at which many other hydrothermal dolomite reservoirs and ore deposits are thought to have formed (Davies and Smith, 2006).

The exposure of en echelon dolomitized bodies in the Palatine Bridge Quarry (STOP 1) is interpreted to be a scaled analog for the Trenton Black River reservoirs. Most of the faults that have associated dolomitization in the Mohawk Valley also appear to have been active during Trenton and Utica time (during the Late Ordovician Taconic Orogeny) and largely inactive after that time. On seismic data, most dolomitized wrench faults in New York die out in the Trenton and Utica and sags are commonly filled in during Trenton or Utica time. This suggests that most of these faults were active during the Taconic Orogeny but were not reactivated during subsequent mountain building events.

Smith (2006) has presented the following model for the development of the Black River hydrothermal dolomite reservoirs (Fig. 6). This model is speculative, but is supported by all of the known facts at this time. Black River Group carbonates were deposited on relatively stable craton (Fig. 6A). Major collision between North America and Volcanic Island Arc begins during earliest Trenton time and continues through the Late Ordovician and into the Silurian (Ettensohn and Brett, 2002). This collision led to reactivation of appropriately oriented older faults or activation of new faults. Near the thrust front, thrust loading led to normal faulting oriented subparallel to orogenic belt. In the more distal parts of the craton, strike-slip faulting is initiated along appropriately oriented faults.

High-pressure, high-temperature fluids flowed up active basement-rooted strike-slip and transtensional faults (particularly in dilational parts of fault zones) during the time of Trenton and Utica deposition, hit low permeability beds at the base of the Trenton and flowed out laterally into the more permeable limestones of the Black River. Cooling hydrothermal fluids leached the limestone and produced vugs in a migrating front moving away from the fault zone (Fig. 6B). As permeability was enhanced by fracturing and leaching, warmer dolomite-supersaturated fluids migrated farther from fault zone precipitating dolomite (Fig. 6C). These fluids first produced a halo of matrix dolomite, particularly on the downthrown sides of faults in negative flower structures. Because the fluids flowed up from greater depths where pressures are higher, the elevated pressure of the fluids may have led to hydro-fracturing (*sensu* Phillips, 1972), enlargement of existing fractures, and further brecciation. Some dissolution vugs may have formed prior to and during matrix dolomitization. Matrix dolomitization was followed by further fracturing, brecciation and vug development as tectonic activity continued (Fig. 6D). Fractures and vugs were lined or filled with saddle dolomite soon after their formation. This later mineralization occurred during active fracturing as is demonstrated by episodic filling of fractures as they opened.

As time passed, fluids evolved and precipitated a range of other minerals including quartz, bitumen, sulfides and calcite. Bitumen may have formed when kerogen within the altered formation and near the faults was heated by the hydrothermal fluids and small quantities of oil formed that coated some pores and fractures ("forced maturation" of Davies, 2001). If the faulting was over by Late Ordovician or Early Silurian time (as it appears to be on many seismic lines), that would make most or all of the diagenesis Late Ordovician to Early Silurian in age. If the faulting continued or recurred during the Devonian Acadian or Pennsylvanian Alleghanian Orogenies some of the later stages of mineralization may have occurred during those times. Some calcite cementation may have occurred during later pressure solution of the adjacent limestones under normal burial conditions.

A similar sequence of events is interpreted for much of the mineralization of faults and fractures in the Mohawk Valley. Faults with at least a component of strike-slip are much more likely to be mineralized by hydrothermal fluids, especially at dilational jogs along the faults.

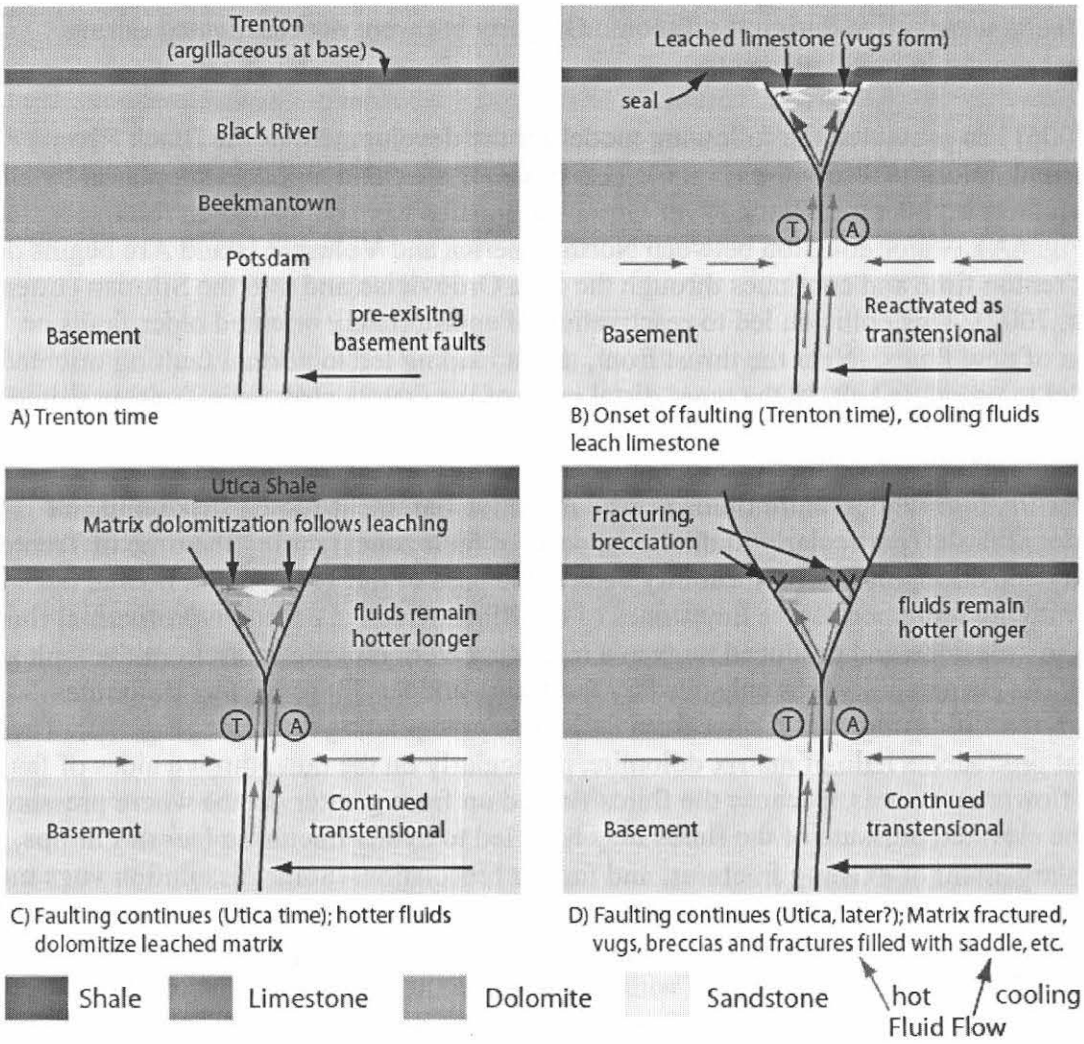


Figure 6. Schematic Model for Development of Black River Hydrothermal Dolomite Reservoirs. From Smith (2006)

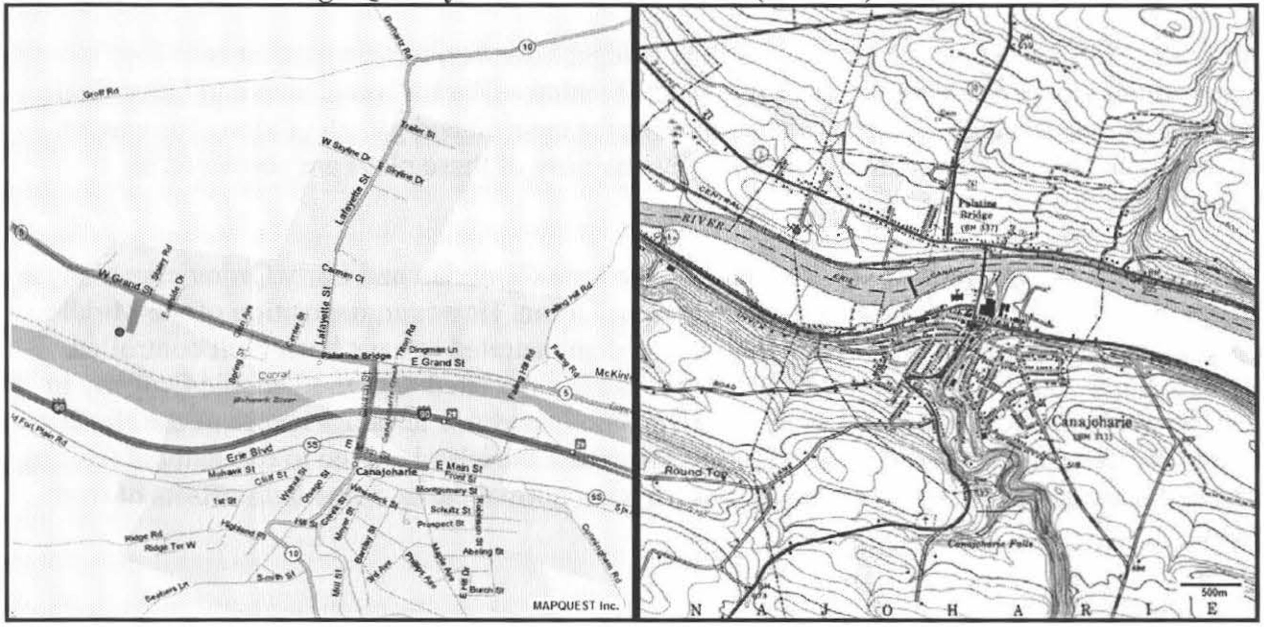
FIELD TRIP STOPS

Field Trip begins at Canajoharie Exit (#29) of New York State Thruway (I-90)

	Leg	Cum.
Right onto E. Main St. (NY-5S)	**0.2 mi**	**0.2mi**
Right onto Church St. (NY-10)	**0.3mi**	**0.5mi**
Left onto W. Grand St. (NY-5/NY-10)	**1.1mi**	**1.6mi**
Left onto unnamed access road near Palatine Motel	**<0.1mi**	**1.6mi**

Park at end of access road if gate is open (permission is needed)

STOP 1: Palatine Bridge Quarry **GPS (NAD27): 533685E 4750885N**



The Palatine Bridge study site is located in an inactive quarry along the Mohawk Valley, approximately 50 miles west of Albany, NY. The outcrop occurs as a highly localized dolomite alteration in the Tribes Hill limestone that makes up the floor of the quarry. Although there are at least three areas of the quarry that have been dolomitized, research has been focused on the one region most accessible. The site consists of two dolomite bodies (Figs 7&8). The eastern most body (body 1) is a long, linear feature approximately 55 feet long, 5 feet wide, and has a strike of 305°. The second body (body 2) is located immediately west of the first, and is also a linear feature with similar strike, however this body is substantially longer than the first, measuring 110 ft. Body 2 is broken into two parts which are separated by a southerly bend, referred to as the jog. The dolomite is easily distinguished from the surrounding limestone by its distinct orange color and massive texture.

Analog Comparison

Although it is much smaller than the hydrothermal dolomite fields in production today, all other characteristics of the quarry are virtually identical to those of its larger counterparts (Fig. 9). Hydrothermal dolomite fields such as the Rochester field of Ontario, CAN, the Albion-Scipio fields of Michigan, and the numerous gas fields of South Central NY all bear striking resemblance to the Palatine Bridge Quarry outcrop.

Setting

The Palatine Bridge Quarry lies within the Tribes Hill unit of the Upper Beekmantown Group. It is separated from the Precambrian basement by the Little Falls dolostone (lower Beekmantown Group) and the Potsdam sandstone which may or may not be present as it thins to the east. The Tribes Hill is a thin to medium-bedded limestone which was deposited in a shallow, peritidal to subtidal environment. It is underlain by the Late Cambrian Little Falls dolostone which is described as a thick-bedded dolostone and is also believed to have formed by deposition in a shallow, peritidal to subtidal environment. The Little Falls is approximately 400 ft. thick in this portion of the Mohawk Valley.

The Tribes Hill Limestone outcrops in Palatine Bridge; however, further south it is unconformably overlain by the Upper Ordovician Trenton - Black River Group and Utica Shale. The Trenton and Black River units are well known for their oil and gas plays along the eastern portion of the US and into southern Ontario. The majority of these plays are contained in hydrothermal dolomite reservoirs.

The Beekmantown Group was deposited during the Late Cambrian and Early Ordovician along a passive margin following the opening of the Iapetus Ocean. However, deposition of the Middle Ordovician Trenton - Black River Group has been demonstrated to have been fault controlled. Active tectonism during the Middle-Late Ordovician is associated with the Taconic Orogeny in which Proto-North America collided with the Taconic Island Arc terrain. Flexure of the North American plate during its attempt to be sub ducted under the island arc led to extensional faulting and produced a series of north east-south west striking normal faults, some with offsets of over 1000ft.

Field Relations

There are many characteristics of the outcrop that indicate a fault related hydrothermal origin. The central sag flanked by monoclines is a typical feature of many hydrothermal structures (Fig. 10). Fault breccia and vuggy porosity can be observed in several places (Fig. 11). These areas are commonly located near, but not limited to, the tips of each body. An intense fault and fracture zone surrounds the entire outcrop increasing the width of the affected area to approximately 15 ft. (Fig. 12). Many faults have vertical slickenlines which indicate a stress regime that was predominantly extensional. Groups of faults commonly join to form a relay ramp structure as seen in Figure 13.

Ground Penetrating Radar

In the spring of 2004 a shallow ground penetrating radar survey was run over body 2. The purpose of this survey was to aid in the excavation process and to get a profile view of the outcrop. Although the radar was only able to penetrate a couple meters, it showed that the outcrop has geometry very similar to that of the Trenton / Black River gas plays (Fig. 14). Each body consists of a central syncline, or sag, that is flanked by smaller anticlines on either side.

Cores

A series of six cores 40 - 60 ft. deep were taken from strategic points on the outcrop so that cross sections could be constructed both along strike and perpendicular to the bodies. The perpendicular cross section (Fig. 15) demonstrates that the dolomitization is highly localized as Hole Six, less than 20 ft. outside the body, is almost completely undolomitized. The parallel cross section (Fig. 16) shows that the limestone gap between bodies 1 and 2 is only 3 feet thick. The two bodies join at depth.

Trenches

Six trenches measuring 3'wide by 15'long by 18"deep have been cut across the outcrop (Fig. 17) to expose the folds of the body as well as the dip and offset of the fractures (Fig. 18).

Paragenic Sequence

Examination of thin sections made from outcrop and core samples indicate a fairly complicated diagenetic history including multiple episodes of faulting and mineral precipitation (Fig. 19).

Geochemistry

Strontium isotope analyses done on dolomite samples yield values significantly higher than that of seawater during the time of Tribes Hill deposition (Fig. 20&21). Limestone and calcite samples plot on the curve as expected. The elevated strontium content is interpreted to be caused by interaction of the parent fluid with silici-clastic rocks, such as the Grenville basement, for an extended period of time.

Stable Isotope analyses show that dolostone crystals formed from a fluid much lighter than seawater dolomites (Fig. 22). It is believed that these lighter isotope ratios are an indication of higher temperature fluids traveling upward from deeper, hotter depths.

Fluid inclusion analyses conducted on 40 samples indicate that both dolomite and calcite formed at temperatures greater than 100ºC (Fig. 23). Although thermal chronology studies indicate that the Tribes Hill has been buried to a geothermal temperature of over 100ºC, core analysis and paragenic sequencing suggest that dolomitization occurred at a shallow depth before significant burial.

Figure 7. View of the Entire Outcrop (looking north).

Figure 8. View of the Entire Outcrop (looking west).

