SEDIMENTOLOGY AND STRATIGRAPHY OF THE CAMBRIAN-ORDOVICIAN POTSDAM GROUP (ALTONA, AUSABLE AND KEESEVILLE FORMATIONS), NORTHEASTERN NY

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INTRODUCTION

Geological Setting

The Cambrian to Lower Ordovician Potsdam Group is the lowermost unit of the Paleozoic platform succession overlying rocks of the 1 – 1.5 Ga Grenville orogen within the Ottawa Embayment and Quebec Basin, two semi-connected fault-bounded basins that form an inboard salient of the St. Lawrence platform succession in eastern Ontario, northern New York State and western Quebec, over an area of approximately 26,000 km^2 (Figure 1). Potsdam strata was deposited from the Late Early Cambrian until the Early Ordovician at subequatorial latitudes between 10^o – 30^o south approximately 200 – 400 km inboard of the south-facing Laurentian margin, during the late postrift and subsequent passive margin phase associated with the rifting and breakup of Rodinia (Torsvik et al. 1996; McCausland et al. 2007, 2011; Lavoie, 2008; Allen et al., 2009; Figure 2). It is mainly a siliciclastic unit that, in general, exhibits an upwards progression from terrestrial to marine deposits (Sanford and Arnott, 2010; with some exceptions, including the Altona Formation and Riviere Aux Outardes Member, see below). This terrestrial to marine progression is shared by stratal equivalents of the Potsdam Group on the Laurentian margin and in other North American cratonic basins that collectively form at the base of the Sauk Megasequence, a transgressive Megasequence that records eustatic rise across much of Early Paleozoic Laurentia preceding the Taconic Orogeny (Sloss, 1963; Lavoie, 2008).

There is no consensus from the existing Potsdam literature to suggest whether the Ottawa Embayment and Quebec Basin were pre-existing basins that were passively filled during the Early Paleozoic or were active rift or tectonically-reactivated basins. Also poorly understood is the relationship between these basins to structures within the rift margin to the east. However, features of the Potsdam including its highly irregular isopach distributions, presence of internal unconformities, variable provenance, localized soft-sediment structural deformation, in-situ brecciation, and debris flows adjacent to faults all suggest that tectonism played a role in Potsdam sedimentation, probably by the reactivation of inherited zones of tectonic weakness and pre-existing faults that developed in the Proterozoic (e.g. Wiesnet and Clark, 1966; Wolf and Dalrymple, 1984; Landing et al., 2009; Sanford and Arnott, 2010). In fact, the Ottawa Embayment and Quebec Basin lie in an area of prolonged rifting referred to as the Ottawa-Bonnechere Graben, a probable aulocogen that became active in the Neoproterozoic and was reactivated episodically until the Mesozoic and even until more recent times (Kay, 1942; Kumarapeli and Saull 1966; Kamo et al. 1995; Roden-Tice et al. 1999; Aylesworth et al. 2000; Malka et al. 2000; Bleeker et al. 2011); though the exact timing of episodic tectonic events is poorly constrained. Also poorly understood from existing literature is the approximate configuration of the basins and adjacent highlands during the Cambrian-Ordovician and the original extent of Cambrian-Ordovician strata due to post-Ordovician faulting, Mesozoic hotspot migration and unroofing of the Adirondack Dome (Kay, 1942; Fisher, 1968; Isachsen, 1975; Crough 1981; Roden-Tice et al. 1999).

The Potsdam Group is made up of four formations: the Altona, Ausable, Hannawa Falls and Keeseville Formations (Figure 3), which are described in more detail below. This trip will focus on the Potsdam strata in from the southern Quebec Basin and westward along the axis of the Oka-Beauharnois Arch that separates the Quebec Basin and Ottawa Embayment. In this area the Altona, Ausable and Keeseville Formations are present and exposed (Figure 4).

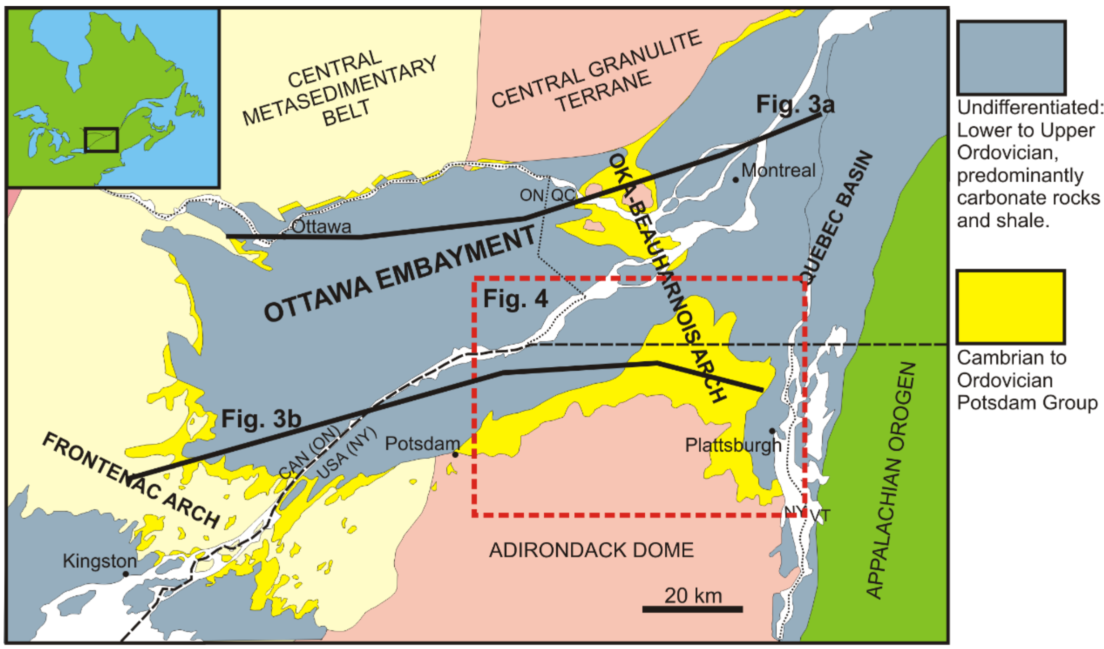

Figure 1: Base map of the Potsdam Group in the Ottawa Embayment and Quebec Basin. The solid black lines represent the ~E-W stratigraphic correlations in Figure 3, and the red square outlines the location of the map in Figure 4.

Previous Investigations of the Cambrian – Early Ordovician Stratigraphy of the Ottawa Embayment and Quebec Basin

The Potsdam Group is one of the oldest named rock units in North America (Emmons, 1838) and for almost 200 years has been studied locally in either New York State, Ontario and Quebec (Emmons, 1838, 1841; Logan, 1863; Alling, 1919; Chadwick, 1920; Wilson, 1946; Clark, 1966; 1972; Otvos, 1966; Fisher, 1968; Greggs and Bond, 1973; Brand and Rust, 1977; Selleck 1978a & b; Wolf and Dalrymple, 1984; Globensky, 1987; Salad Hersi et al. 2002; Dix et al. 2004; Landing et al. 2009; Sanford, 2007; see also Sanford and Arnott, 2010 for detailed discussion). Many of the early studies and a few more recent studies are essentially geological reports that form the basis for the Potsdam lithostratigraphic framework and the existing unit names in New York, Ontario and Quebec (e.g. Emmons, 1838, 1841; Logan, 1863; Alling, 1919; Chadwick, 1920; Wilson, 1946; Clark, 1966, 1972; Fisher, 1968; Wolf and Dalrymple, 1984; Globensky, 1987), while other generally more recent studies have provided depositional age constraints, interpretations of depositional environments stratigraphic revisions and sequence stratigraphic interpretations (e.g. Greggs and Bond, 1973; Brand and Rust, 1977; Selleck 1978a & b; Wolf and Dalrymple, 1984; Globensky, 1987; Salad Hersi et al. 2002; Dix et al. 2004; Landing et al. 2009; Sanford and Arnott, 2010). Of these studies, only few (Lewis, 1963; Otvos, 1966; Sanford and Arnott 2010) include systematic examination of the Potsdam Group throughout the entire Ottawa Embayment and Quebec Basin, while the rest were generally confined to either New York, Ontario or Quebec. Other recent studies of the Potsdam Group have focused mainly on the paleoecology of Cambrian-Ordovician invertebrate trace makers and their preserved ichnological record, and include evidence of the earliest terrestrial animal life on Earth (Clark and Usher, 1917; Bjerstedt and Erickson 1989; MacNaughton et al. 2002; Hagadorn and Belt 2008; Collette and Hagadorn 2010; Hagadorn et al. 2011).