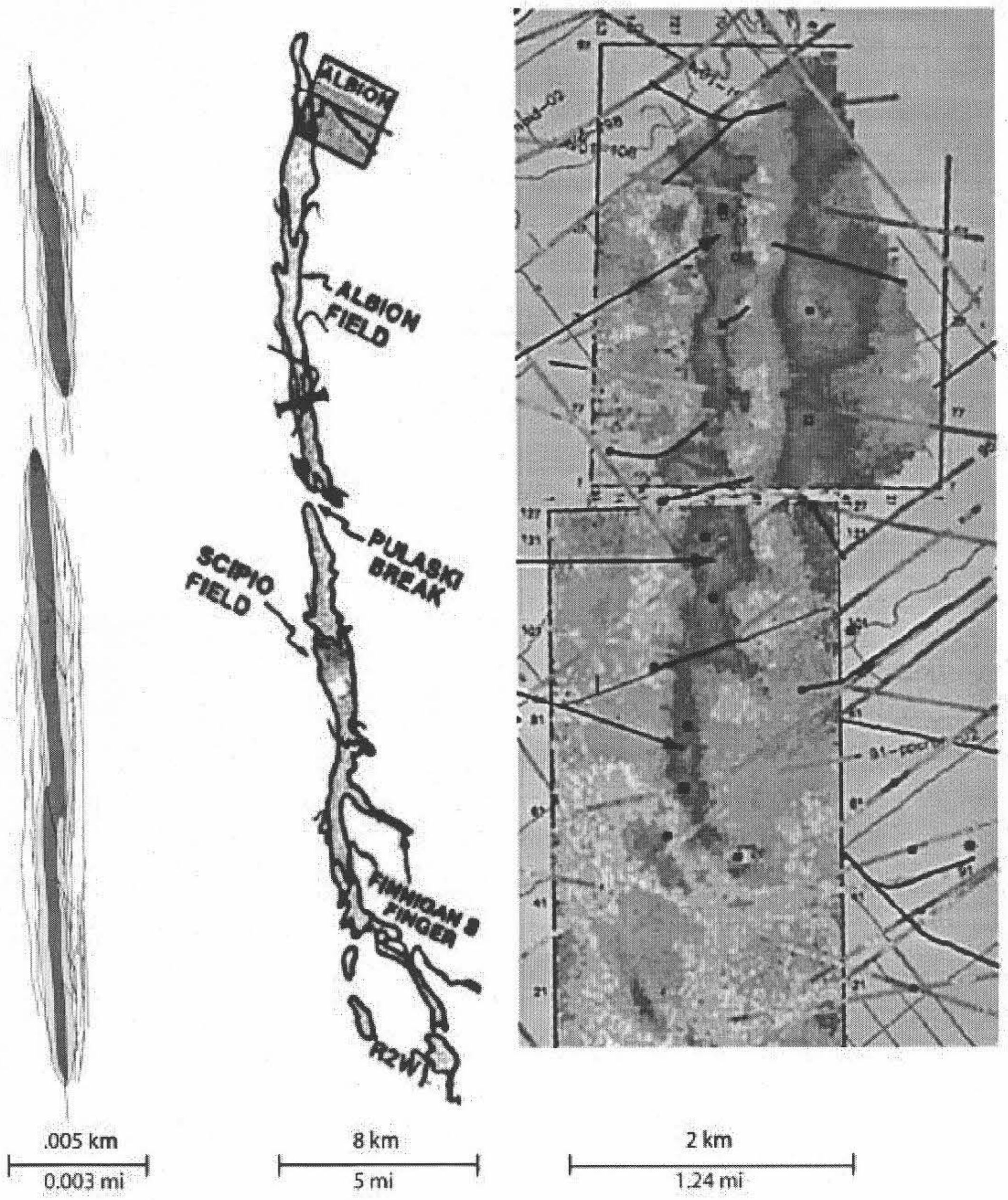


Figure 9. Comparison of Palatine Quarry Dolomite (left) with Albion-Scipio Play in Michigan (center) and 3-D Seismic Line of Rochester Field in Ontario. Not to Scale

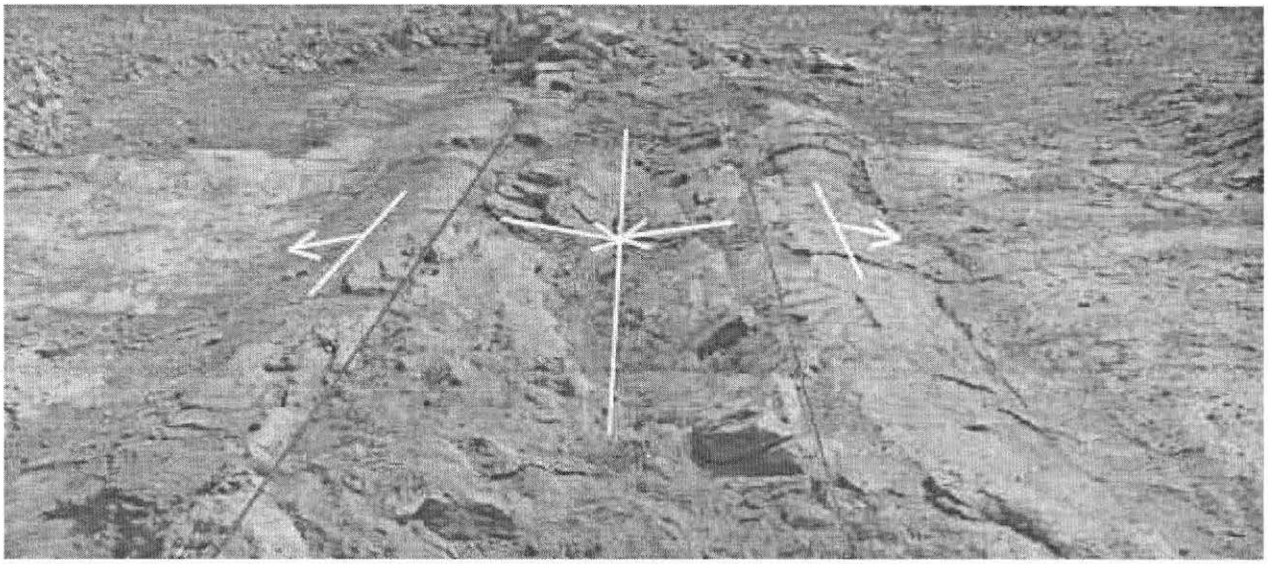


Figure 10. Central Sag Flanked by Monoclines

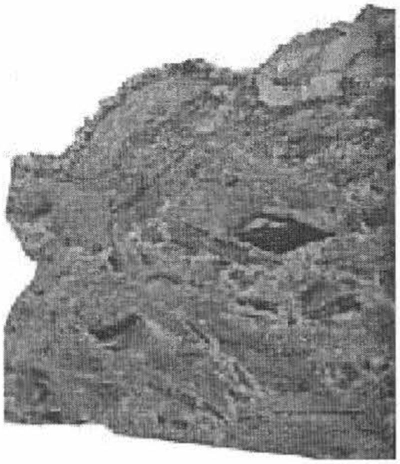


Figure 11. Fault Breccia (left) and Dolomitized and Calcite-filled Vug (right)

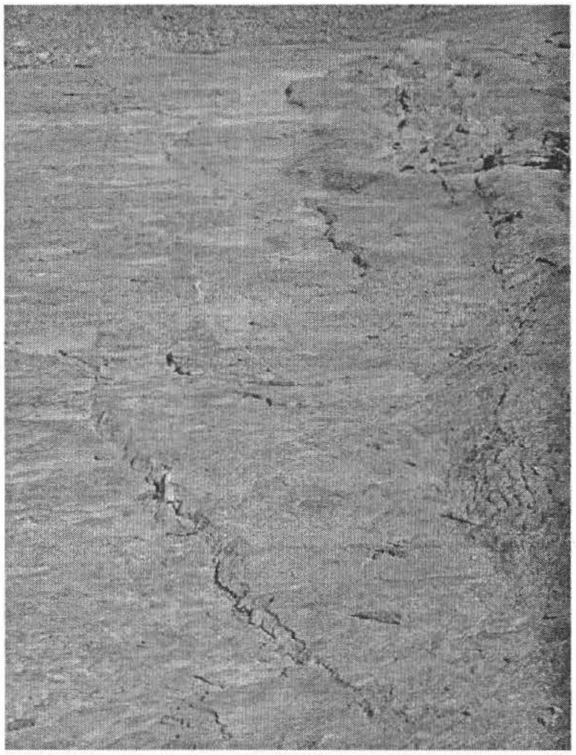


Figure 12. Fault and Fracture Zone Surrounding the Dolomite Exposure

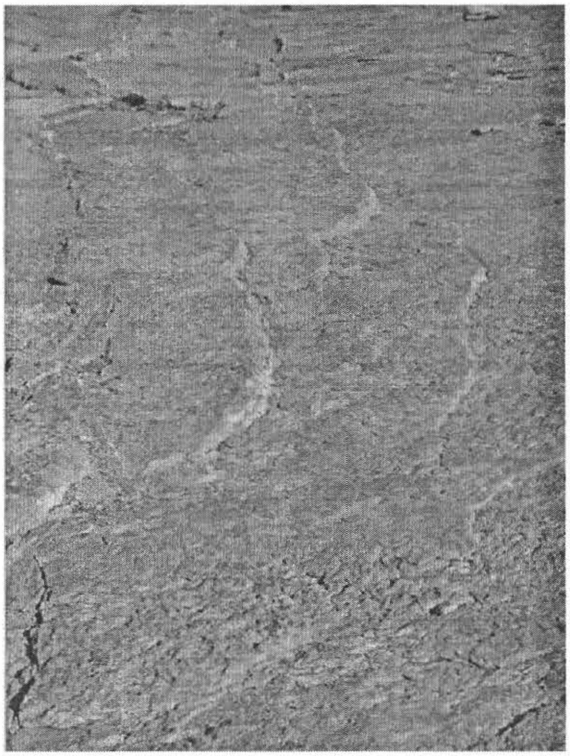


Figure 13. Relay Ramp Structures

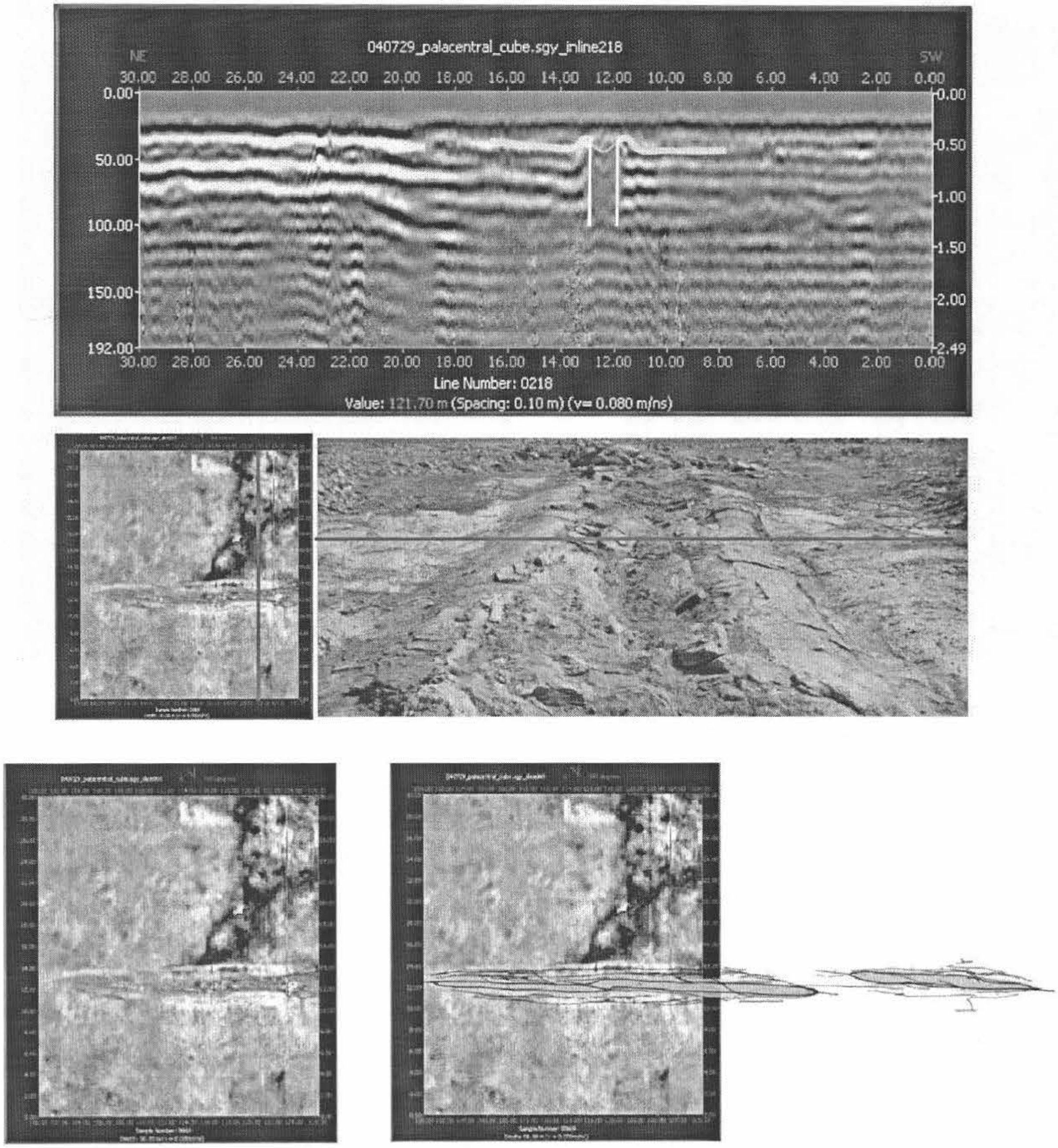
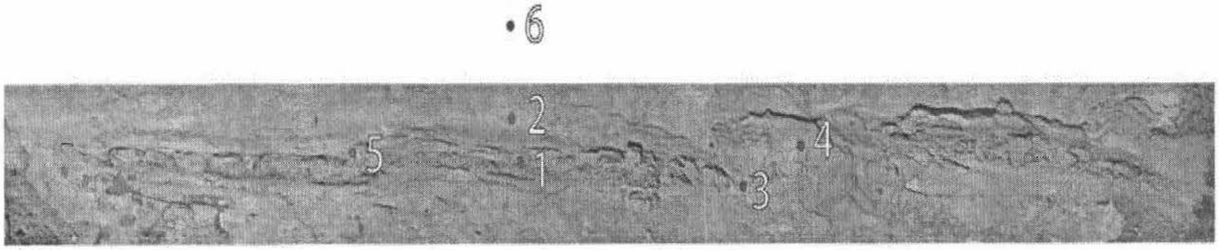


Figure 14. A Compilation of GPR Images



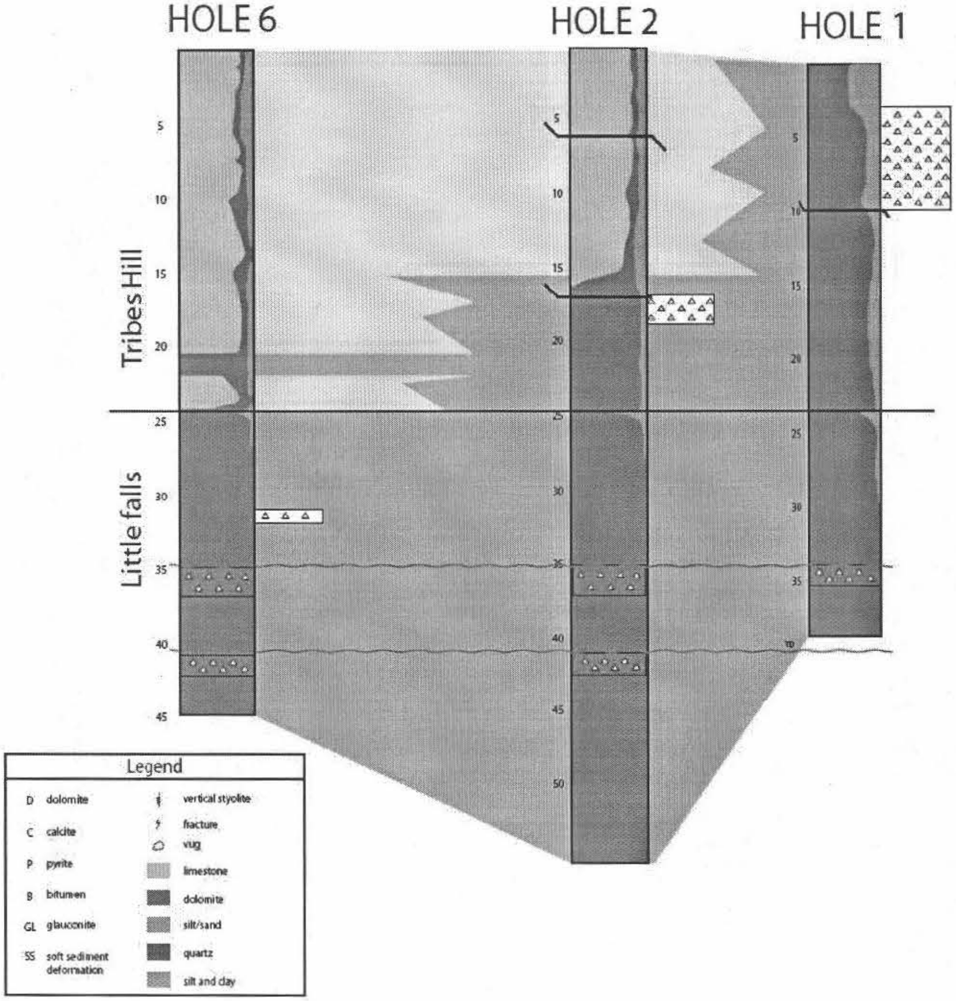


Figure 15. Cross-Section Perpendicular to Body Across Holes 1, 2, and 6

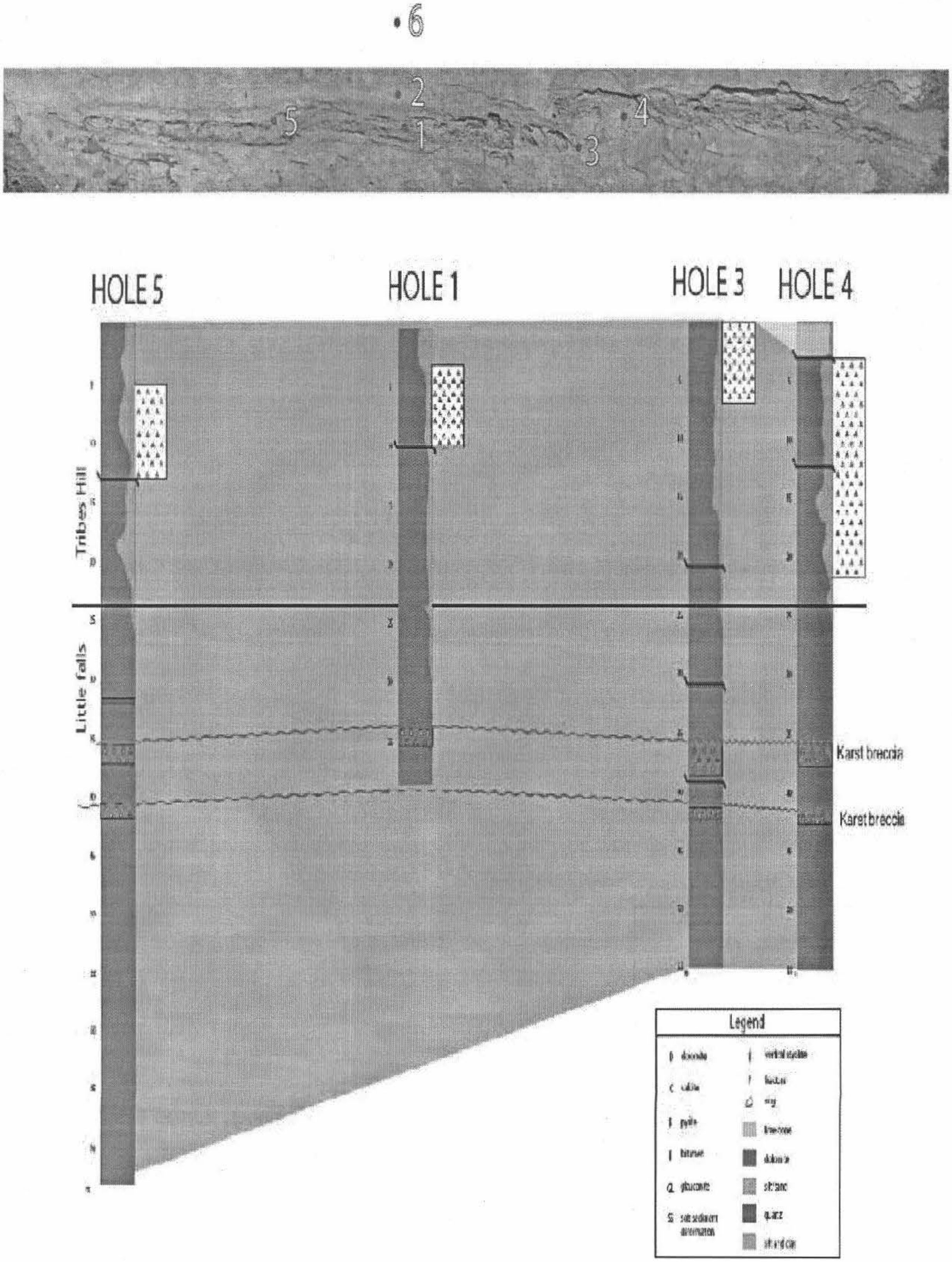


Figure 16. Cross-Section Parallel to the Bodies Across Holes 1, 3, 4, and 5

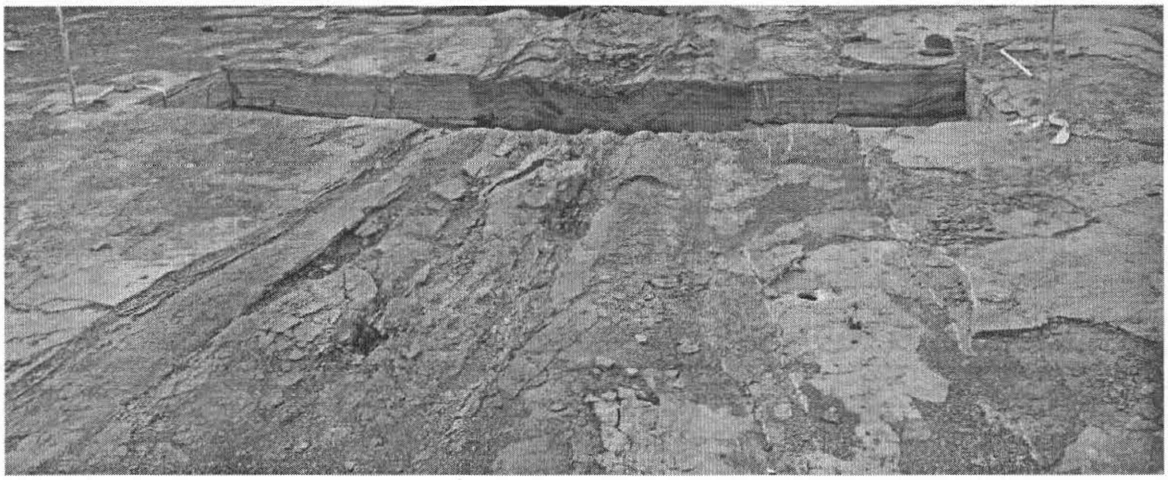


Figure 17. The Western Wall of Trench 4

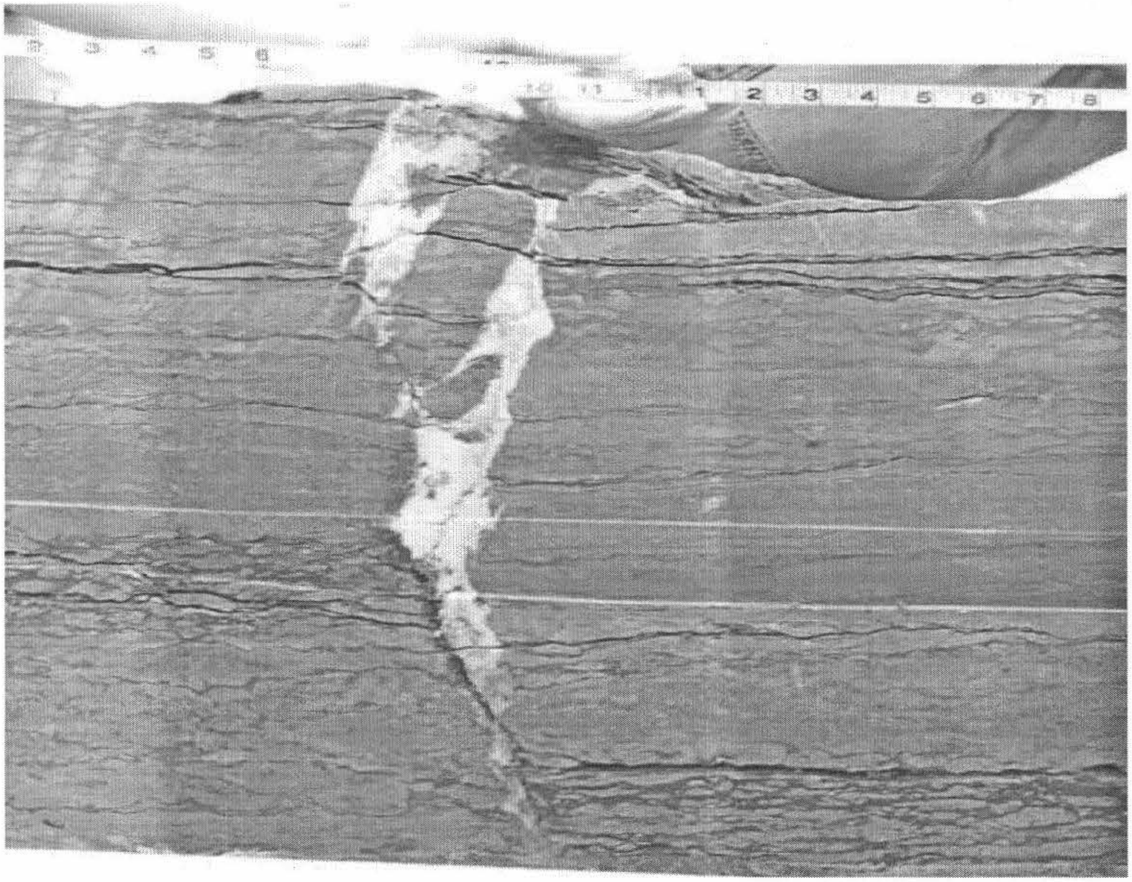
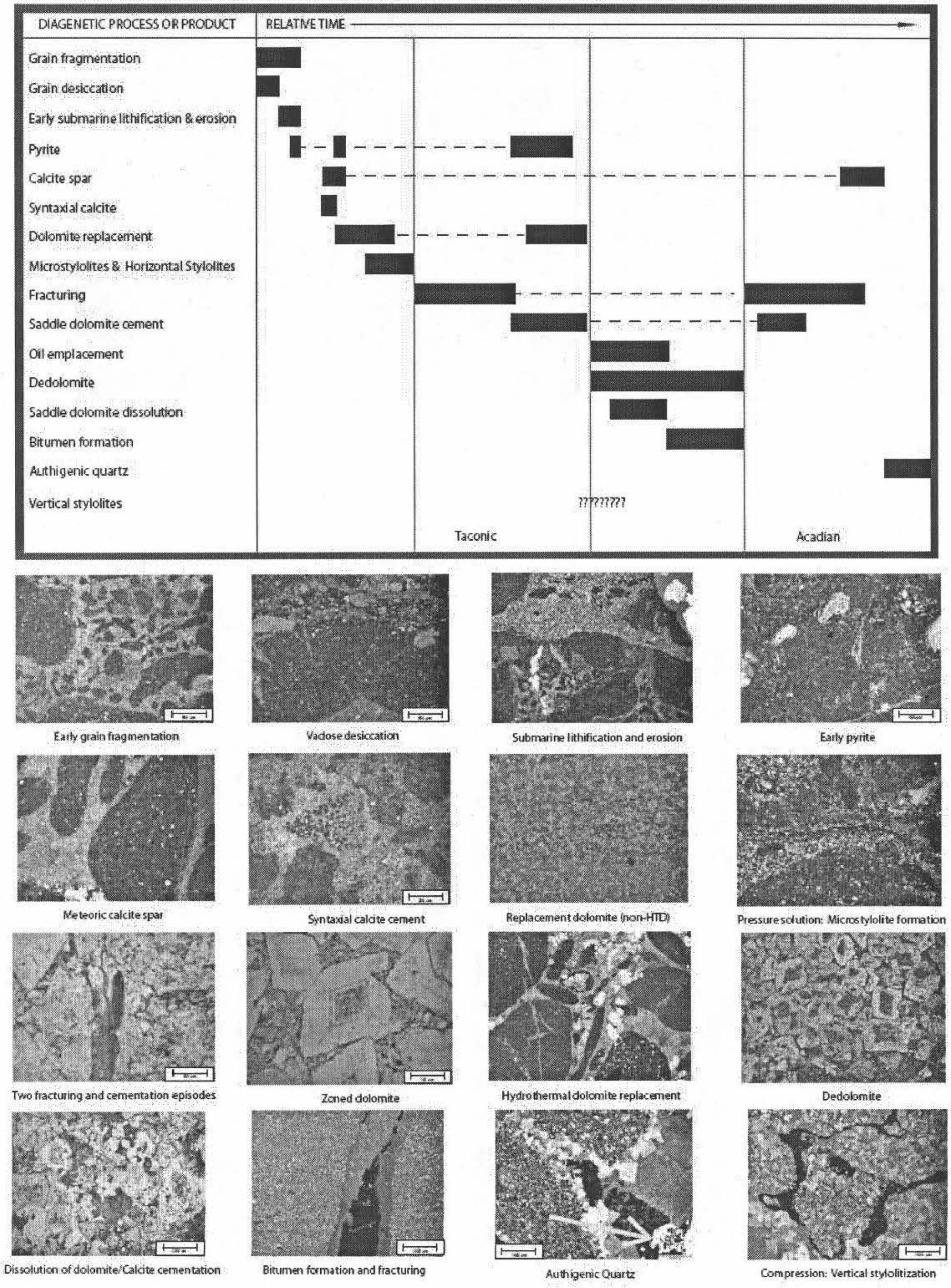


Figure 18. A Bifurcating Calcite-filled Fracture Appearing in one of the Trench Walls. Note the offset along the dark shaly layer.



Early grain fragmentation

Vadose desiccation

Submarine lithification and erosion

Early pyrite

Meteoric calcite spar

Syntaxial calcite cement

Replacement dolomite (non-HTD)