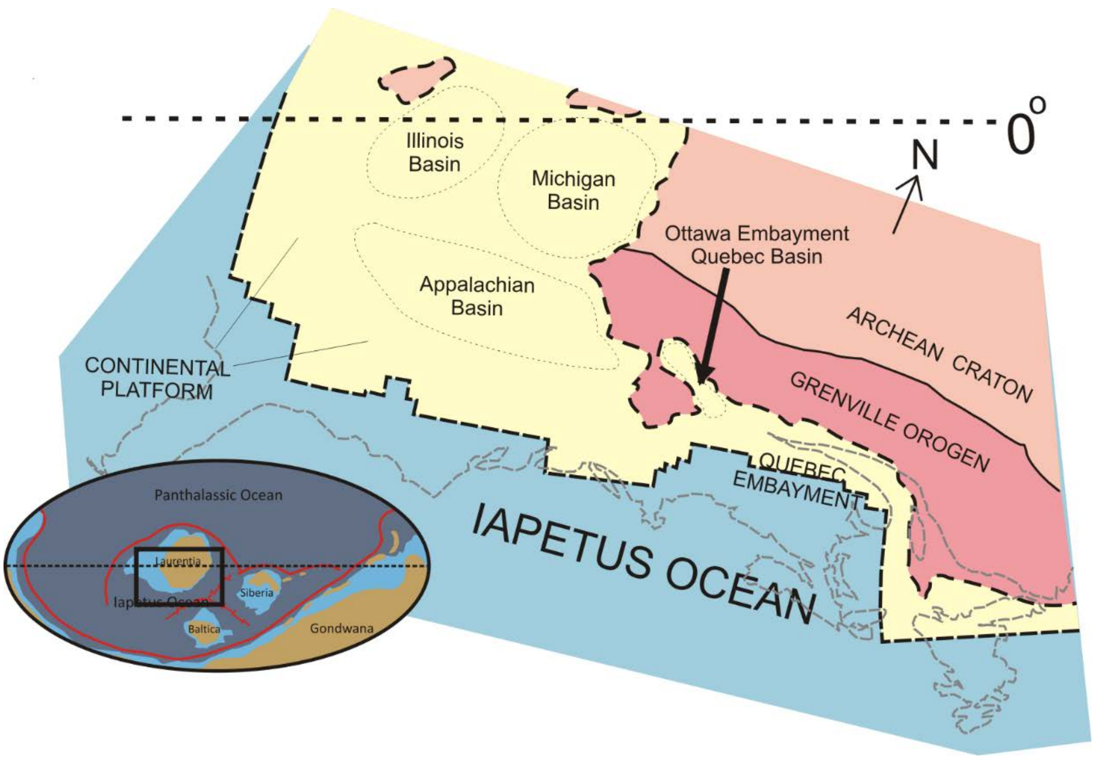

Figure 2: Paleogeographic map showing the location of the Ottawa Embayment and Quebec Basin relative to the global position and orientation of Laurentia in the Late Cambrian.

Recent studies by Landing and coworkers (2009) described the Altona Formation as shallow marine sandstone which onlapped the Laurentian craton. Faunal evidence allowed Landing to establish that this unit is *Olenellus* zone in age, an older age for the basal Potsdam than had previously been known. Brink (2014 and ms in prep.) examined the Altona Formation northwest of Plattsburgh, NY and described details of its stratigraphy (see field trip stop descriptions below). The work of Sanford (2007) and Sanford and Arnott (2010) provide comprehensive descriptions of the Potsdam Group throughout the Ottawa Embayment and Quebec Basin and a basis for ongoing sedimentological and stratigraphic investigations by the first author of this paper.

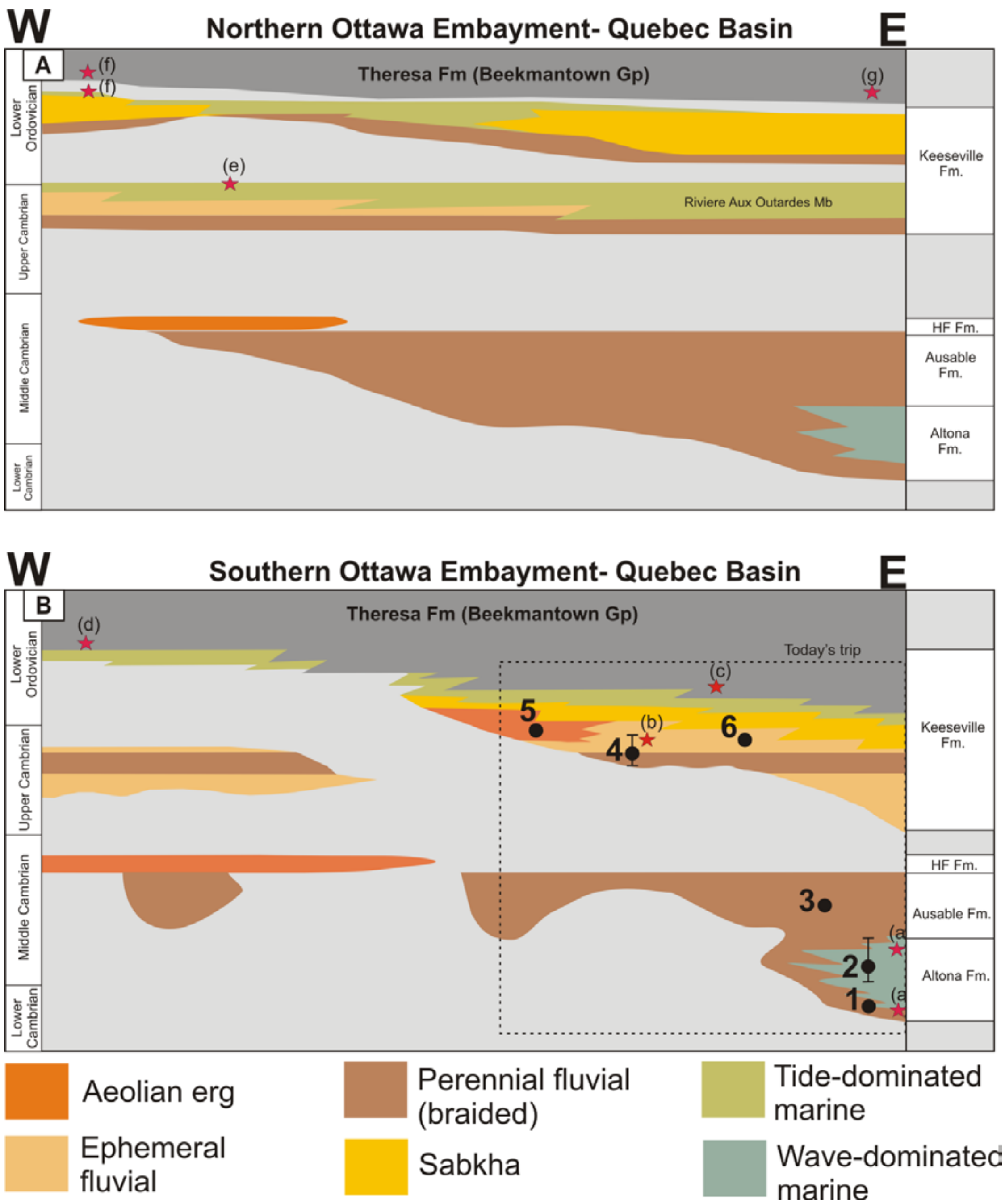

Figure 3 (A, B): Stratigraphic correlation of units of the Potsdam Group in the northern (A) and southern (B) parts of the Ottawa Embayment-Quebec Basin. The approximate stratigraphic locations of today's field trip stops are indicated by numbers 1-6. Biostratigraphic age controls are shown by the red stars: (a) Landing et al., 2009; (b) Fisher, 1968; (c) McCracken, 2014; (d) Greggs and Bond, 1973; (e) Nowlan, 2013; (f) Brand and Rust, 1977; (g) Salad Hersi et al., 2002. HF Fm. = Hannawa Falls Formation.

Potsdam Group Stratigraphy

Altona Formation

The Altona Formation represents the oldest Cambrian unit in northern New York, recording cyclic deposition in shallow marine and fluvial environments under both fair-weather and storm conditions. It occurs in the western Quebec Basin where it thins from the north to the south. In northeastern New York it is ~80 m thick and exposed in fault blocks along the northeastern Adirondacks, whereas in subsurface ~20 km north of downtown Montreal it only reaches a thickness of ~36 m.