Pressure solution: Microstylolite formation

Two fracturing and cementation episodes

Zoned dolomite

Hydrothermal dolomite replacement

Dedolomite

Dissolution of dolomite/Calcite cementation

Bitumen formation and fracturing

Authigenic Quartz

Compression: Vertical stylolitization

Figure 19. Paragenic Sequence and Photomicrograph Examples of each Type

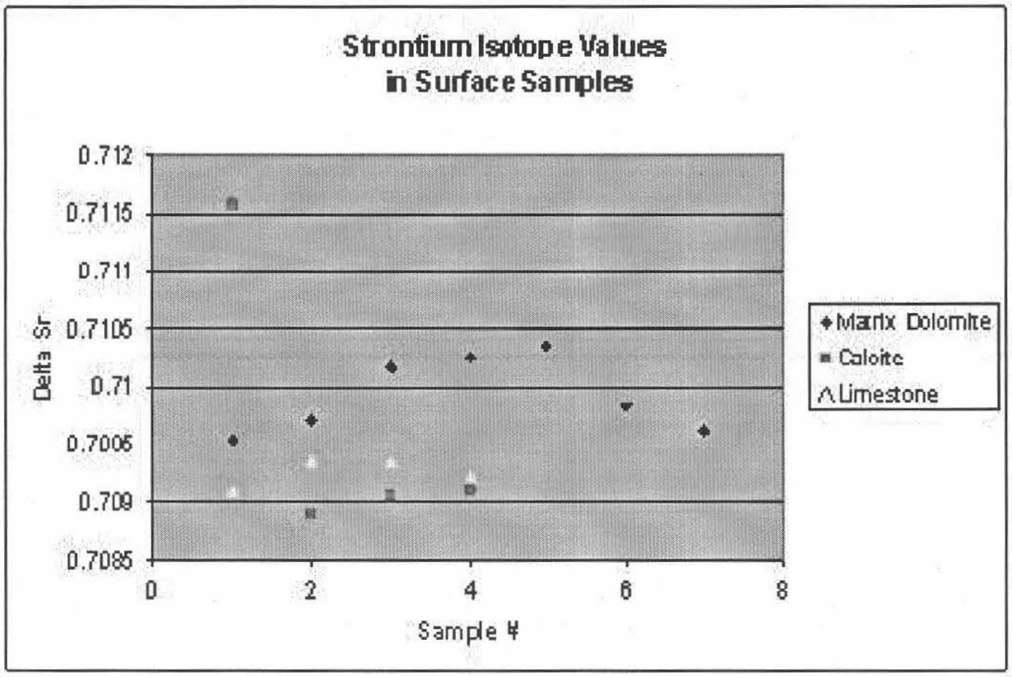


Figure 20. Graph of Strontium Isotope Values for Quarry Samples

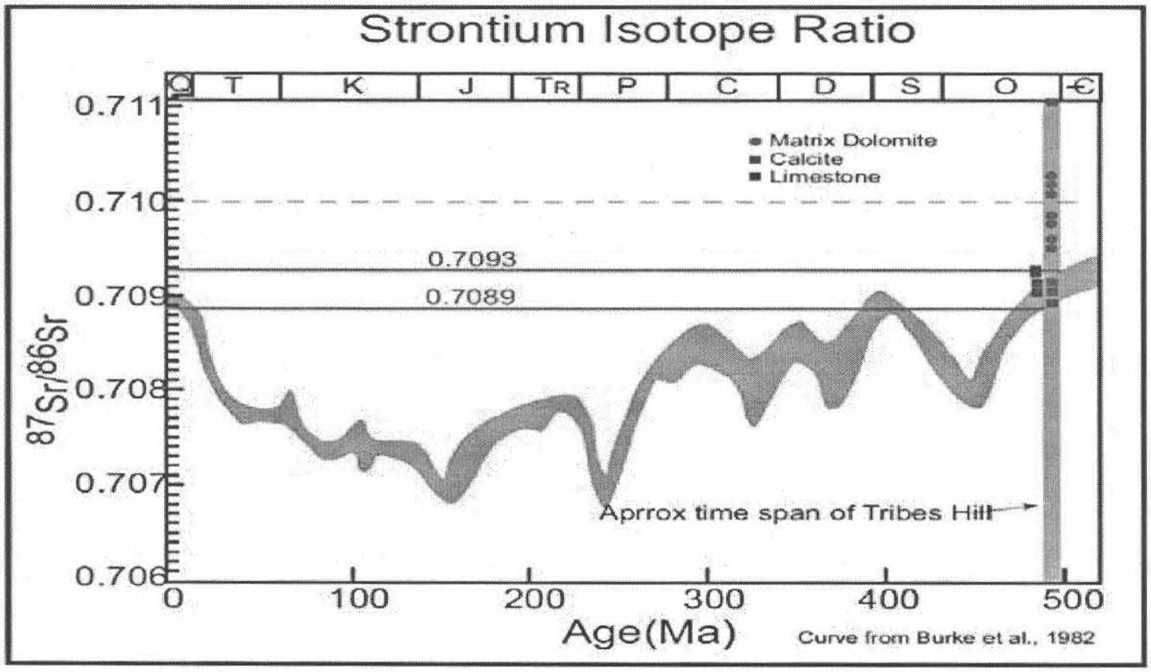


Figure 21. Strontium Isotope Content of Quarry Samples Plotted on Prehistoric Ocean Content Curve

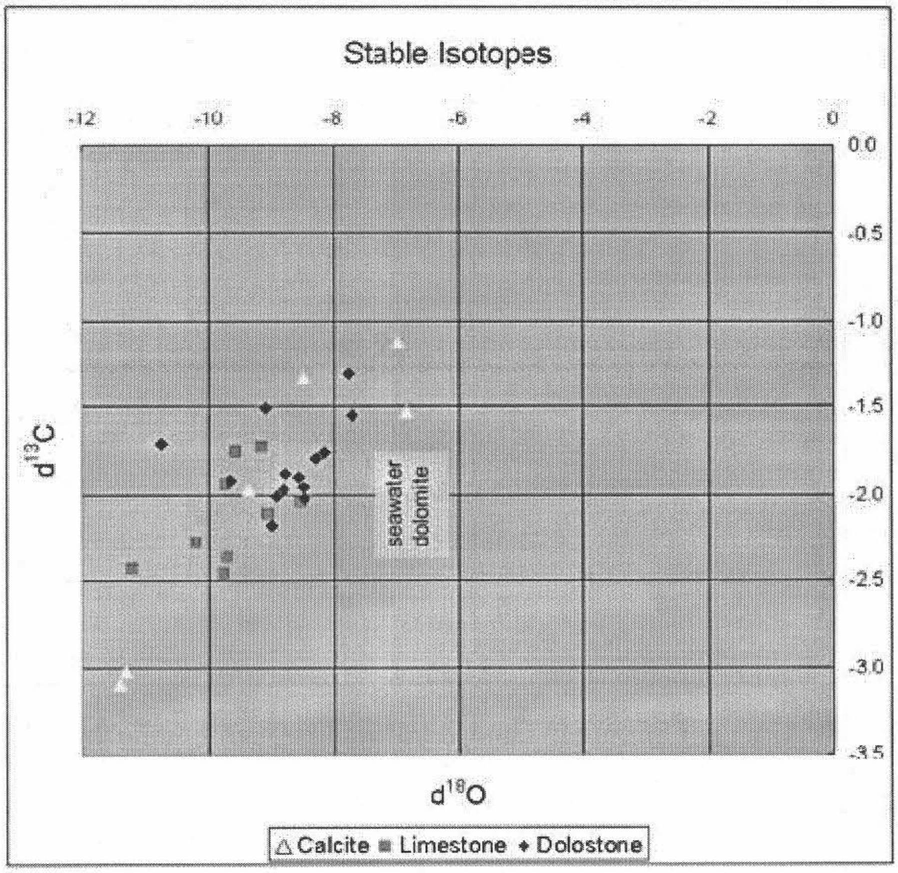


Figure 22. Plot $\delta^{18}O$ vs. $\delta^{13}C$ for Samples of Calcite, Limestone, and Dolostone from the Quarry

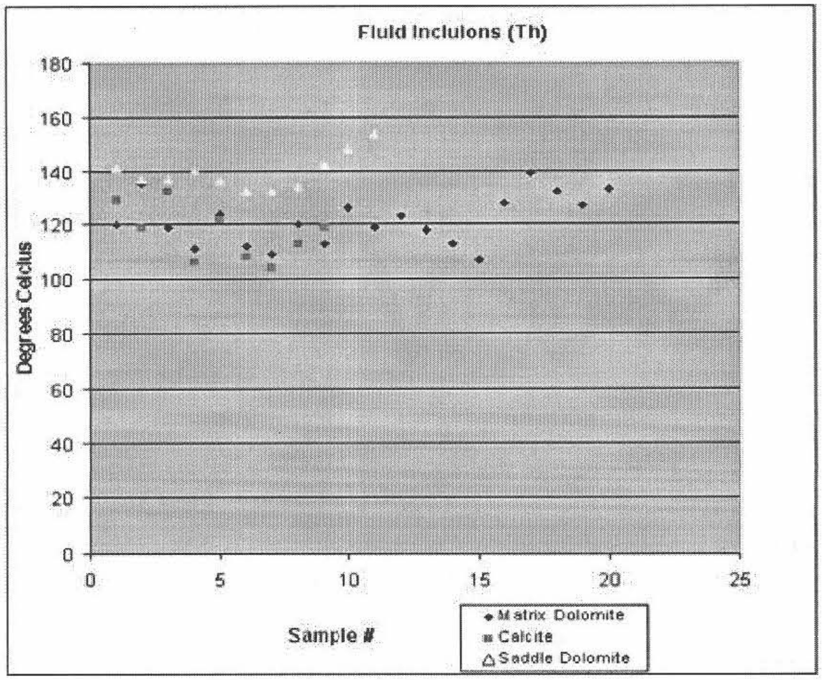
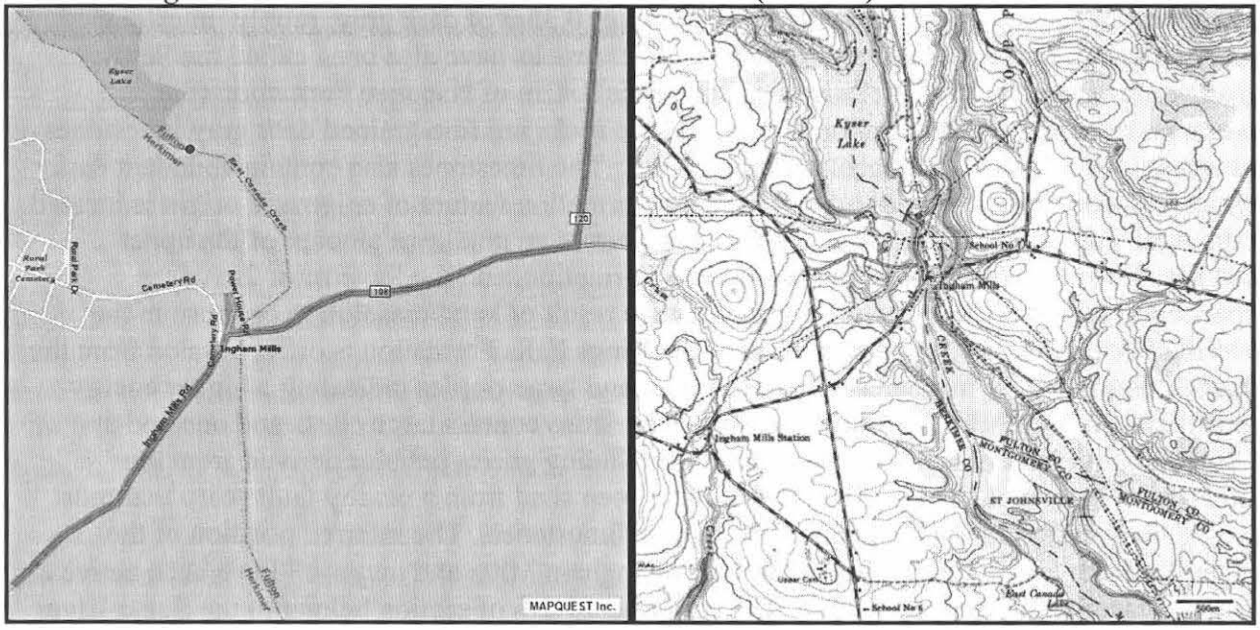


Figure 23. Homogenization Temperatures for Fluid Inclusions from Quarry Samples

Reverse Direction on unnamed quarry access road	**<0.1mi**	**1.6mi**
Left on NY-5	**11.1mi**	**12.7mi**
Right on Snell's Bush Rd. (CR-23)	**3.8mi**	**16.5mi**
Right on Ingham Mills Rd. (CR-127)	**0.8mi**	**17.3mi**
Left on Powerhouse Rd.	**<0.1mi**	**17.3mi**

Park in front of Powerhouse and walk to dam spillway

STOP 2: Ingham Mills GPS (NAD27): 519170E 4767490N



Ingham Mills is a well known paleontological and stratigraphic locality due to the complete Trenton/Black River section at this location (Fig. 24). The section here is over 23m thick and is the farthest eastward extent of the Watertown and Napanee Formations. The section is exposed on the spillway beneath the hydro dam that holds back the waters of Keyser Lake. The lowermost outcrop at the base of the spillway is a buff-weathering, fine-grained dolostone. This dolostone has previously been classified as the uppermost surface of the Little Falls Formation (Cameron et al., 1972; Cameron and Kamal, 1977; Mitchell and Marsh, unpublished data 1998). The hummocky nature of the surface does resemble thrombolitic horizons within the Little Falls Formation, though the fine-grained texture of the dolostone is very rare within this formation. However, new observations reveal that this is not a simple sedimentary contact. The dolomite observed at the section is actually an aureole of dolomitization hosted within the Lowville limestone along a fracture trending 290° (Fig. 25). On the north side of this fracture, the limestone layers clearly "onlap" over the dolomite body, but on the south side of the fracture, the dolostone grades rather abruptly into limestone within the same bedding plane. This gradation indicates that this dolostone was formed by migration of a dolomitizing fluid through the limestones along this fracture trend. The geometry of this dolomitization aureole and the surrounding limestones are strikingly similar to those observed at the Palatine Bridge Quarry (STOP 1).

Above the dolomite body another 8.66m of Lowville Formation is exposed. The rocks here consist of blue-gray to dove-gray, very fine-grained limestone. Many horizons are riddled with vertical burrows of *Phytopsis tubulosum* and vertical fingers of anthraxolite (filling in voids of dissolved burrows?). One layer in the upper Lowville contains large colonies of *Tetradium* both over-turned and in life position. Two horizons within the Lowville show distinct tidal channel structures. The lowermost of these horizons show a rubbly lag on the lower surface of the channel. The rocks herein assigned to the Lowville Formation have been previously designated as Gull River by Cameron and others (1972), whereas Cornell (2003) classified the lowermost 3m of this section as the Pamelia Formation and assigned the remainder to the Lowville Formation. At the top of the Lowville Formation lies 0.35m of dark gray, rubbly limestone which we assign to the Watertown Formation. These rocks have also been called the Selby Formation by Cornell (2003). Above this horizon is 3.42m of Napanee Formation (the lowermost formation of the Trenton Group). These rocks are fine-grained dark gray limestones that weather to a distinctive chocolate brown color. The limestones also contain abundant dark gray, calcareous shale interbeds. A prominent deformation feature of enigmatic origin is located on the west side of the outcrop; this feature incorporates an unknown amount of the upper Lowville, the entire thickness of the Watertown Formation, and the lowermost 2m of the Napanee Formation. This structure is probably the result of karst/dissolution collapse in the Lowville Formation. The overlying 9.3m of the Kings Falls Formation is differentiated from the Napanee Formation by its coarser-grained texture and large ripples indicating a higher energy depositional environment. A few of the rippled horizons contain large clasts and one bed at 14.2m contains clasts of some underlying units including gneiss pebbles derived from the Precambrian basement. These clasts had to have been shed from a nearby fault scarp that must have existed nearby during the deposition of these limestones. The inferred position of the Dolgeville Fault lays a mere 400m to the west of Ingham Mills and may well have been active at this time (Jacobi and Mitchell, 2002). The uppermost 1.2m of section belong to the Sugar River Formation, which is differentiated from the underlying Kings Falls by a decreased grain size, absence of high-energy ripples, and numerous bedding planes with abundant *Prasopora* colonies.

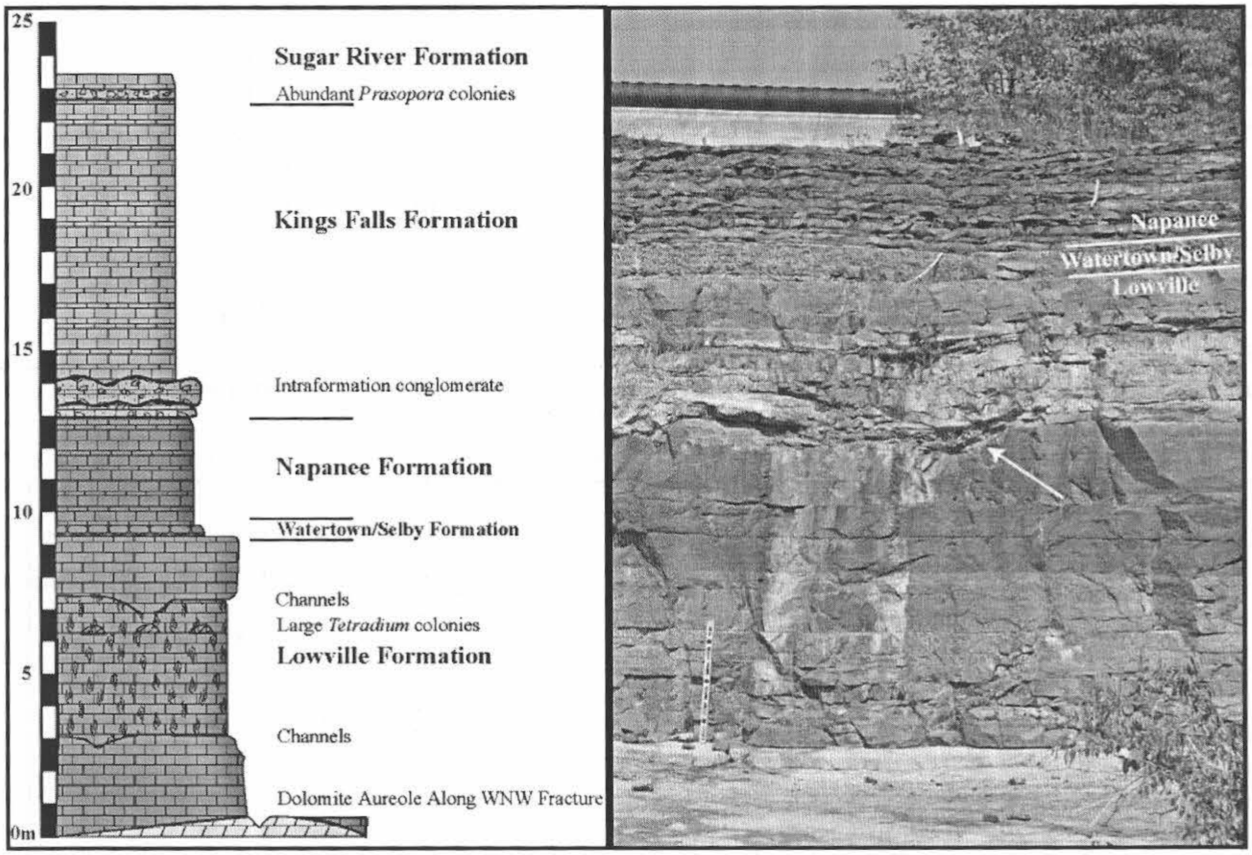


Figure 24. Stratigraphy at Ingham Mills. Stratigraphic column (left) showing 23m section present at this locality. Photo (right) showing ledgy nature of the Lowville Formation. White arrow points to a tidal channel. Note column does not correspond directly to the photo.