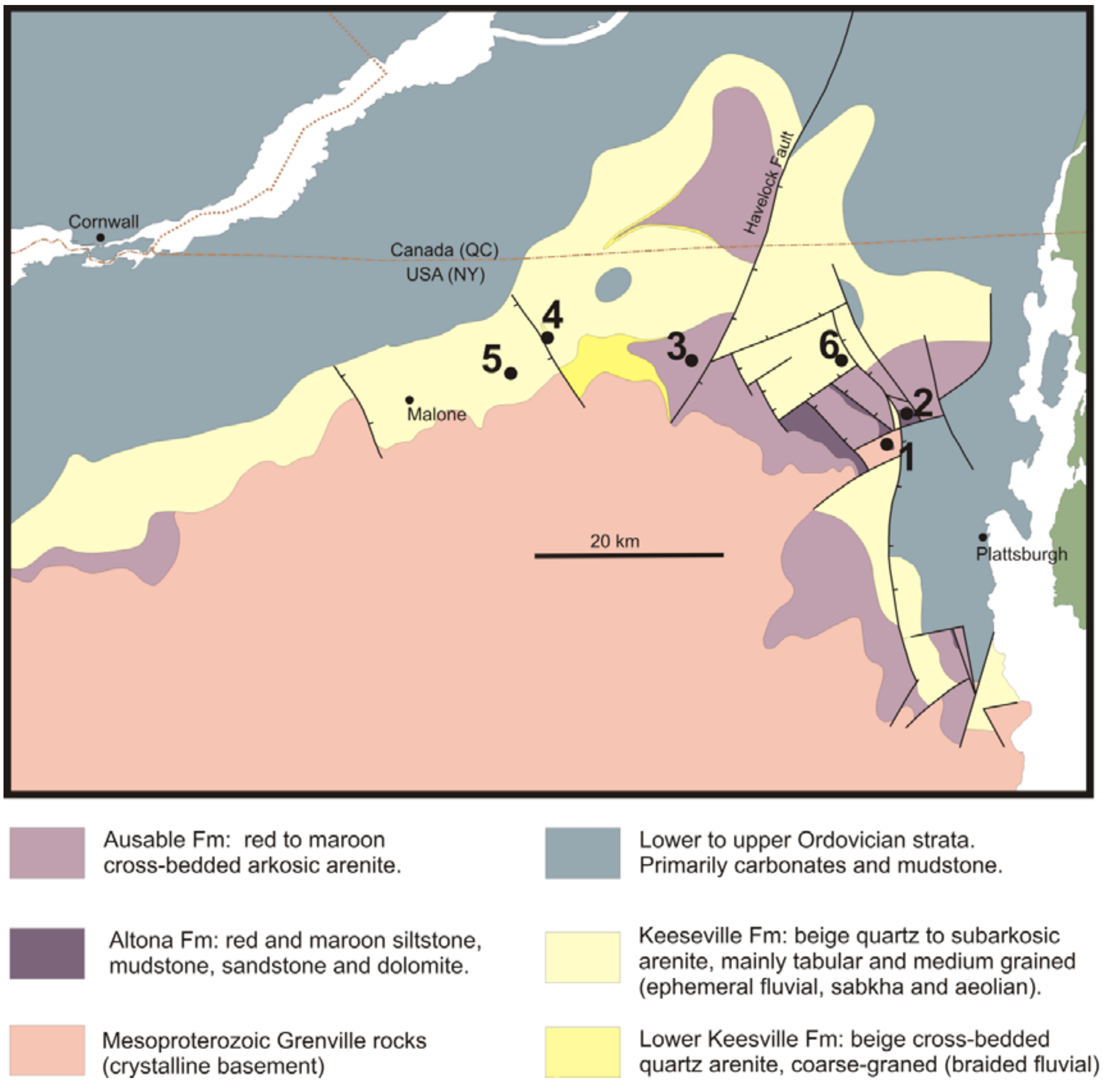

Figure 4: Simplified geologic map of the Northeastern Adirondack margin highlighting the Potsdam Group. Today's field trip stop locations are shown by numbers 1-6.

Lithofacies descriptions, stratigraphic trends and environmental interpretations were developed from detailed measurement and description of five outcrops and one well log through the Altona. Based on the recognition of sedimentary structures such as hummocky cross stratification, oscillatory ripples, graded bedding, trough and tabular cross stratification, and bioturbation, as well as subtle lithologic changes, six lithofacies representing non-marine, middle to upper shoreface, offshore, and carbonate ramp environments were identified (Table 1). The lowermost horizons of the Altona are found to lie only one meter above Precambrian basement. Although poorly exposed, the basal beds are interpreted to be sheetflood deposits (alluvial) that were reworked on the shoreface. The uppermost Altona, approaching the contact with the overlying non-marine Ausable Formation, is characterized by inter-tonguing marine to non-marine siltstones and cross stratified medium sandstones. Throughout the 84-meter thick section, stratigraphy records a transition from upper/middle shoreface to carbonate ramp deposition and offshore muds before cycling between upper shoreface, carbonate ramp and non-marine deposits before grading into the Ausable Formation. Although conformable and gradational in the southern Quebec Basin (see above) the Altona-Ausable contact in the Northern Quebec Basin is abrupt.

Table 1. Altona Formation lithofacies and environmental interpretations (from Brink, 2014).

Litho-facies	**Description**	**Interpretation**	**Representative Stratigraphy**
1	fine to mdm-grained well sorted ss. Upward-bundling ripples, combined flow ripples, swaley cross bedding. May have erosive bases to trough cross stratification	2D and 3D wave-generated ripples on storm-influenced upper-middle shoreface	base of Atwood Farm
2	heterolithic: dolostone, siltstone and fine-grained ss. Coarse-tail graded bedding and cross stratification may be present. Bioturbation	offshore carbonate ramp influenced by storm-generated seaward transport of sand	Middle of Atwood Farm
3	arenaceous dolostone containing poorly sorted mdm-grained sand exhibiting graded bedding and cross lamination	nearshore carbonate ramp (more proximal than L2); possible eolian deposition of sand	base of Atwood Farm.
4	heterolithic: red and grey mudstone with thin laterally discontinuous beds of sand, silt and dolostone; SS beds are cross laminated with planar bases, HCS present (Jericho locality). Bioturbation	lower shoreface to offshore with periodic tempestite deposition	Atwood Farm, Jericho
5	poorly exposed poorly sorted mdm-grained feldspathic ss, possible graded bedding and cross lamination	nearshore wave(?) reworked tempestite deposits	top of Atwood Farm
6	mdm to coarse-grained poorly sorted	fluvial (sheetflow) to marginal marine	onlap PC basement; top of Atwood Farm

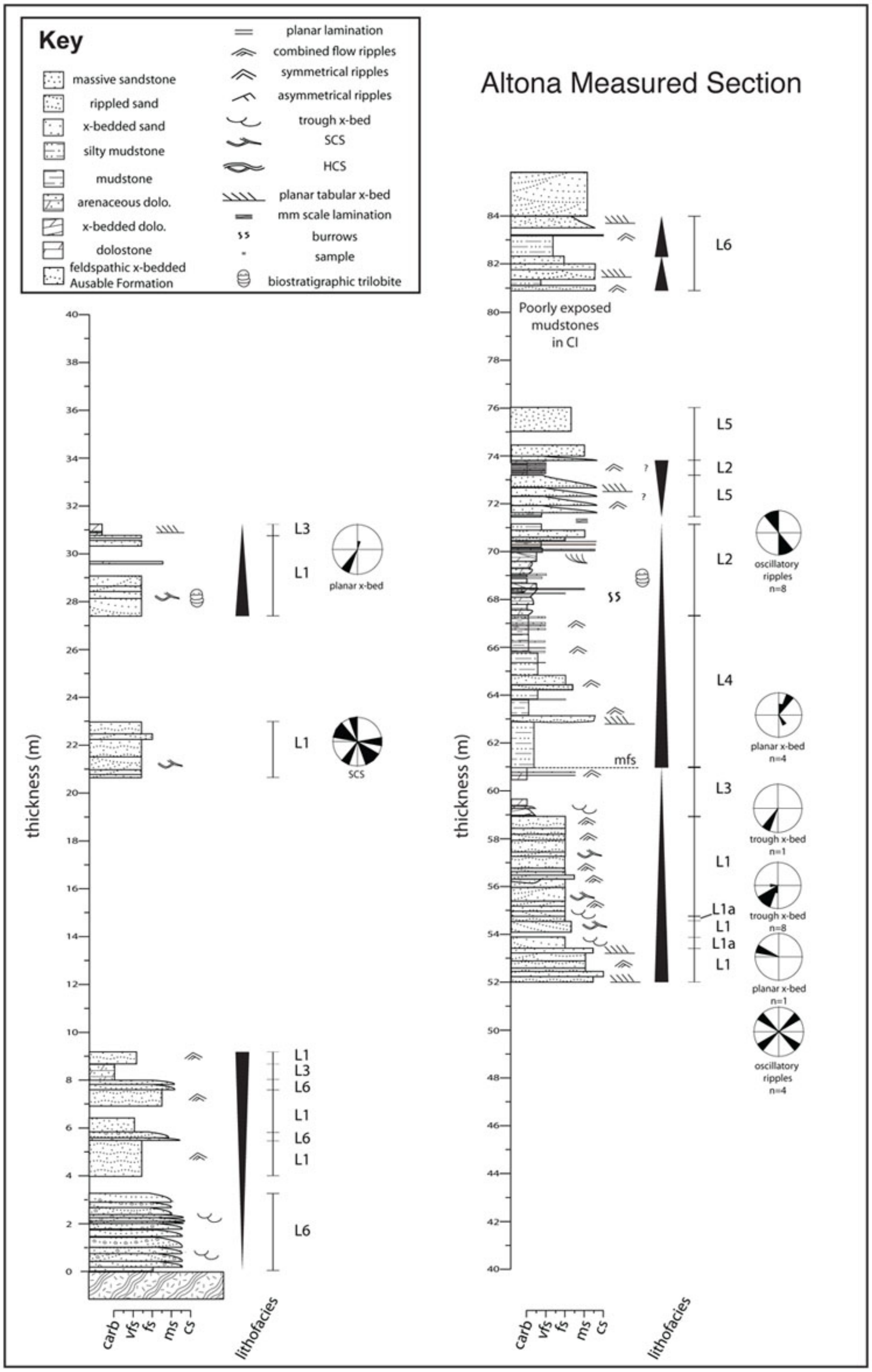

Figure 5. Composite stratigraphic column for the Altona Formation.

The provenance of the Altona sandstones was determined from thin section point counts, XRD and SEM analysis. Sandstones are subarkose to arkose in composition ($Q_{19}F_{5}1L_{0}$ to $Q_{95}F_{5}L_{0}$) with an accessory mineral suite including ilmenite, apatite, rutile, and zircon. Integrating the compositional data, particularly the accessory mineral suite, with detrital zircon dates obtained by Chiarenzelli et al. (2010) of 1000- 1300 Ma suggests that Adirondack meta-sediments are a likely source rock.