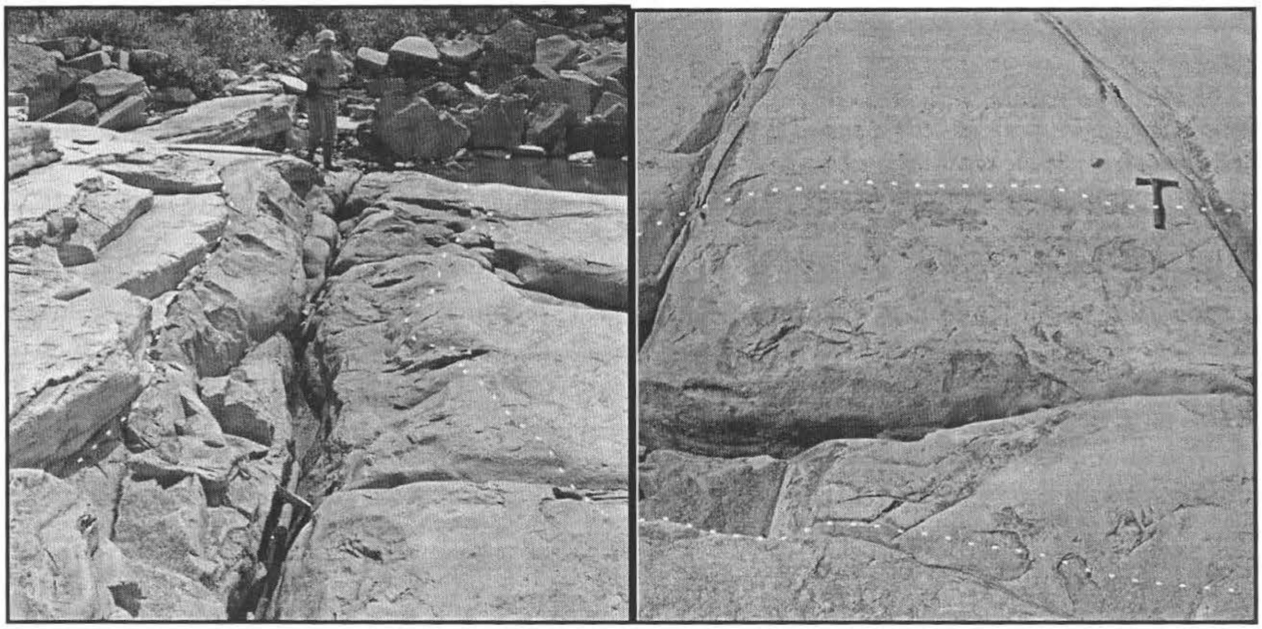
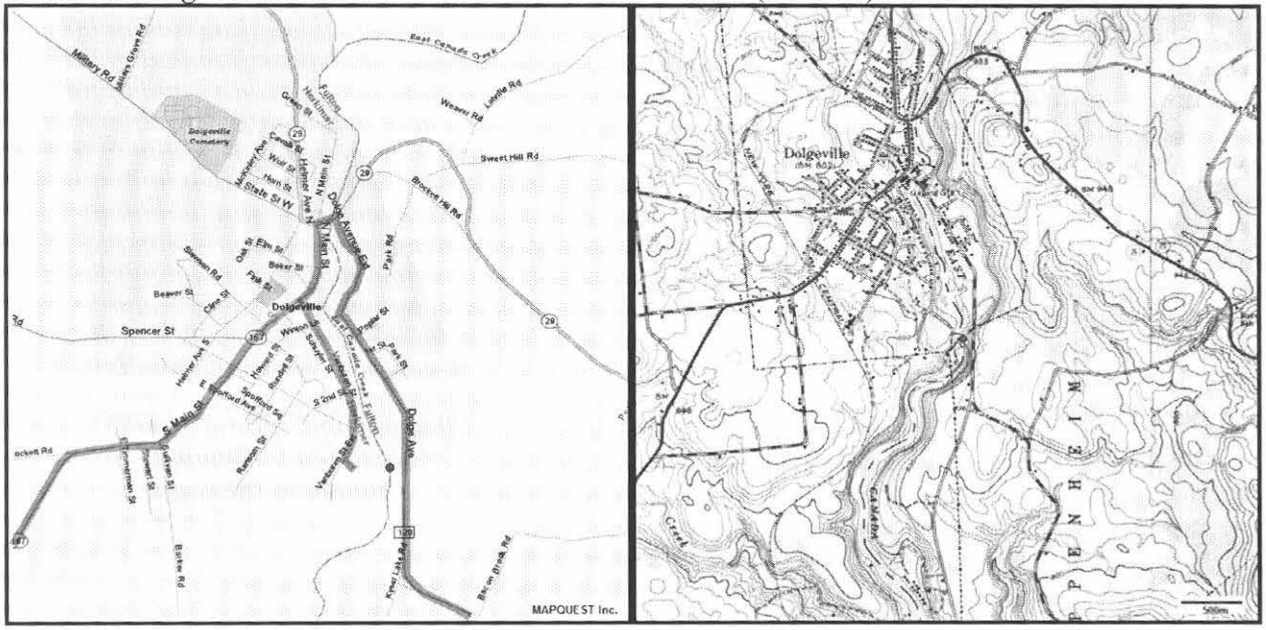


Figure 25. Photo (left) of WNW-trending Dolomitized Fracture (photo looks ESE). Note monoclinal dolomitization contact on the left side of fracture and gradational contact on the right. Photo (right) shows gradational nature of the aureole. Dotted lines show contact between limestone and dolostone.

Reverse Direction on Powerhouse Rd.	**<0.1mi**	**17.3mi**
Left on Ingham Mills Rd. (CR-108)	**0.6mi**	**17.9mi**
Left on CR-120	**2.6mi**	**20.5mi**
Name Change CR-120 to Dolge Ave	**0.6mi**	**21.1mi**
Right on Dolge Ave Ext.	**0.3mi**	**21.4mi**
Left on State St. East (NY-29)	**<0.1mi**	**21.4mi**
Left on N. Main St. (NY-167)	**0.3mi**	**21.7mi**
Left on VanBuren St.	**0.6mi**	**22.3mi**
Left on Power House Rd.	**<0.1mi**	**22.3mi**

Park at Dolgeville Hydroelectric Power Project and walk down to East Canada Creek

STOP 3: Dolgeville Dam **GPS (NAD27): 519040E 4770790N**



The power dam at Dolgeville on East Canada Creek is the most accessible exposure of the Dolgeville Fault (Fig. 26). The fault plane itself is not visible at this outcrop, though the effects of faulting are clearly and dramatically observed in the downthrown block. The fault disappears beneath thick glacial cover to the north and cannot be traced reliably for any great distance. To the south, the actual fault plane outcrops along the east bank of Kyser Lake (now accessible only by boat) and consists of a well-cemented fault breccia with iron/sulfide mineralization (Fig. 27). Cushing (1905) drew an excellent cross-section of this southern outcrop along East Canada Creek as it was before the dam at Ingham Mills raised the river level to create Kyser Lake (Fig. 28). The fault does not outcrop south of this location, but stratigraphic evidence reveals that it probably crosses the southern part of the lake and continues southward (with diminishing throw), where it passes somewhere between West Crum and East Canada Creek. If the fault crosses the Mohawk River, then the throw is severely reduced. At the Dolgeville Dam, the fault trends roughly N-S and drops down to the west (antithetic to the other major faults). Cushing (1905) estimated the throw of the fault at >300ft (91.4m), whereas Fisher (1954) estimated 450ft (137.2m). The Dolgeville Fault here exhibits dip slip kinematic indicators. Minor drag folds have nearly horizontal axes, and down-dip slickensides (Fig. 26 inset) occur on minor faults and on bedding around some of the folds (Jacobi and Mitchell, 2002). Farther south Bradley and Kidd (1991) also found downdip slickensides on a minor fault near the Dolgeville Fault (their Figure 8a). Thus, if these kinematic indicators are related to Ordovician motion, then the Dolgeville Fault was primarily a dip slip (normal) fault. We believe this fault originated in response to plate stress as it descended into the trench. The fact that this fault cross-cuts gravity anomalies and that the N-trending fractures (Dolgeville trend) usually post-date the NNE-trending fractures (Little Falls trend) indicate that slip on this fault likely initiated relatively late as a result of peripheral bulge tectonics and is younger than the Little Falls Fault. There are a few folds and faults that indicate a later reversal in motion on the Dolgeville fault.

At this site, the upthrown block consists of sub-horizontal Little Falls dolostone that outcrops along Dolge Ave. overlooking the falls. Looking northeast at the spillway outcrop, the downthrown block consists entirely of Indian Castle black shale with rare limestone beds. The beds of the falls are sub-horizontal near the powerhouse, but slowly begin to dip to the west nearing the fault. At the small line of trees, the bedding dip abruptly increases across a minor fault. The beds then continue to gradually increase in dip to angles measured as high as 59°W, although the beds are much steeper on the inaccessible shear cliff-face. Within the steeply dipping beds, the Dolgeville/Indian Castle contact is gradational, with an upsection increase in the thickness of the intervening shales. No time gap is thought to exist at this locality between the Dolgeville and the Indian Castle (Jacobi and Mitchell, 2002). The lack of a significant, observable "Thruway disconformity" (viewed at STOP 5) is consistent with the lack of a significant number of the distinct folds that characterize the NYS Thruway outcrop. No unequivocal slump folds, no time gap, and no locally angular unconformity all suggest that the "Thruway disconformity" is not a regional unconformity rather it is a slide scar, and the sediment slide did not affect this section (Jacobi and Mitchell, 2002). That scenario is consistent with the tectonic position of this outcrop—it is in the base of the Dolgeville graben, whereas the NYS Thruway outcrop is located on the horsts of the Little Falls fault system.

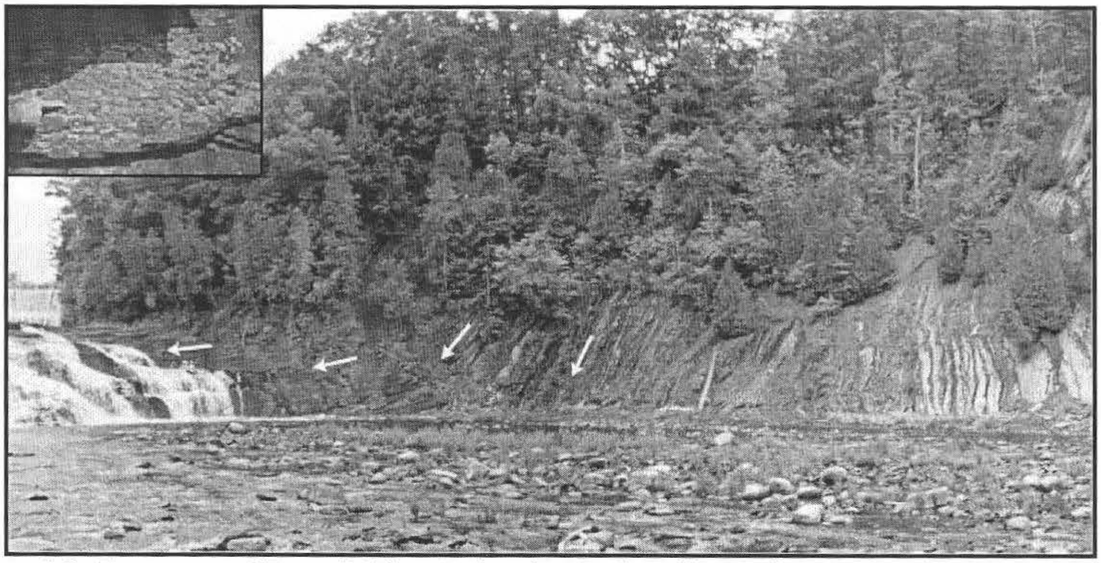


Figure 26. Exposure of Drag-folding Related to Dolgeville Fault at Dolgeville Dam. White arrows highlight changes in bedding dip associated with folding. Inset shows down-dip slickenlines observed here. The Indian Castle Member shales grade into Dolgeville Formation shales and limestones from left to right and the units are drag folded against the fault (to the left of picture). The Little Falls Formation is exposed on the upthrown block.

Figure 27. Fault Breccia Observed Along East Bank of Kyser Lake (south of the Dolgeville dam).

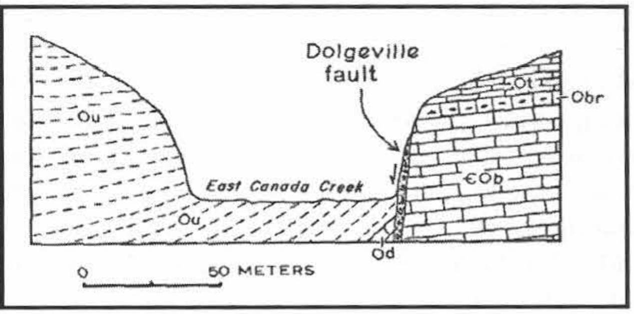
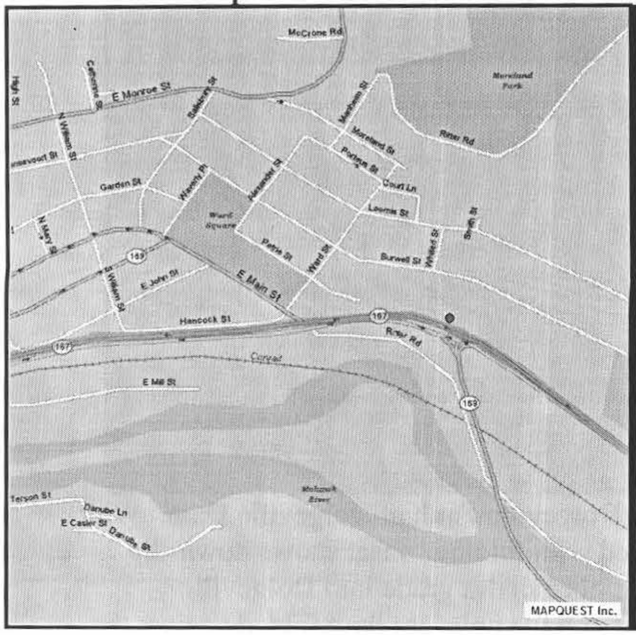


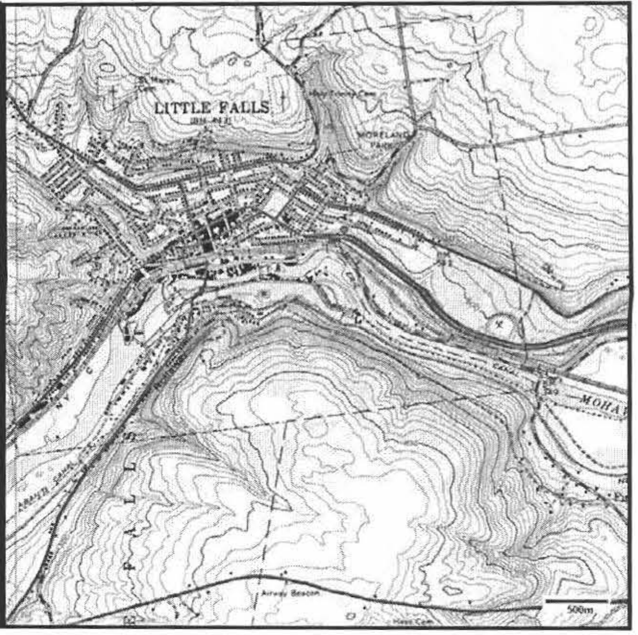
Figure 28. Schematic Cross-Section of Dolgeville Fault at Southern Exposure. Stipple pattern is fault breccia seen in Figure 27. From Cushing (1905).