The Altona Formation stratigraphy includes the transition from a transgressive systems tract to highstand systems tract, an interpretation based on interpretation of depositional environments and the identification of parasequences and associated flooding surfaces. The TST stratigraphy consists of basal onlap with marginal marine and fluvial deposits followed by shallow marine shoreface deposition and culminating in carbonate ramp deposition (HST). Parasequences lower in the Altona exhibit retrogradational stacking characteristic of the transgressive systems tract. Within the middle of the Altona section the first appearance of offshore mudstones marks the maximum flooding surface and the onset of the highstand systems tract. The carbonate-mudstone interval in the Altona stratigraphy represents a highstand condensed section characterized by low sedimentation rates, an interpretation based on the paucity of coarser sediment and the presence of burrows.

Ausable Formation

The Ausable Formation of probable Middle Cambrian age comprises coarse-grained and pebbly arkosic sandstone formerly assigned to the Ausable Member in northeastern New York (e.g. Alling, 1919; Fisher, 1968) and the Covey Hill Formation in Ontario and Quebec (Clark, 1966, 1972; Sanford and Arnott, 2010). The Ausable Formation is braided fluvial in origin (see below) and over most of the Ottawa Embayment – Quebec Basin unconformably overlies Precambrian Grenville basement, representing ~500 Myr of erosion and non-deposition, except where it overlies the Altona Formation in the Quebec Basin. It is conformably overlain by the Hannawa Falls Formation in the southwestern Ottawa Embayment, but elsewhere is overlain unconformably by the Keeseville Formation. Fossils that could provide depositional age constraints are absent in the Ausable Formation as are other features such as ash beds or sources of young detrital zircons that could directly constrain its depositional age. However, in the southern Quebec Basin biostratigraphic age constraints are available from the underlying Altona Formation (Landing et al., 2009) and overlying Keeseville Formation (Walcott, 1891; Fisher, 1955; Flower, 1964) that constrain the depositional age of the Ausable Formation to Middle Cambrian.

The Ausable Formation is thickest at ≥ 450 m in the Valleyfield Trough, approximately ~40 km southwest of the island of Montreal and maintains significant thicknesses (typically ~300 – 400 m thick) south- and northwards along the western Quebec Basin and the axis of the Oka-Beauharnois Arch. In the northern Ottawa Embayment the Ausable thins continuously eastward to ~8 m thick in the hanging wall trough of the Gloucester Fault beneath downtown Ottawa. The Ausable is generally absent throughout the southern Ottawa Embayment except for isolated accumulations, ~0.5 - 25 m thick, along the northern Adirondacks (e.g. along the St. Regis River in Nicholsville NY and near Redwood NY), and immediately east and south of the Big Rideau Lake in Ontario and in a few other locations on the Frontenac Arch. These units are correlated to one another regionally on the basis of stratigraphic position, detrital composition (i.e. arkose) and similarity in detrital zircon populations (see below).

The Ausable Formation consists of a lithofacies assemblage of poorly- to moderately-sorted coarse-grained cross-stratified sandstone with subordinate conglomerate and rare planar stratified sandstone and fine-grained beds and lamina collectively interpreted to have been deposited by sandy and gravelly braided rivers. Dune and unit bar cross-strata commonly build low angle downstream-accreting elements, 0.5 - 5 m thick, interpreted to record the build-up and downstream migration of low relief in-channel and bank-attached compound braid bars (e.g. Lunt and Bridge, 2004; Bridge and Lunt, 2006, see Stop 3: Great Chazy River, North Branch Near Ellenburg). Common thin (≥ 7 cm) laterally-continuous beds consisting of fine-grained muddy sandstone are interpreted as overbank deposits. In many places rip-up clasts of these layers are present, even where the layers have been eroded. Petrographic analysis reveals that these layers contain eluvial clay and silt, amorphous iron oxides, degraded detrital feldspar and swollen detrital biotite, which collectively record subaerial weathering under humid conditions on floodplains. Braided fluvial strata are organized into recurring packages, 1.3 – 7 m thick and bounded by laterally continuous surfaces, that record the deposition of successive channel belts (see Stop 3: Great Chazy River, North Branch Near Ellenburg for more details).

A combination of detrital framework mineralogy, detrital zircons (from the first author and from Chiarenzelli et al., 2010) and regional paleoflow analysis suggests that the fluvial Ausable Formation was sourced mainly from local hinterlands now covered by Paleozoic strata in the southern Ottawa Embayment with some sourcing from farther north in the Laurentian craton (Figure 6). Paleoflow analysis shows that regional fluvial systems formed a roughly radial pattern emanating from what are now the south-central Ottawa Embayment and adjacent Adirondack Lowlands, with eastward paleoflow in the northern Quebec Basin, southeastward paleoflow in the southern Quebec Basin and southwestward paleoflow along the northwestern margin of the Frontenac Arch. Detrital zircon ages all form mono-modal cumulative probability peaks of ~1.17 Ga with a narrow distribution of ages (Figure 7) similar to the age of plutonic rocks common in the Frontenac Terrane of the Central Metasedimentary Belt and northern Adirondacks which extends from the Frontenac Arch/Adirondack Lowlands northeastward beneath Paleozoic cover to the Laurentian Massif bordering the northern Ottawa Embayment (Marcantonio et al., 1990; Chiarenzelli and McLelland, 1991). However, one sample of the Ausable from the northern Quebec Basin just west of Montreal suggests major contributions from the ~1.17 Ga source but with additional cumulative probability peaks of ~1.11 and ~1.44, and ~2.65 Ga (Figure 7). Though the Archean zircons are probably from Grenville cover sequences, the other peaks most likely indicate mixed sourcing from areas farther to the northwest in addition to local sources.

The Ausable Formation is unconformably overlain by the Keeseville Formation along the axis of the southern Oka-Beauharnois Arch that separates the southern Ottawa Embayment and Quebec Basin. The contact is exposed in outcrop along the Riviere Aux Outardes in Franklin, QC; ~3 km north of the U.S.-Canada border, and is also present in several cores in southern Quebec. It is a cryptic and previously unrecognized disconformity that separates arkosic braided fluvial strata of the Ausable and quartz arenite braided fluvial of the Keeseville Formation. The top of the Ausable is characterized by an erosional surface with ~15 – 25 cm of relief and capped by a ~4 – 10 cm thick massive pebble conglomerate. This conglomerate is preferentially cemented by intergranular silica that preserves high intergranular volumes, and over the ~1.5 – 2 m of Ausable section below this conglomerate detrital feldspar grains are preferentially degraded, detrital biotite degraded and swollen and eluviated matrix is present. Collectively these features suggest the development of an initial lag, probably by aeolian deflation, and subsequent development of a silcrete paleosol with an upper duricrust and underlying illuviated horizons.

This disconformity probably represents a gap in time spanning the Middle to Late Cambrian, though biostratigraphic age constraints are not present across the contact.

In the western Ottawa Embayment and along the Frontenac Arch the contact separating the Ausable and Hannawa Falls Formation is conformable and transitional. It is characterized by a ~0.3 – 1.9 m thick section of cobble-pebble conglomerates interbedded with upper medium- to coarse-grained wind-ripple stratified sandstone. Eluviated matrix, degraded feldspar and coarse-very coarse sandstone deflation lags are common in the wind-ripple stratified sandstone beds. An upward loss of feldspar from the avg. ~30% that characterizes the Ausable to ≤8% that characterizes the Hannawa Falls Member also occurs across this interval. Altogether, these transitional beds record deflation of fluvial strata, loss of feldspar through aeolian abrasion, and episodic flash flooding during a climate shift from humid to arid conditions sometime in the Middle Cambrian preceding erg deposition of the Hannawa Falls erg succession (see below).

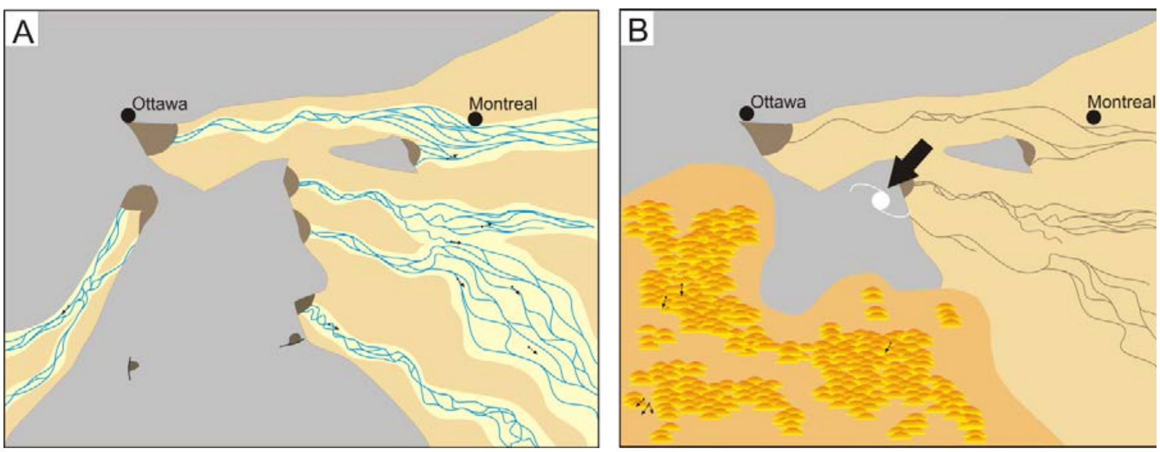

Figure 6: Inferred paleogeographic reconstruction of the Ottawa Embayment and Quebec Basin in the Middle Cambrian during deposition of the Ausable Formation (A) under humid conditions and later deposition of the Hannawa Falls Formation (B) under arid conditions. Panels are constructing using mean paleoflow from key sections (black dots with arrows) in conjunction with detrital zircon ages (see Figure 7 and text for more discussion). Large arrow on B indicates the prevailing wind direction.

Hannawa Falls Formation

The Hannawa Falls Formation is defined by the commonly red but locally buff to white quartz arenites of aeolian and sandy sheetflood-dominated ephemeral fluvial origin (see below). These occur as patchy isolated stratigraphic outliers, ~2 – 22 m thick, at or near the base of the Potsdam succession in the western Ottawa Embayment and throughout the Frontenac Arch/Adirondack Lowlands in eastern Ontario and northern New York (Jefferson and St. Lawrence Counties). The Hannawa Falls Formation is a major part of the unit formerly defined as the Hannawa Falls Member by Sanford and Arnott (2010), including the well-known red bed exposures along the Raquette River south of the town of Potsdam first described by Emmons (1838). Although previously not recognized as a stand along formation, it is considered such herein on the basis of its distribution, distinctive red coloration due to hematite rims on detrital quartz grains (in most places) and characteristic large-scale aeolian cross-stratification. It conformably overlies the Ausable Formation (see above description from the top Ausable Formation) or unconformably overlies Grenville basement where the Ausable is absent. It is unconformably overlain by the Keeseville Formation (see description below). The Hannawa Falls Formation is undated but is most likely Middle Cambrian and perhaps upper Middle Cambrian based on its conformable relationship with the Middle Cambrian Ausable Member. Most of the Hannawa Falls Formation consists of large-scale cross bedding interpreted to record the migration of aeolian dunes in an arid erg setting, while some strata near the top and base of the Hannawa Falls Formation record ephemeral fluvial sheet flood deposition. Based on its areal distribution and the scale of aeolian dune cross-bedding the Hannawa Falls Formation records the formation of an inland erg succession covering 19,600 km^2 km over the western Ottawa Embayment, with the development of sheetflood-dominated fluvial systems in places during the later phase of the Hannawa Falls sedimentation.

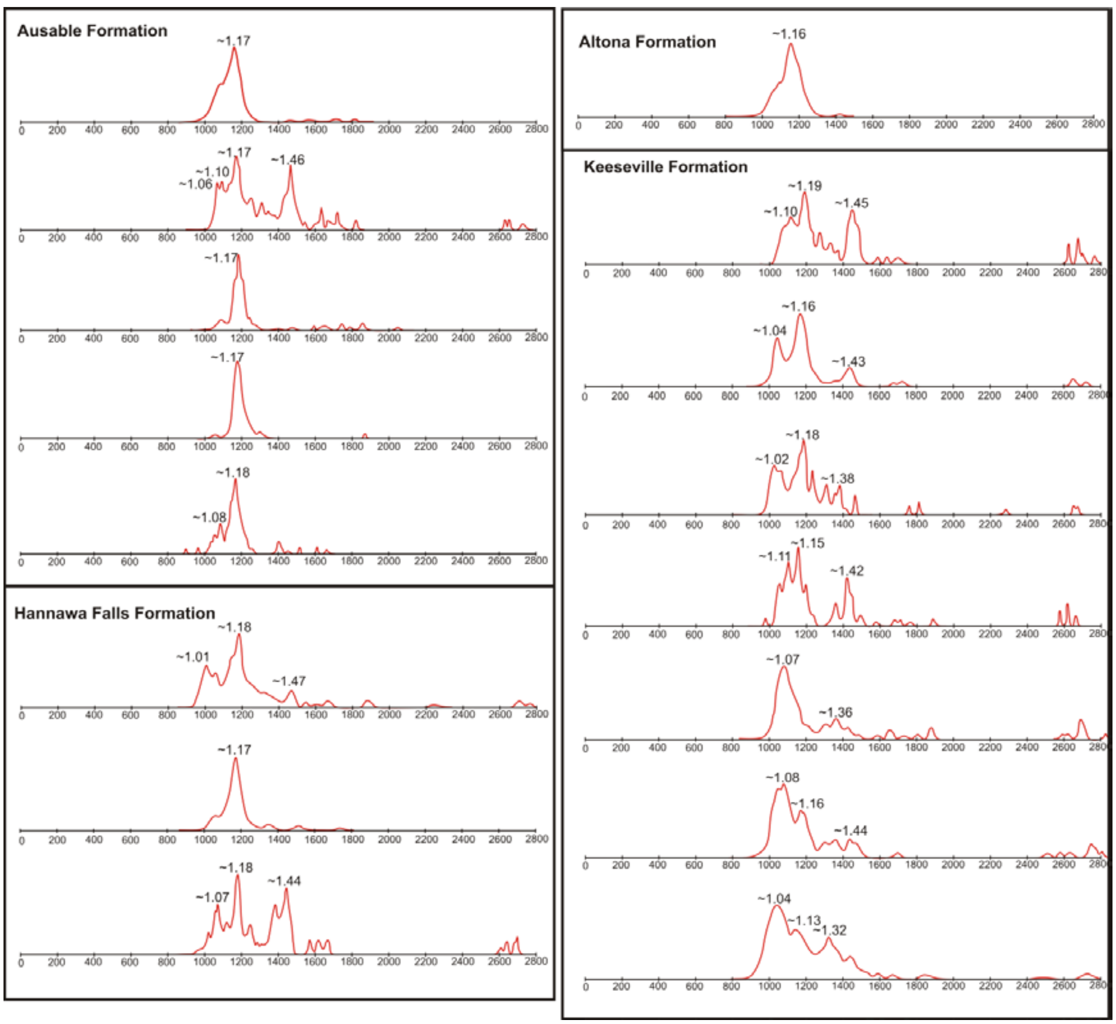

Figure 7: Detrital zircon ages from the Potsdam Group. Data is partly from Chiarenzelli et al. (2010) supplemented by samples from the first author of this paper. See text for discussion of ages. The x axis is in myr and the labelled peaks (i.e. ~1.17) are in Gya.

The change in detrital composition from arkose to quartz arenite along the transitional Ausable – Hannawa Falls contact can be attributed to (a) the mechanical breakdown of feldspar during a change to windblown transport, and/or (b) sedimentary recycling, and/or (c) a change in regional sediment sources due to a change in regional transport mechanism from local fluvial drainage to regional windblown transport (as shown in Figure 6). Detrital zircons from the Hannawa Falls suggest a combination of all three factors. Similarities to detrital zircon assemblages to those of the Ausable (i.e. with prominent ~1.17 and ~1.44 Ga peaks, Figure 7) suggest sourcing from unconsolidated braided fluvial strata of the Ausable Formation. However, some younger detrital zircon peaks (~1.02 – 1.05 Ga) indicate possible input directly from Grenville basement in the Northern Adirondacks (Chiarenzelli and McLelland, 1991). Paleowind directions also support this interpretation, with mean paleowinds from the modern northwest indicating sand transport towards the west and southwest away from Ausable braided fluvial deposits (Figure 6b). Furthermore, the abundance of early diagenetic iron oxide cements and rims in this unit suggests that either a small amount of Fe-bearing minerals were present as detrital grains or formed a residual iron-oxide dust that coated quartz grains during transport and/or following deposition.

The Hannawa Falls is unconformably overlain by the Keeseville Formation. The contact is an erosional disconformity locally but is more commonly expressed as an angular unconformity in areas where underlying Hannawa Falls strata is locally tilted or folded and truncated by flat-bedded Keeseville strata (e.g. Sanford and Arnott, 2010). Lithified clasts of Hannawa Falls are commonly present in the lower ~1 – 2 m of overlying Keeseville strata and in addition a ~0.3 – 2 m horizon of exceptionally red and relatively poorly-cemented sandstone occurs in Hannawa Falls strata directly beneath the unconformity. Within this horizon intergranular hematite and kaolinite cements preserving high primary intergranular volumes occur at the expense of later pore-filling silica cements common elsewhere. Typically, the concentration of hematite and kaolinite cements increases upwards gradationally towards the unconformity defining a crude zonation. Therefore, this horizon is interpreted as a paleosol, specifically a ferric oxisol (under the classification of Mack et al., 1993), a.k.a. laterite, formed by groundwater leaching and near-surface precipitation of insoluble residual Fe- and Al-rich phases. The time gap represented by this unconformity is not known due to an absence of depositional ages above and beneath the unconformity, but potentially spans the Late Middle Cambrian to the middle Late Cambrian (perhaps 5 - 10 Myr). Based on similarity in stratigraphic position and probable age, this unconformity is correlated to the one that separates Ausable and Keeseville strata farther west.

Keeseville Formation

The Keeseville Formation is defined by buff to white silica-cemented supermature quartz arenite with ≤ 5% detrital feldspar and local quartzite clast cobble-boulder conglomerates with quartz arenite matrix. The term Keeseville Formation (Sanford and Arnott, 2010) replaces Keeseville Member (from Emmons, 1841; Fisher 1968) and also the Nepean Formation in Ontario (from Wilson, 1946) and the Cairnside Formation in Quebec (from Clark, 1966; 1972). The Keeseville unconformably overlies the Ausable or Hannawa Falls Formation or Grenville Basement throughout most of the Ottawa Embayment and Quebec Basin. In spite of its uniform detrital composition across the Ottawa Embayment and Quebec Basin the Keeseville Formation nonetheless records deposition under a number of terrestrial to marine environments, is dissected by at least one internal regional unconformity over much of the study area, has diverse provenance based on detrital zircon analysis and spans a long interval of geologic time from the Latest Middle Cambrian to the Middle Early Ordovician. The contact between the Keeseville Formation and overlying carbonate-cemented Theresa Formation is conformable or unconformable (see descriptions and discussion below). Based on available age constraints and contact relationships the Keeseville Formation and the base of the Theresa Formation are diachronous and young to the west-northwest in general (also see Fisher, 1968; Sanford and Arnott, 2010).