Reverse Direction on Power House Rd.	**<0.1mi**	**22.3mi**
Right on VanBuren St.	**0.6mi**	**22.9mi**
Left on Main St. (NY-167)	**6.8mi**	**29.7mi**
Right on NY-5/NY-167	**0.7mi**	**30.4mi**

Park along wide shoulder near base of incline across from intersection with NY-169

STOP 4: Outcrop at Intersection of Rts. 5 & 169 GPS (NAD27): 512400E 4765390N





Cushing (1905) described several outcrops of the Little Falls Fault in the field area. Today, these outcrops no longer exist or are severely degraded. The only locality that exposes the fault plane is the Thruway cut south of the Mohawk River (STOP 5). To the north of this locality, a strong NNE-trending topographic lineament is easily recognized. In the creek to the east of Moreland Park, a NNE-trending fracture intensification domain (FID) occurs within the Little Falls Formation along with loose blocks of stock-work breccia. The fractures within this FID have an average strike of 038° with a frequency of 20 fractures/m. This lineament appears to offset both the Precambrian-Little Falls contact and the Little Falls-Tribes Hill contact with the western side down-dropped. To the south, this topographic lineament truncates Moss Island on the west side. Across the Mohawk River, this lineament is clearly visible as a small cleft in the "Rollaway". The Precambrian-Little Falls contact appears to be offset down to the east across this cleft, though no other evidence for faulting was observed at that locality. The fact that the westerly block is down-dropped on the north side of the Mohawk River, whereas the easterly block is down-dropped on the south side indicates that this splay is either a scissors fault or there is an unrecognized cross fault between the two localities. At the present location, this lineament is expressed as the small creek that we see at the stop. At this site, we observe another NNE-trending (average strike = 040°) FID (fracture frequency = 13.5 fractures/m) and also a fairly dramatic change in lithology in the Precambrian basement. The east side of the creek is well-foliated charnockitic gneiss, whereas the west side is darker, much more mafic, poorly-foliated gneiss. Slickenlines can be observed on both NNE and WNW surfaces at this outcrop (Fig. 29). Fractures of the NNE-trend increase in frequency nearing the fault (Fig. 30). The preferred growth orientations of crystals within the slickenlines indicate that the NNE trending fault experienced right lateral oblique slip with the SE fault block down-dropping (Fig. 29A). This sense of motion is opposite to the stratigraphic offset along this splay of the Little Falls Fault on the north side of the Mohawk River, thus the offset on the Little Falls Fault may be the result of several cumulative slip events with fault motion reversing at intervals throughout its history.

The slickenlines on the WNW surface are sub-horizontal (plunge = 04°) and indicate left-lateral slip with the northern block being slightly down-dropped (Fig. 29B). Leaving the creek and looking at the road cut exposures along Rt. 5, another WNW-trending surface shows well-developed slickenlines. The slickenlines at this location record left-lateral oblique slip with a slight down on the south component (Fig. 29C). This sense of offset does not agree with the offset along the inferred WNW transfer fault to the north, but it is consistent with the sense of motion required to drop the Precambrian-Little Falls contact down on the south side of the Mohawk River (on an inferred WNW fault). On the north side of the river, this contact lies at 560ft (170.7m), whereas on the south it is at 400ft (121.9m). This offset can be partially explained by regional dip on this contact, which is estimated at 03° to the south based on the topographic gradient observed on the north side of the Mohawk River. Projecting this dip across the Mohawk River would account for only 125ft (38.1m) of offset. The kinematics of all the slickenlines (Fig. 29D) at this locality are consistent with the expected motions in an eastward-directed far-field compressional regime, though these faults probably experienced several stages of slip and reversals in sense of motion.

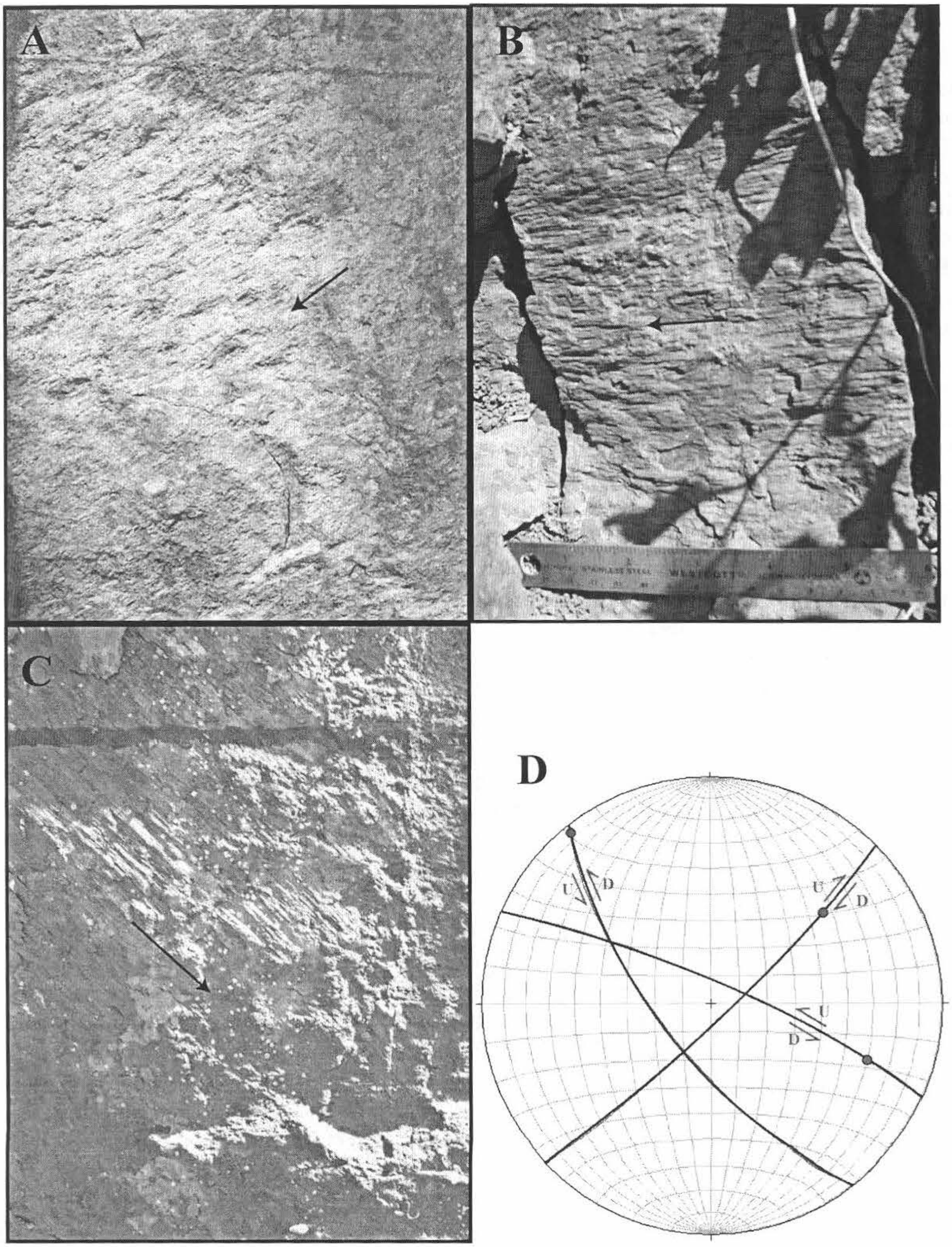


Figure 29. Slickenline Data from STOP 4. Arrows show likely relative slip of the block that the photographer is standing on (slip determined from crystal growth directions). **(A)** Slickenlines on NNE-trending fracture (photo taken looking WNW) **(B)** Slickenlines on WNW-trending fracture (photo taken looking NNE). **(C)** Slickenlines on WNW-trending fracture (photo taken looking NNE) **(D)** Stereoplot of slip planes and crystal lineations. Arrows show inferred direction of slip and U and D indicate up and downthrown side

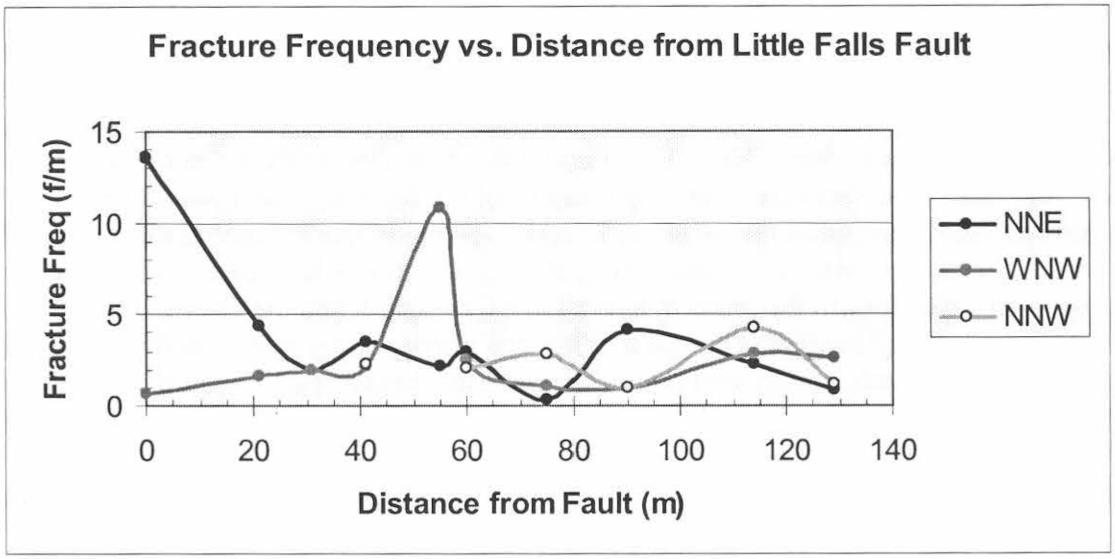


Figure 30. Plot of Fracture Frequency vs. Distance from Little Falls Fault "B" at STOP 4.

Right on NY-5/NY-167	**0.6mi**	**31.0mi**
Right on Albany St. Ramp	**0.1mi**	**31.1mi**
Right on NY-167S	**2.1mi**	**33.2mi**
Left on NY-5S	**0.5mi**	**33.7mi**
Right on Paradise Rd.	**0.8mi**	**34.5mi**

END ROAD LOG (Total Mileage: 34.5mi)

Park in construction zone at northwest corner of Paradise Rd. and Thruway intersection

STOP 5: Thruway Cut S of Little Falls

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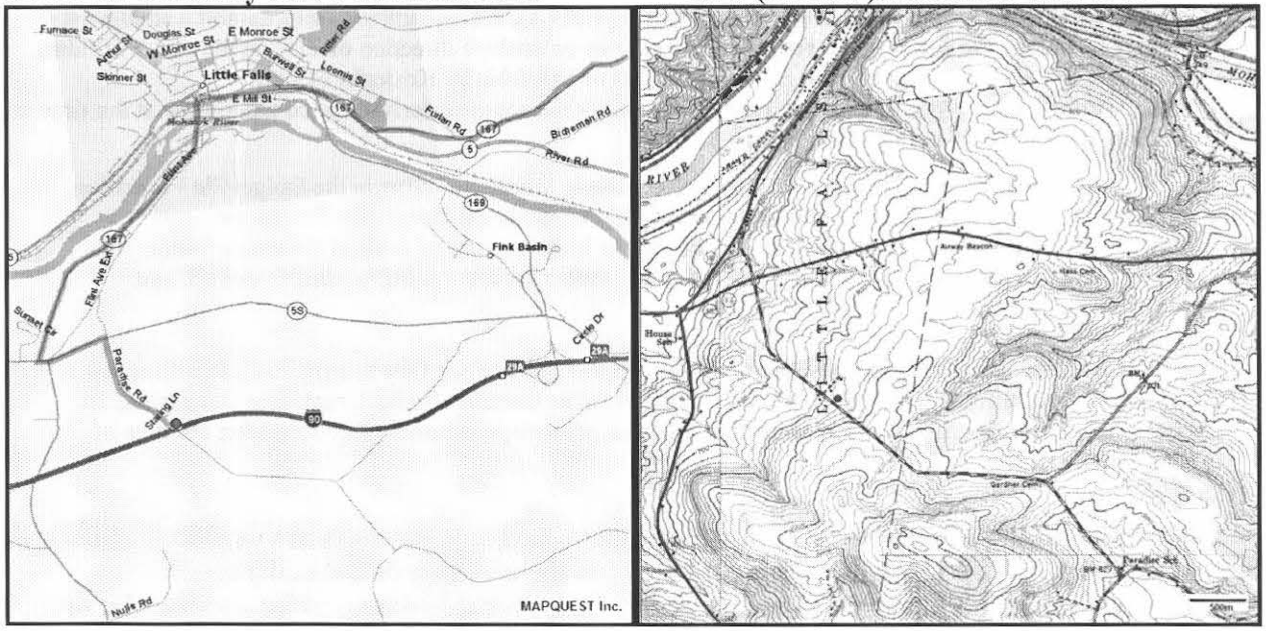

The NYS Thruway roadcut south of Little Falls provides a 1.2 mile long look at the ribbon limestones of the Dolgeville Formation, the overlying black shale of the Indian Castle Member, and the unique contact between these two units (Fig. 31). At the Thruway roadcut, the upper few meters of the Dolgeville Formation are intensely folded. Fisher (1979) first studied these folds in 1953 when the roadcut was dug. Fisher (1979) noted the dominant westward vergence of the folds, and suggested that westward slumping away from the foredeep (not toward the basin) had caused these folds. He proposed that westward gravity sliding of the Taconic Giddings Brook "Slice" into the foredeep (Magog, or Snake Hill, Basin), which was located east of the thruway roadcut along an axis between the Hudson River/Lake Champlain and the Green Mountains/Taconics) had depressed the crust below the gravity slides and caused the Adirondack Arch to rise. Since the arch was located east of the roadcut, the rising arch would have reversed the original eastward slope to a westward slope, and thus the slumps traveled west, not east, off the carbonate ramp. The overlying Indian Castle Member lies largely undisturbed above the local unconformity known as the Thruway Discontinuity (after Baird and others, 1992).

Fisher's (1979) fold vergence was supported in general by studies by two of Jacobi's students who analyzed the outcrop in the 1980s (Ritter, 1983; Koslosky, 1986). Jacobi and Mitchell (2002) further analyzed the folds and paleoflow indicators at this site. Most of the folds are disposed in "trains" and affect only a relatively few beds; i.e., they are intrastratal (or intraformational), disharmonic folds. As described in Jacobi and Mitchell (2002):

> Only kink band folds (box folds) affect more than a few beds. At the unconformity, eroded crestlines and troughs filled with breccia from the ribbon limestones, demonstrate that at least here the folds were exposed at the seafloor to erosive processes. These folds are not the result, therefore, of relatively deeply buried bedding-parallel slip. Both Fisher (1979) and Koslosky (1986) suggested that the folds were "slump folds" related to downslope slump processes, based on fold form and character. Highly contorted crestlines of some folds indicate that these folds underwent variations in strain along their axes as the sediments were transported downslope during the sliding event(s).
>
> At this stop (near milepost 213), the asymmetric folds have fairly straight crestlines and west vergence. Application of the arc separation method (Fig. 32) yielded a down-paleoslope direction of 234.5° at the time of folding (Fig. 33). At a western outcrop (at milepost 214.8), the asymmetric folds exhibit a southwest vergence and the arc separation method yielded a down-paleoslope direction of 229° at the time of folding. These values are in accord with the detailed analyses of 698 folds by Koslosky (1986).
> Other features (Fig. 34) in the eastern outcrop that suggest a southwesterly-directed paleoslope at the time of sliding include the following observations:
>
> 1. small west-directed thrusts that affect single limestone layers in the Dolgeville Formation,
> 2. westward-directed intrastratal micro-fold nappe in the Dolgeville Formation,
> 3. imbricate, east-dipping clasts in breccias in the troughs of folds at the unconformity that suggest a westerly current flow immediately after the folding (sliding event[s]), and
> 4. a small slide scar that faces west.
>
> Paleoflow data from the Dolgeville Formation at this outcrop imply a flow toward 207°; this direction is only 27° away from the paleoslope determined from the asymmetric folds. Graptolites and parting lineations above the unconformity show that the local paleoslope reversed directions after the time of slumping.