Six depositional environments are interpreted from detailed lithofacies and architectural analysis of Keeseville lithofacies associations: braided fluvial, sheetflood-dominated ephemeral fluvial, aeolian, lacustrine, sabkha/playa and tide-dominated marine. On this fieldtrip we will visit examples of braided fluvial, sheetflood-dominated ephemeral fluvial and aeolian facies associations (see Stops 4 – 6). Aeolian strata of the Keeseville are described by Hagadorn et al. (2011) (at the Rainbow Quarry, Stop 5) and generally consist of large scale-cross stratified sets made up mainly of inversely-graded aeolian grain flow and wind ripple strata. Braided fluvial strata in the Keeseville are similar to those in the Ausable Formation. Sheetflood-dominated ephemeral fluvial strata, however, are unique to the Keeseville Formation and previous unrecognized (However, Sanford and Arnott 2010 suggest their presence). These are now recognized on the basis of dominant planar-stratified sandstone consisting of mixed aeolian, adhesion and shallow water facies and deflation lags that record aeolian reworked/deflated terminal splay deposits (e.g. Abdullatif, 1989; Hampton and Horton, 2007; Nichols and Fisher, 2008). These are usually interstratified with lesser and coarse-grained scour-based supercritical bedform strata (cross-stratified sets formed by antidunes, chutes-and-pools and cyclic steps) recording high energy sheet flood conditions. Rare channel features filled with dune cross-stratification recording the souring and filling of distributary channels also occur locally. Ephemeral fluvial strata were deposited in an arid or semi-arid fluvial environment where the recurrence interval between geologically-significant floods could be 100s or even 1000s of years (Knighton and Nanson, 1997; Tooth, 2000; see Stops 4 and 6). In places, delicate surface features including enigmatic adhesion warts and wrinkles are common, as are desiccation cracks, collectively indicating windblown adhesion and early surface cementation and/or binding, most likely by a combination of microbial mats and efflorescent salts (e.g. Goodall et al., 2000; Vogel et al. 2009).

The oldest known Keeseville Formation strata occur in the lower parts of the Ausable Chasm near the town of Keeseville, and are assigned to latest Middle Cambrian based on *Crepicephalus* Zone trilobite assemblage (Walcott, 1891; Flower, 1964; Lochman, 1968; Landing et al., 2009), while the upper parts of the ~140 m thick Chasm section are probably Upper Cambrian (Hagadorn and Belt, 2008). The Keeseville Formation here consists of deposits of a supratidal coastal sabkha. Neither the lower contact between the Keeseville and Ausable formations nor the upper contact between the Keeseville and Theresa formations are exposed here.

About ~45 – 60 km north of the Ausable Chasm, over a ~2000 km^2 area straddling the New York Quebec Border north of the Adirondack highlands, the Keeseville Formation is ~65 – 120 m thick and consists of a conformable succession of intercalated ephemeral fluvial and braided fluvial strata with rare aeolian deposits (see Stops 4 - 6), capped by sabkha and finally overlain sharply by tide-dominated marine strata. The intercalated fluvial strata are ~45 – 80 m thick and well-characterized by outcrops in and around the town of Altona and Moores and at the Chateauguay Chasm farther west (Stop 4), as well as at the nearby Ducharme Quarry near Covey Hill and near Franklin in Quebec. Ephemeral – braided fluvial contacts are sharp (as in Chateauguay Chasm, stop 4) and record a change in regional climate from arid/semi-arid to humid (and vice-versa). Sabkha deposits near the top of the Keeseville here are ~10 – 40 m thick and are sharply overlain by ~9 – 17 m thick tide-dominated marine strata. The latter strata grade upward conformably into the Theresa Formation by an increase in the thickness and proportion of dolomite cemented beds, making it difficult to pinpoint the exact Potsdam-Theresa contact.

The Keeseville here is most likely Upper Cambrian, but the highest beds may be lowermost Ordovician. Such an age is supported by: (a) correlation to ephemeral and braided Keeseville strata in the Western Ottawa Embayment that unconformably overlie the late Middle Cambrian Hannawa Falls Formation, (b) trilobite faunas reported by Fisher (1968) from the Chateauguay Chasm, and (c) conodonts from the lower part of the overlying Theresa analyzed as part of this study (McCracken, 2014) that suggest a Lower Ordovician (probably Late Tremadocian) age for the basal Theresa in this area.

In the northern Quebec Basin near Montreal ~40 – 60 km north of the NY-QC border the Keeseville Formation reaches thicknesses of ~180 m. Lithofacies are generally similar here as farther south, however this area an unconformity dissects the Keeseville Formation into two unconformity-bound units (i.e. allounits). At the top of the lower Keeseville allounit is a locally carbonate-bearing tide-dominated marine unit called the Riviere Aux Outardes member, which is overlain by fluvial and marine strata of the upper Keeseville allounit. These two allounits including the Riviere Aux Outardes member extend westward to the northwestern Ottawa Embayment in the Ottawa area where the Keeseville Formation is only ~30 m thick. Here, conodonts from the Riviere Aux Outardes Member provide a lowermost Lower Ordovician age (Nowlan, 2013), supporting a Lower Ordovician age for the upper part of the Keeseville Formation in this area. The presence of the marine Riviere Aux Outardes member and the unconformity that dissects the Keeseville Formation in the northern Ottawa Embayment indicates that a latest Cambrian – earliest Ordovician transgression and regression occurred here, but is not recorded farther south in the northern Champlain Valley. In the northern Ottawa Embayment sabkha or tide-dominated marine strata of upper Keeseville allounit is unconformably overlain by the Theresa Formation (e.g. Salad Hersi et al., 2002; Dix et al., 2004), though new age constraints suggest that this unconformity is of shorter duration that previously thought. Near Montreal the basal Theresa Formation is Tremadocian (Salad Hersi et al., 2002), whereas near Ottawa it is Arenigian (Brand and Rust, 1977) indicating westward transgression.

In the southwestern Ottawa Embayment the Keeseville Formation unconformably overlies the upper Middle Cambrian Hannawa Falls Formation. Although relatively thin (~8 – 26 m) the Keeseville here is subdivided into two allounits by an internal unconformity, much like in the Northern Ottawa Embayment. The lower allounit of probable Upper Cambrian age is ~5 – 18 m thick and consists of ephemeral and braided fluvial strata capped locally by a silcrete horizon (Selleck, 1978). The contact between ephemeral and braided fluvial strata in this area is correlated to the Upper Cambrian ephemeral-braided fluvial contact farther east (Figure 3b). Tide-dominated marine deposits of the upper Keeseville allounit are ~5 – 10 m thick, of probable lowermost Ordovician age and onlap the locally erosional surface of the lower fluvial allounit recording marine tidal ravinement and subsequent deposition. The contact between the upper marine Keeseville and Theresa Formation is sharp. It is unclear whether the Keeseville-Theresa contact is a subtle paraconformity or simply a flooding surface at this location; however, the latter is more likely because of the lack of evidence for erosion or paleosol development in the uppermost Keeseville. The basal Theresa is the same age or slightly younger (uppermost Tremadocian; Greggs and Bond, 1973) than the Theresa Formation ~180 km farther east along the NY-QC border and near Montreal, and is older than the Theresa farther north near Ottawa.

The provenance of the Keeseville Formation is as complex as its stratigraphy and involves a combination of sedimentary recycling and direct souring from previously insignificant source areas of the nearby Grenville Basement. Detrital zircon samples from the generally terrestrial Upper Cambrian Keeseville succession are either identical to that from the Ausable Formation in the north with prominent ~1.17 and ~1.44 Ga peaks, or form larger peaks of younger ages (~1.02 - 1.1 Ga) but still with prominent ~1.17 and minor ~1.44 Ga peaks common to the underlying Ausable and Hannawa Falls formations. This suggests significant sedimentary recycling from the underlying Ausable and Hannawa Falls formations, but with increasing input probably from the adjacent Northern Adirondacks and along the suture zone between the Frontenac and Elzevir terranes along the western and northwestern margins of the Ottawa Embayment. Up section in the mainly marine Lower Ordovician Keeseville in the western Ottawa Embayment these younger Grenville sources (~1.02 - 1.1 Ga) predominate with very little "Ausable/Hannawa Falls" signal remaining, most likely recording the progressive loss of detritus through sedimentary recycling and/or by dilution by the progressive input of sediment from newer sources.