The major splay of the NNE-striking Little Falls Fault ("C") cuts the units in this stop (Fig. 35). The fact that bedding dip in the downthrown Utica (on the east side of the fault) is not perpendicular to the fault plane is evidence that this fault probably experienced oblique slip at this location (Jacobi and Mitchell, 2002). The newly recognized oblique-slip slickenlines along faults in the Precambrian basement at Little Falls (STOP 4 along Little Falls Fault "B") are consistent with the sense of rotation on the block inferred from the anomalous dip. In the past, no kinematic indicators were observed in the fault surface at the Thruway, but with the recent NYS Thruway slope abatement project, we may find kinematic indicators. Minor splays of the Little Falls Fault occupy valleys to the east and are recognized by minor changes in dip across the valleys. It is our contention that motion on these faults reversed the local paleoslope, causing the slumping activity recorded as the slump folds and the Thruway disconformity (a slide scar). This motion was related to the plate descending into the trench. (It should be noted that others maintain that the paleoslope did not reverse; Brett and Baird, 2002).

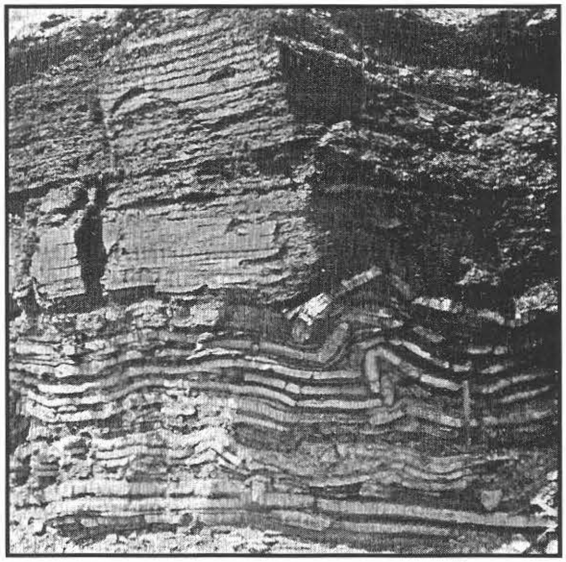

Figure 31. Photo of the Thruway Discontinuity. Undisturbed Dolgeville Formation at bottom of photo, overlain by folded layers of this formation, followed by an abrupt transition to undisturbed black shales of the Indian Castle Member. From Fisher (1980).

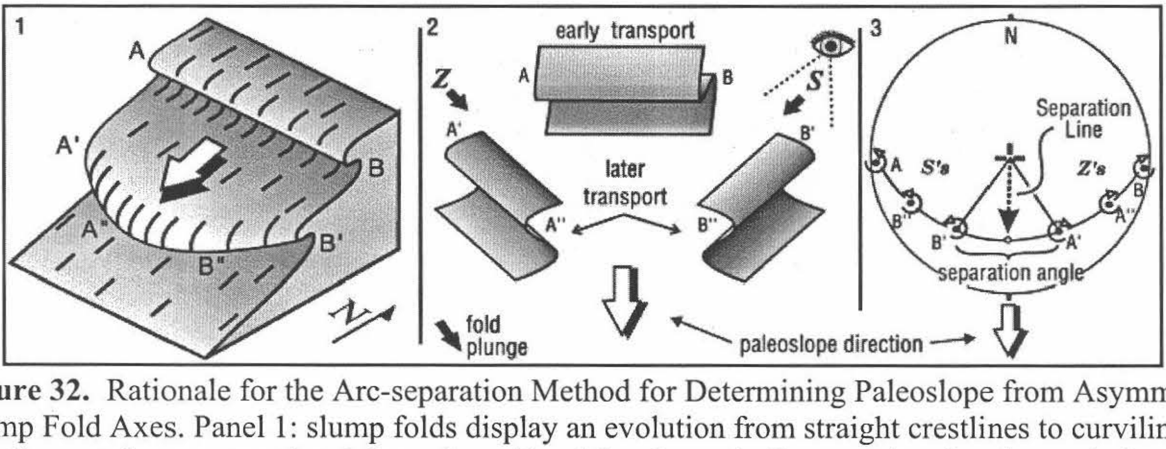

Figure 32. Rationale for the Arc-separation Method for Determining Paleoslope from Asymmetric Slump Fold Axes. Panel 1: slump folds display an evolution from straight crestlines to curvilinear crestlines as they are translated downslope. Panel 2: schematic diagram showing the evolution from straight crestlines to *Z* and *S* asymmetric folds (the asymmetry of folds, *Z* and *S*, is defined looking downplunge, opposite to the upslope view in the panel). Panel 3: stereonet plot of the axes shown in Panel 1; paleoslope is directed between the cluster of *Z* and the cluster of *S* asymmetric fold axes. From Jacobi and Mitchell (2002).

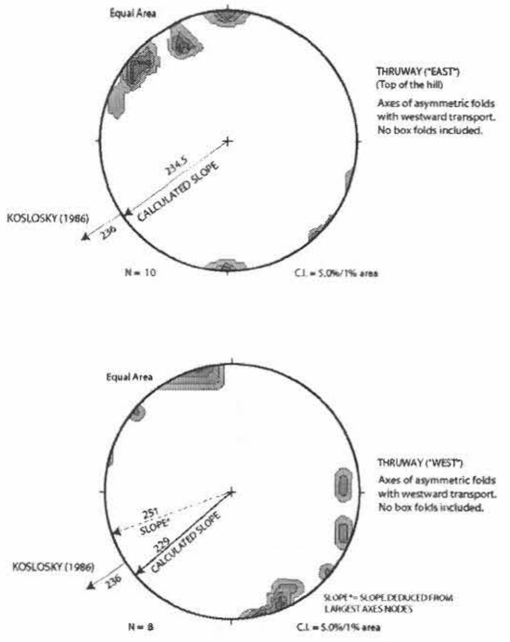

Figure 33. Stereoplots Using the Arc-Separation Method. Folds exposed at STOP 5 (Thruway East stereonet, top) yield a paleoslope of 234.5°. Folds exposed west of STOP 5 (Thruway West stereonet, bottom) yield a paleoslope of 251°. From Jacobi and Mitchell (2002).

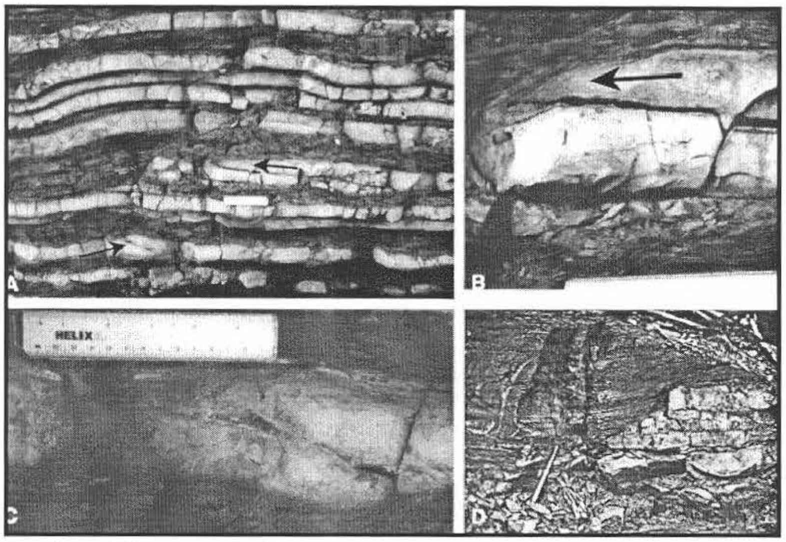

Figure 34. **(A)** Dolgeville Formation at Thruway East Below the Paradise Road Overpass. A recumbent, isoclinal fold is located immediately above the ruler at the left-directed arrow. A forced fold above the recumbent fold developed as a consequence of the asymmetric recumbent fold and associated thrust. Thrust in Fig. 34C is located below the ruler at the right-pointing arrow. Photo looks north. **(B)** Small intrastratal westward-directed, asymmetric, recumbent fold at Thruway East. Note the isoclinal folding of layering in the fold nose left of the arrow. **(C)** Small intrastratal thrust at Thruway East under the Paradise Road overpass. Photo looks north. Ramping thrust only affects one ribbon limestone, and implies west over east transport (i.e., the slump trajectory was to the west). Thrust can be seen in Fig. 34A below ruler. **(D)** Mini-slide scar at Thruway East. The abrupt termination of the top two ribbon limestones is consistent with a mini-slide scar that faces west. Photo looks north. From Jacobi and Mitchell (2002).

Figure 35. Little Falls Fault "C" at the Thruway Cut (photo looks NNE). Offset is down to the east, juxtaposing Dolgeville Formation and lowermost Indian Castle Member (west block) with Indian Castle Member. A minor splay can be seen on the right with an unknown offset within the black shales.

OPTIONAL FIELD TRIP STOPS

Manheim Power Station GPS (NAD27): 520880E 4763220N

At the Manheim Power Station, the Manheim Fault is exposed along both sides of East Canada Creek (Fig. 36). Access from the Power Station driveway is on the west bank and permission is needed as this is private property. From this side of the creek, the rocks are easily accessed even at high water. The rocks along this bank superficially resemble the interbedded ribbon limestones and shales of the Dolgeville Formation and have been designated as such by previous workers (Megathlin, 1938; Fisher, 1954; Bradley and Kidd, 1991). However, faunal evidence indicates that the rocks observed here are the "Allen Road beds" of the Flat Creek Member (Mitchell, 2006 personal communication). Numerous fractures and veins dissect the outcrop at this locality. The fractures are of NE, WNW, and NNW orientations. It was expected that the NE-trending (fault-parallel) fractures would increase in frequency nearing the fault plane, but actually the NNW (fault-perpendicular) fractures show the most marked increase (Cross, 2004;

Cross et al., 2004; Fig. 37). At the northern extent of the outcrop on this side of the creek is a fault breccia. This breccia contains lithologies similar to those of the adjacent Flat Creek Member consisting of large, rounded clasts of limestone that are well-cemented in a dark, calcareous mud matrix. Across the creek on the eastern side, one can see beds of the Flat Creek Member drag-folded upward on the eastern block to angles approaching 60°SE juxtaposed against gently dipping (07°SE) beds of the Little Falls Formation on the western block (Bradley and Kidd, 1991). Here the fault strikes roughly 50° (it is drawn as roughly N-trending in Fisher, 1980) and drops down to the east (Cross, 2004). According to early workers (Conrad, 1837; Vanuxem, 1838) there is a one inch thick calcite vein with associations of galena and pyrite present, which were mined for a brief period in the area of the fault. In addition, the fault zone hosts a peridotite dike. Similar dikes in the area roughly parallel the fault trend and have been dated using Rb-Sr as 130±10 million years old (Fisher, 1980). Estimates of the offset on this fault vary greatly with Darton (1895) claiming 152ft (46.3m), Megathlin (1938) 60ft (18.3m), Fisher (1954) 400 ft (121.9m), and Bradley and Kidd (1991) 131ft (39.9m).

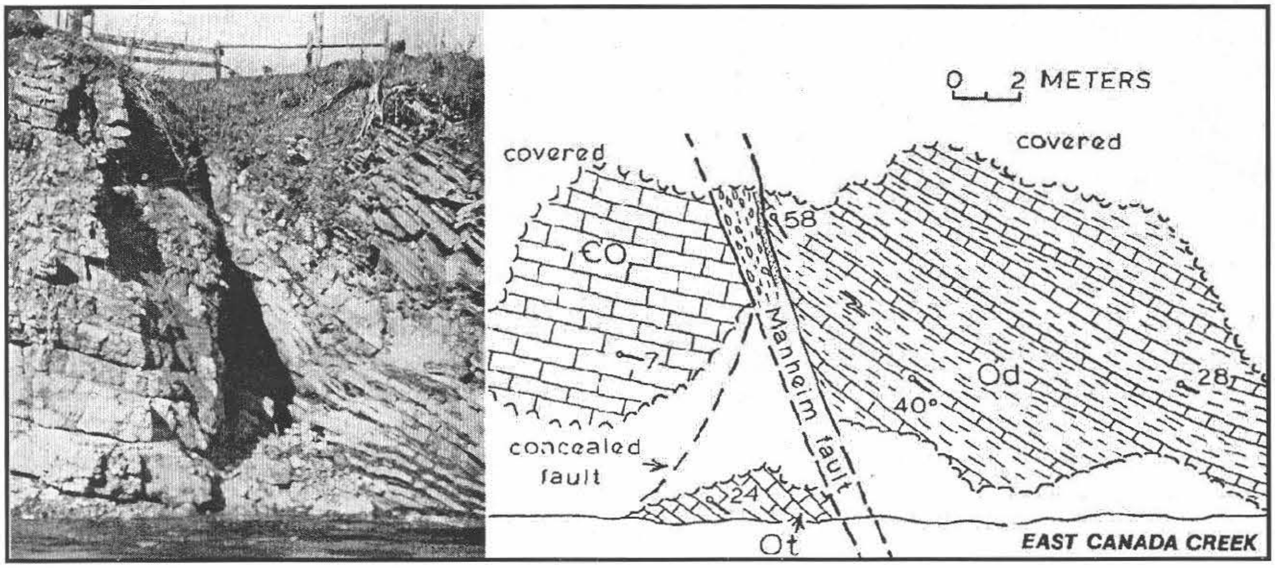

Figure 36. Manheim Fault at Manheim Power Station. Photo (left) looking northeast at the outcrop of the fault surface. From Megathlin (1938). Sketch (right) of outcrop showing bedding dips and fault breccia. From Bradley and Kidd (1991). This fault juxtaposes drag-folded Flat Creek Member (called Dolgeville Formation by previous workers at this locality) against Little Falls Formation with the east side down-dropped.

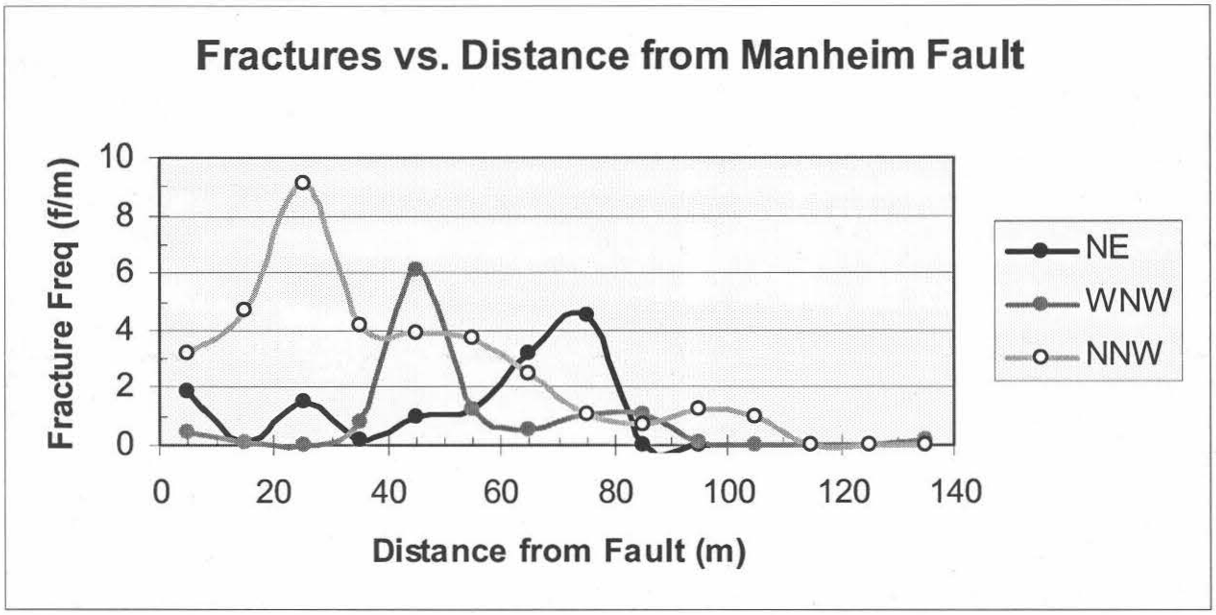

Figure 37. Fracture Frequency vs. Distance from Manheim Fault. From Cross (2004).