Definition of the Keeseville – Theresa contact remains elusive in spite of many years of study, and has previously been defined by the base of the lowermost pervasively carbonate-cemented bed (Cushing, 1908; Wilson, 1946; Brand and Rust, 1977; Williams and Wolf, 1982) or the top of the uppermost silica-cemented bed (Salad Hersi and Lavoie, 2000) and is either unconformable (Greggs and Bond, 1973; Salad Hersi et al., 2002; Dix et al., 2004), conformable (Cushing, 1908; Wilson, 1946; Clark, 1972; Brand and Rust, 1977; Selleck, 1984) or both (Sanford and Arnott, 2010). Numerous complications arise from the lithologic criteria used to define the Keeseville-Theresa contact. First of all, the presence of the Riviere Aux Outardes member which is locally dolomitic and occurs well below the top of the Keeseville complicates the use of the "lowermost dolomitic bed" as the base of the Theresa and silica-cemented strata present in the mid to upper Theresa complicate the use of the "uppermost quartz arenite bed" as the top of the Keeseville. In addition, parts of the overlying Theresa Formation are lithologically similar to the uppermost marine unit of the Keeseville Formation (Fisher, 1968; Greggs and Bond, 1973; Selleck, 1984) which further complicates placement of the contact. Finally, where an unconformity is recognized it does not usually coincide with either of the lithologic criteria used to define the base of the Theresa, and therefore this unconformity may actually occur fully within in the upper Keeseville or the lower Theresa, depending on how these units are defined. For now we consider the base of the lowermost carbonate-cemented bed as the best criteria to define the Keeseville – Theresa contact. Based on this criterion the available age constraints suggest the Keeseville –Theresa contact is diachronous, younging from Tremadocian to Arenigian towards the west-northwest. Unconformities developed in the northern Ottawa Embayment and Quebec Basin where the Theresa transgressed terrestrial or shallow marine Potsdam strata deposited on topographic highs (e.g. Salad Hersi et al., 2002; Dix et al., 2004), whereas the contact is gradational in the southern Quebec Basin where accommodation was space was greater (e.g. Clark, 1972). The contact in the southwestern Ottawa Embayment, although sharp, is interpreted as a conformable flooding surface.

Comparison to the Cambrian Stratigraphy of Vermont

The Cambrian section in Vermont was deposited on a thermally subsiding shelf margin of the Iapetus Ocean. The late Precambrian Pinnacle, Fairfield Pond and Tibbit Hill Formations record the formation of Iapetus Ocean crust on the rifted Grenville margin; dates for the Tibbit Hill in Vermont are ~615 Ma (O'Brien & van der Pluijm, 2012). Overlying the rift-related Precambrian units, the poorly age-constrained Cheshire Quartzite. The succeeding Dunham Dolostone contains *Salterella conulata* fossils (Mehrtens and Gregory 1984) which are thought to be correlative to the base of the Olenellus trilobite zone (Yochelson, 1983). While there are general similarities in the Cambrian stratigraphy along strike in the Appalachians (for example, all units record fluctuating sea level on a shallow marine shelf) the Cambrian stratigraphy of western Vermont is slightly different from that to the north (Newfoundland) and south (Pennsylvania, Tennessee, Virginia). Unlike these other areas, the Vermont Cambrian stratigraphy consists of cyclically alternating siliciclastic and carbonate deposition from the earliest Cambrian into the Lower Ordovician. Goldberg and Mehrtens (1997) suggested that at least in the Lower Cambrian, both local uplifts of Grenville basement contributing siliciclastic material to the Iapetus shelf in the Vermont region occurred in concert with fluctuating sea level.

In addition to the shallow marine shelf sequence, the Cambrian stratigraphy of northwestern Vermont includes an intrashelf basin, termed either the St. Albans Reentrant (Mehrtens and Dorsey 1987) or the Franklin Basin (Shaw, 1958), which existed along strike of the shallow marine units to the south. Cherichetti et al. (1998) suggested that asymmetrical rift geometry controlled facies and thickness variation in the syn-rift stratigraphy and it is possible that these differences in subsidence history influenced deposition of the succeeding Cambrian stratigraphy (Mehrtens and Brink, 2014). Despite being thrust westward approximately 80 km (Stanley, 1999) the stratigraphy within the upper plate of the Champlain Thrust is coherent, and contacts between the shelf and basin sediments along the margin of the St Albans Reentrant/Franklin Basin are preserved. The relationship between the St Albans Reentrant/Franklin Basin and the Ottawa Bonnechere aulacogen on the Laurentian craton to the west is not clear but as early as 1983 Landing suggested that the SAR/Franklin and the Ottawa Bonnechere basins were genetically related.

Because of the revised age of the base of the Potsdam Group (Landing, et al, 2009) the Altona Formation is now interpreted to be at least in part coeval with the Monkton Formation in Vermont The bulk of the Monkton is a heterolithic wave and tidally-influenced unit that records tidal flat progradation basinward, however there is significant paleoenvironmental variation in the Monkton, which records fluvial, tidal and wave-generated sedimentary structures. The “classic” Monkton are those lithofacies exposed in the Burlington area, where the unit is commonly known as the “red rock.” This Monkton displays the classic prograding tidal flat shallowing-upward cycles (SUCs). The most complete exposure of the Monkton is found in the Colchester area, where a continuous 286 meter thick section of tidal sand shoals interfinger with tidal flat sediments. A significant covered interval of nearly 100 meters occurs below the lowest exposed overlying Winooski Dolostone. In the Burlington area the Monkton/Winooski contact is exposed in Whitcomb’s Quarry in Winooski, and the contact is entirely gradational and defined by the uppermost bed of red silts and sands of the Monkton. Thus, it is presumed that the Colchester covered interval also represents the progressive increase in carbonate matrix within wave-reworked sands of the shelf margin.

Figure 8 presents the proposed sequence stratigraphy correlation of the Monkton and Altona Formations. Two possible interpretations of the correlation are presented, depending on whether the covered interval at the top of the section represents the top of the Monkton (the preferred interpretation) or includes the base of the overlying Winooski (less likely, as this would make this unit significantly thicker here than elsewhere in Vermont). The onset of carbonate sedimentation on the Iapetus margin reflects sea level highstand and resulting decrease in siliciclastic sediment supply into the basin. This sea level stand is represented by the mudstone-dolostone interval in the Altona Formation stratigraphy (68-74 meter interval). The resumption of clastic deposition at the top of the Altona could reflect rejuvenation of a clastic source (uplift) or re-equilibration of sea level and sediment supply. Unfortunately, the poor quality of exposure of this critical interval in the Altona makes it very difficult to distinguish sedimentary structures that would more definitively distinguish the relative contribution of wave-reworked shoreface processes from fluvial input.

A cartoon of the proposed paleogeographic relationship between the Monkton and Altona Formations is shown in Figure 9. Ongoing efforts to retrieve detrital zircons from the Monkton should further establish age and provenance relationships with the Altona Formation. The Danby Formation, which overlies the Winooski Dolostone, is a mixed siliciclastic-carbonate unit which had traditionally been viewed as the shelfward equivalent of the classic Potsdam Sandstone; the unit was actually called the “Potsdam Sandstone” by earliest workers in Vermont (see Cady, 1945). The Danby extends from near the Vermont-Massachusetts border northward to its pinch out on the margin of the St. Albans Reentrant/Franklin Basin. The unit is more carbonate rich to the south (a dolostone) and becomes more arenaceous to the north. Detailed section measurement, description and petrography by Mehrtens and Butler (1989) led to their recognizing mixed siliclastic-carbonate lithofaces recording peritidal to shallow subtidal environments. Ongoing research to retrieve detrital zircon from the Danby should clarify its relationship to the Potsdam.