Miner Rd. Outcrop **GPS (NAD27): 514910E 4771185N**

In the course of widening Miner Rd., an excellent outcrop of the lowermost Tribes Hill Formation was exposed. At this locality, the rocks are a light gray, medium-bedded (11cm average), coarse-grained dolostone. The bedding at this locality trends 002/03W. Several beds show excellent herring-bone cross-stratification typical of a tidal environment. Four distinct fracture sets are present at this outcrop (N, NE, WNW, and NW). At this outcrop, the NE-trending fracture set (average strike = 53°) is master (oldest) and parallel the inferred orientation of the Little Falls Fault just to the east. Reddish staining along the NW set is interpreted as sulfide and/or iron-rich vein mineralization (Fig. 38). The outcrop also hosts many vugs within the dolostone matrix. These vugs are variably filled with white calcite (Fig. 39) and occasional buff-colored dolomite. The presence of the veining and vug development are indicative that this horizon was favorable to the migration of fluids from the nearby fault. Heading south along Miner Rd. from this outcrop, there are excellent exposures of the upper Little Falls Formation in the woods on the western side of the road. These exposures contain stromatolite colonies and also host vugs partially filled with white calcite.

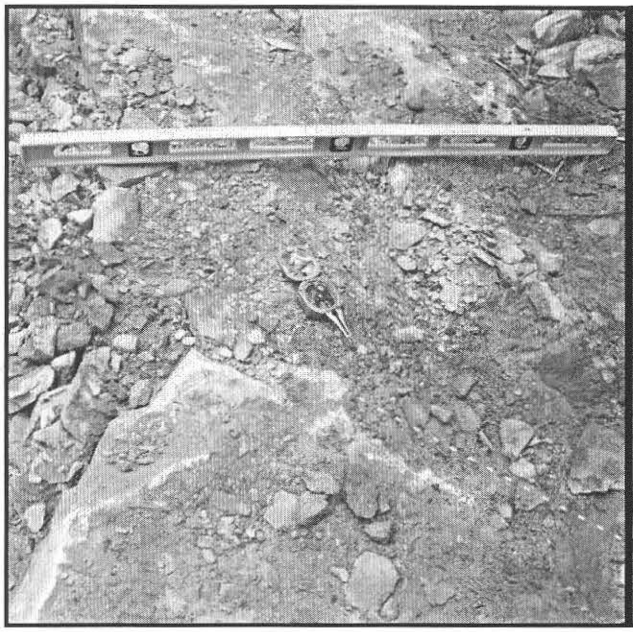

Figure 38. Sulfide Mineralization Along NW-trending Fracture. Fracture orientation is highlighted with dotted line.

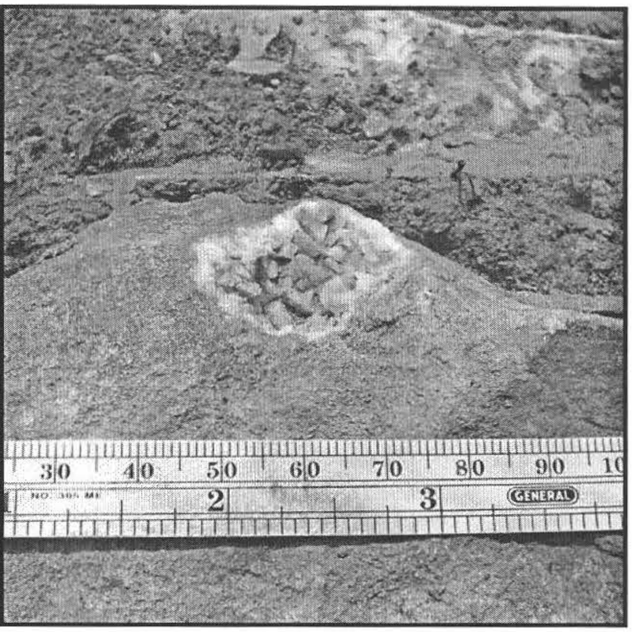

Figure 39. Calcite-filled Vug Within Tribes Hill Formation.

Rt. 167 Overlook **GPS (NAD27): 514585E 4765080N**

The scenic overlook of Rt. 167 just before entering the city of Little Falls, NY provides an excellent vantage point to appreciate the magnitude of the fault offsets in the region (Fig. 40). Though the Little Falls Fault is not directly exposed at this locality, the steep linear scarp must be a close approximation of the fault plane. If one parks in the designated area and walks to the fence, a grand overview of the Mohawk River Valley opens up before you. In contrast to the narrows at Little Falls, NY, in the resistant Precambrian basement, the valley opens broadly to the east in the much less resistant shales of the Utica Group. If the gate is open, it is possible to walk out onto a small outcrop of Precambrian basement at the edge of the scarp. The foliation here is well defined and trends 284/26NE. This foliation is fairly uniform throughout the Little Falls area. Fractures in this outcrop trend NNE and WNW and are mutually abutting. The NNE-striking fractures (average strike = 037°) of this outcrop parallel the topographic lineament and the inferred trend of the major splay ("C") of the Little Falls Fault in this area. While standing on this outcrop of Grenvillian basement, one can look down into the valley approximately 150 feet below and see the Thruway Interchange and its impressive exposures of the Upper Ordovician Indian Castle Member. Cushing (1905) estimates the throw on this fault at this location at 650-750ft (198.1-228.6m), whereas Fisher (1954) estimates 900ft (274.3m). The fault extends northward into the crystalline rocks of the Adirondack Dome and southward where it dies out in the Silurian shales. Across Rt. 167 from the scenic overlook is an old quarry. This quarry contains a 16m section of the lowermost Little Falls Formation, though the lower contact with the Precambrian basement is not exposed here. This section of Little Falls dolostone is very coarse-grained and contains large amounts of quartz and some large detrital feldspar grains. Many beds display cross-bedding and a few isolated horizons host vuggy porosity.

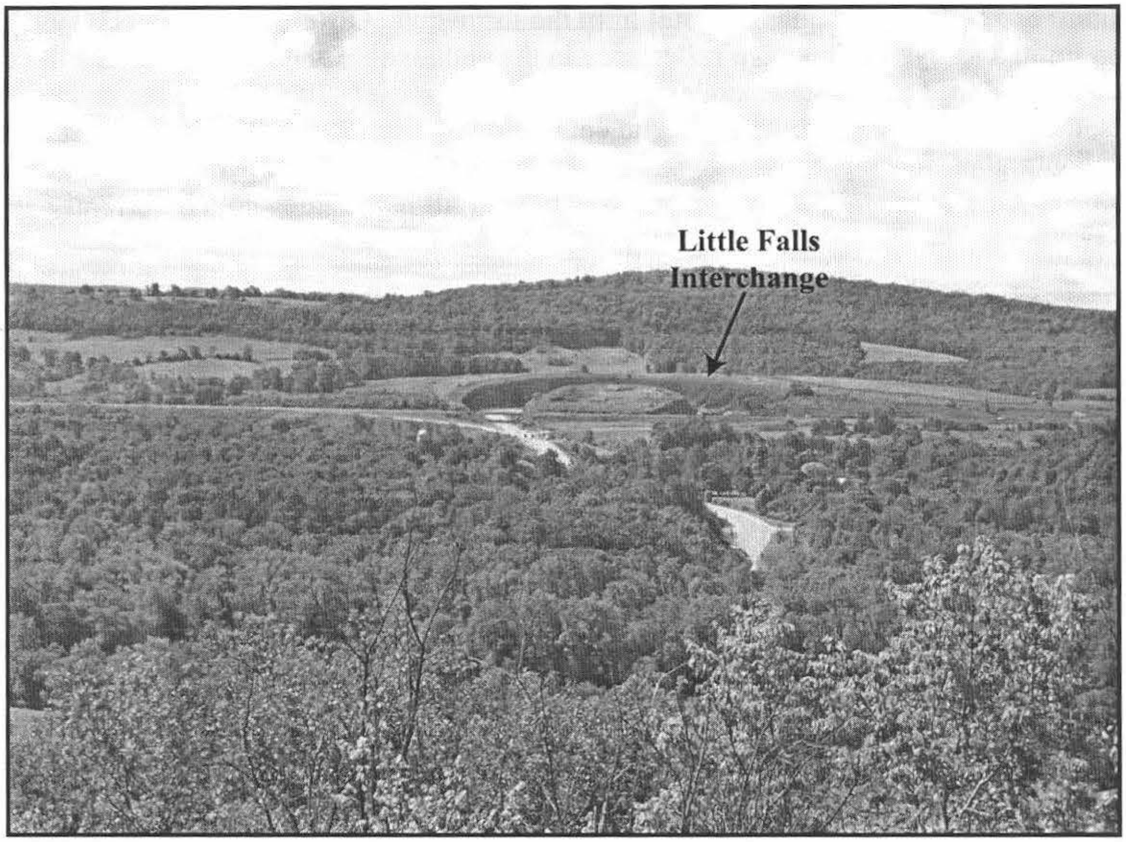

Figure 40. View from Rt. 167 Overlook. Photo is taken looking SSE. Photographer is standing on Precambrian basement looking down across the Little Falls Fault into the Mohawk Valley and the Indian Castle Member exposed in the Little Falls Interchange

Little Falls Bike Path Area **GPS (NAD27): 511580E 4764860N**

The bike path on the south side of the Mohawk River now occupies an old railroad bed. Walking eastward from the designated parking area, large exposures of Precambrian basement can be observed. Approximately halfway through the cut about 20ft from ground level on the south side, the contact between the Precambrian basement and the Little Falls Formation is exposed (Fig. 41). The contact is inaccessible without climbing gear, but clearly visible. Walking back to the parking lot and heading south, there is a footpath that winds its way up above the bike path. Along this path, there are excellent exposures of Little Falls dolostone. These outcrops are buff-weathering, thickly-bedded, coarse-grained dolostone that display cross-bedding, stromatolites, and numerous vugs. These vugs are filled with saddle dolomite, quartz, and anthraxolite (Fig. 42). Dolomite usually lines the vugs, followed by anthraxolite, though a few vugs contain anthraxolite films that pre-date the dolomite. Where quartz is present, it is always the last mineral to precipitate, although anthraxolite commonly occurs as solid inclusions within the crystals. The fact that the age relationships of dolomite and anthraxolite are inconsistent, suggests that these minerals may have significant overlaps in their time of precipitation. Dunn and Fisher (1954) analyzed the anthraxolite from three similar vugs in the area and obtained an average composition of 90.39% carbon, 7.03% water, and minor components of nitrogen, sulfur, and ash. The temperature of precipitation of these vug-filling minerals is poorly studied. Dunn and Fisher (1954) cite Dr F.G. Smith as having obtained a temperature of 51°±2°C for a quartz crystal from the formation. O'Reilly and Parnell (1991), based on limited analysis of bitumen reflectance in the anthraxolite and fluid inclusions in calcite and quartz, developed a four-stage model in which the first stage (<70°C) deposited calcite cements, the second stage precipitated calcite veins and vug fills (70 to 130°C), a third stage of anthraxolite (and presumably dolomite) and quartz (>120°C), and a fourth very high temperature stage 200±10°C. Further fluid inclusion analyses of vein fill in the study area is currently underway.

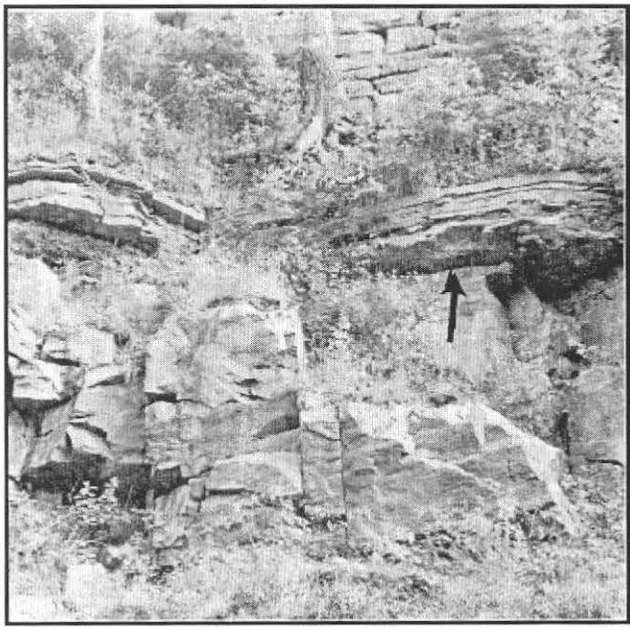

Figure 41. Precambrian-Little Falls Formation Contact (arrow). Exposed in wall of bike path. From Zenger (1981).

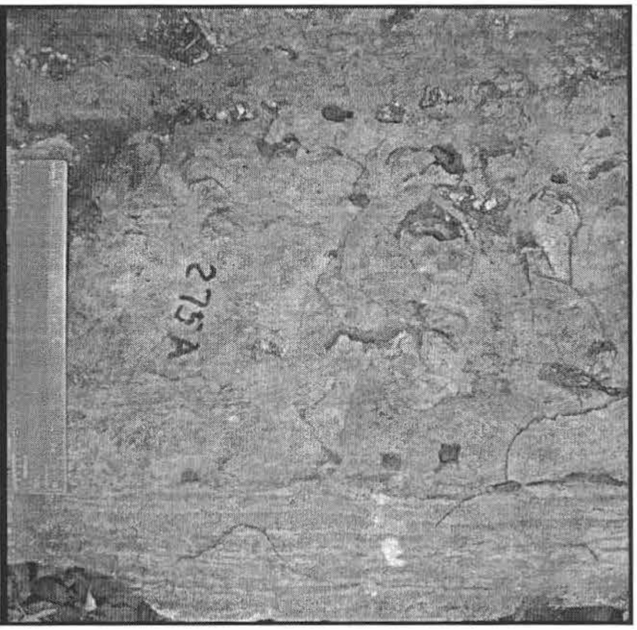

Figure 42. Vugs in the Little Falls Formation. Vugs filled with anthraxolite found in exposures on footpath above the bike path.

Nowadaga Creek **GPS (NAD27): 517265E 4760140N**

The exposures along Nowadaga Creek at the River Rd. bridge offer an opportunity to study the Dolgeville Formation and the contact with the overlying Indian Castle Member. The creek bed downstream of the bridge exposes the upper surface of the Dolgeville Formation and is readily observable at low water levels. The upper beds of the Dolgeville Formation are a complexly interference-folded surface (Fig. 43) and the contact with the overlying Indian Castle Member is very abrupt. For a detailed study of the folds and paleoflow directions at this locality see Jacobi and Mitchell (2002). Downstream from the contact is exposed a nearly complete section of the Dolgeville Formation. Very small (10cm wavelength) asymmetric folds with irregularly-bearing axes are the result of mini-blind thrusts involving single limestone beds (Marsh, 2000). These thrusts suggest that the entire Dolgeville section was deposited during times of instability. The fractures present within the Dolgeville trend NNE, WNW, and NW. There are also veins present in the Dolgeville Formation at this locality. These veins parallel the NNE fracture trend and range in thickness from 1-3mm of white calcite. Upstream of the bridge, the creek is floored by the Indian Castle Formation. This abrupt transition from contorted Dolgeville ribbon limestones and shales to undisturbed calcareous black shales represents a significant time gap, but not as much as that at the Thruway Discontinuity (Jacobi and Mitchell, 2002). In an outcrop on the northern bank, the lower Indian Castle Member is seen to contain a few thin carbonate beds, but overall the lithology is dominated by black calcareous shale. The fractures hosted within these shales show three prominent orientations: NNE, WNW, and NW (Fig. 44).

Figure 43. Interference-folded Upper Surface of the Dolgeville Formation. Downstream of the River Rd. bridge on Nowadaga Creek

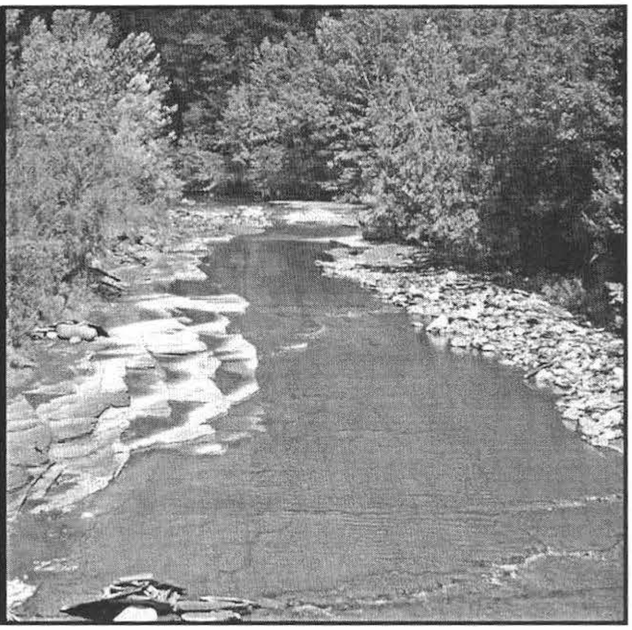

Figure 44. Fractures Within Lower Indian Castle Member. Upstream of River Rd. bridge on Nowadaga Creek. Photo taken looking NW.

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