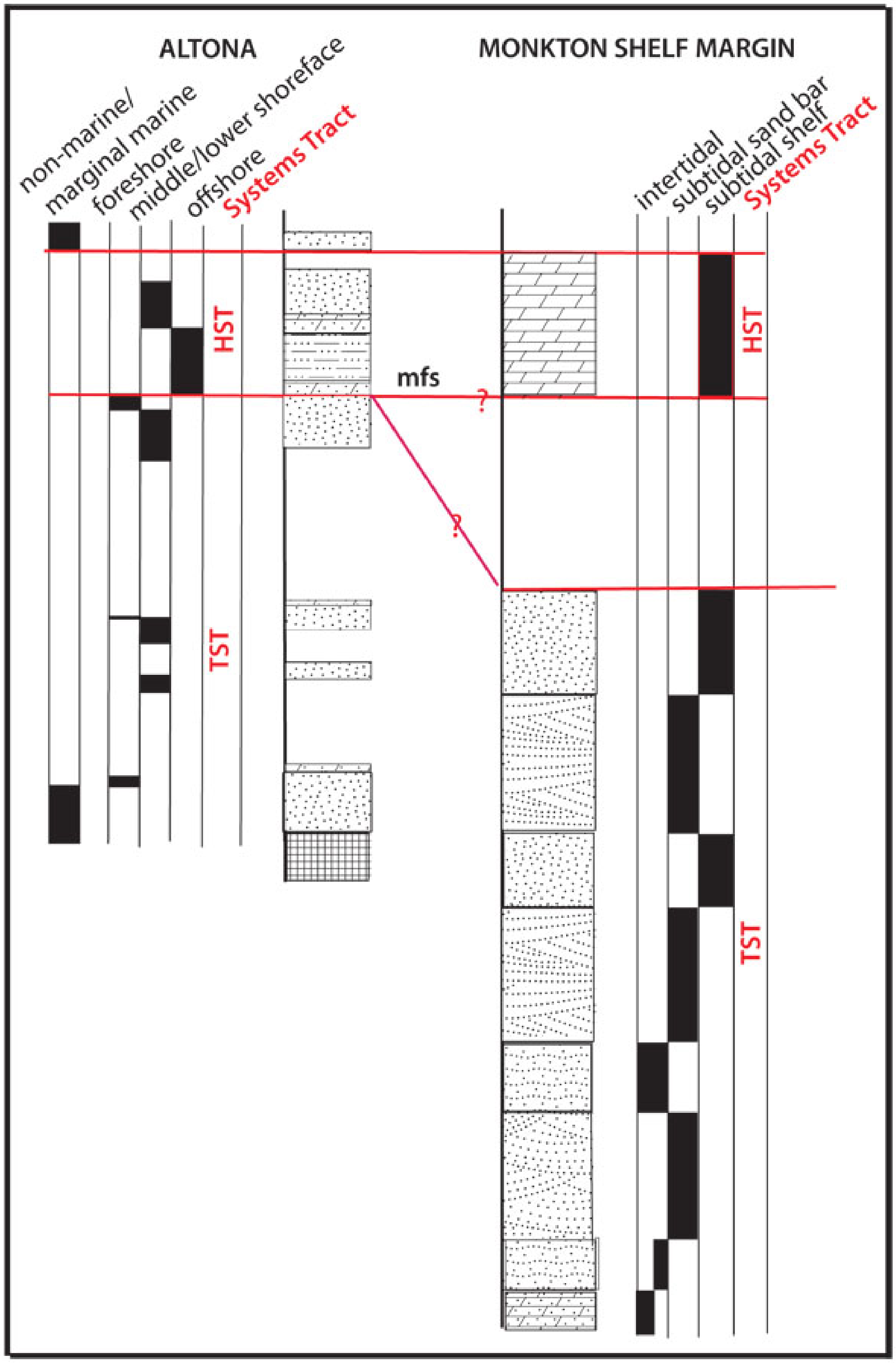

Figure 8. Sequence stratigraphic correlation of the Monkton and Altona Formations.

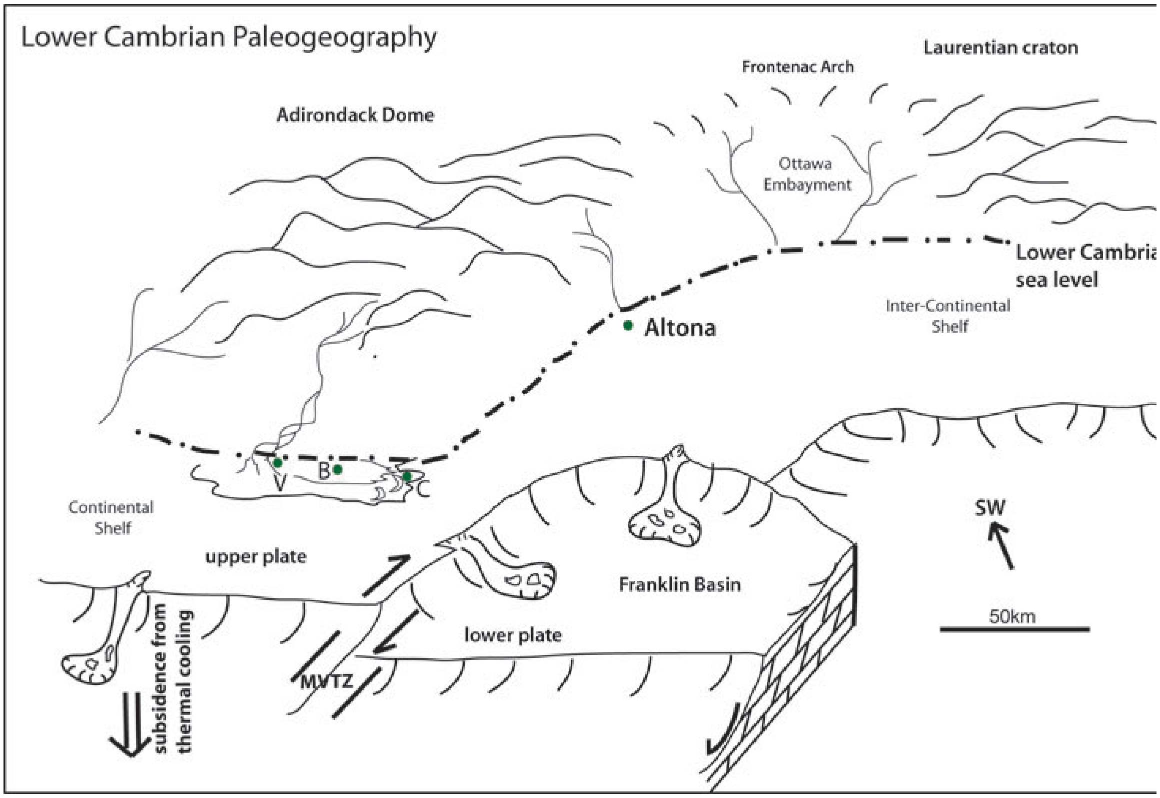

Figure 9. Schematic cartoon illustrating the possible paleogeographic relationship between the Altona (NY) and Monkton (VT) Formations in the late Lower Cambrian (from Brink, 2014). The Monkton is shown lying eastward of the Altona; palinspastically restored the east-west distance between these units ~80 km. Northward (present day coordinates) prograding Monkton tidal flat facies are shown, passing into a sand shoal complex on the margin of the Franklin Basin. The Altona Formation, a wave-dominated deposit, experienced high energy, storm-dominated conditions in a more craton-ward position, thus the cartoon suggests that the Laurentian shelf margin was characterized by headlands and embayments. The cartoon implies that these features might be related to the Franklin Basin/Ottawa-Bonnechere aulacogen, although this relationship is speculative.

FIELD GUIDE AND ROAD LOG

Meeting Point: Southeastern parking lot of Hudson Hall on the SUNY Plattsburgh campus. The lot is located at the corner of Beekman and Broad streets.

Meeting Point Coordinates: 44.696°N, 73.467°W

Meeting Time: 8:30 AM

Distance (miles)		
Cumu-lative	Point to Point	Route Description
0.0	0.0	Assemble in the southeastern parking lot of Hudson Hall.
0.3	0.3	Leave parking lot, turn right at the entrance, immediately right again onto Broad Street and proceed northwestward. At the traffic light with Prospect Street, turn right.
1.0	0.7	Junction with the Tom Miller Road. Turn left.
3.5	2.5	Traffic light and unmarked intersection with the Military Turnpike (Rte 190). Turn right.
4.4	0.9	Intersection with Route 274. Continue straight on Military Tpke.
11.1	6.7	Left turn onto unmarked dirt road accessing a portion of the Parker Sugarbush.
11.2	0.2	Proceed up hill to parking area. Park and walk remaining 0.15 mile up to Stop 1.

STOP 1: MURTAGH HILL, NY: The basal Altona Formation

Location Coordinates: (UTM Z18 NAD83 0611739; 4961998)

Walk up the dirt road until power lines are visible ahead and then veer into the woods on the left. BE CAREFUL OF SYRUP PIPING AND SUPPORTING GUIDE WIRES!! Proceed ~25' to the small stream and walk upstream to Stop 1. NO HAMMER OUTCROP (there is plenty of float available to sample).

This outcrop (Figure 10) exposes the stratigraphically lowest horizons of the Altona Formation in the region. The 3.5 meter thick exposure of coarse-grained, poorly sorted arkosic sandstones of Lithofacies 6 can be observed in close proximity to Precambrian basement rocks. Beds have non-planar (erosional?) bases and may exhibit graded bedding. Planar cross bedding can be present.

Based on grain size, graded bedding and the stratigraphic position of this lithofacies above basement and below arenaceous dolostones it is interpreted as recording sheetflood deposition into the marginal marine setting.

Figure 10. The basal Altona Formation at Murtagh Hill.

Distance (miles)		
Cumu-lative	Point to Point	Route Description
11.2		
11.4	0.2	return to the vehicles and proceed back down the hill to the intersection with the Military Turnpike (Rte 190). southward 0.2 mi to Rte. 9N. Turn Right
12.3	0.9	Proceed east on Rte 190 to Recore Road on the left. Turn left
12.8	0.5	Proceed down Recore Road to the intersection with Harvey Road on the left. Turn left onto Harvey.
14.2	1.4	Continue until T intersection with Atwood Road. Turn Right
14.6	0.4	Pass the Atwood Farms on your left and pull off the road at the farm field access road. STOP 2.

STOP 2: ATWOOD FARM, NY: The Altona Formation

Location Coordinates: (UTM Z18 NAD83 0613785 4964185)

Walk northward across field, following dirt track, until a small stream is reached. Turn right and follow the stream until it joins the branch of the West Chazy River. At the river's edge, turn right and walk downstream approximately 100 feet to the outcrops.

Stop 2A (UTM Z18 NAD83: 0613806 4964506). NO HAMMER!

The first stop exposes Lithofacies 1 of the Altona Formation, between 22 to 24 meters in the Altona composite section (Figure 11). Although covered in moss and lichen, patient viewing will reveal a variety of ripple morphologies that are very characteristic of much of the Altona sandstones. Lithofacies 1 is a very fine to medium grained, moderately well-sorted sandstone containing a variety of sedimentary structures including upward bundling ripple cross laminations, combined flow ripple cross laminations, and swaley cross stratification (Figure 9). Along with these structures, planar cross stratification and dwelling burrows have been identified. Planar cross stratification is up to 1 m thick, pinches out laterally over 10 m, and is generally topped by 2D or 3D weakly asymmetrical ripple cross lamination. Swaley cross stratification up to 2 m thick passes into upward bundling cosets of ripple cross laminations < 0.5 m thick. Individual ripples consist of both form concordant and form discordant morphologies with wavelengths of up to 10 cm and amplitudes < 8 cm. Sandstones are dolomitized, reacting weakly to dilute HCl.

Lithofacies 1 is interpreted to represent sediment that accumulated on a wave-dominated upper to middle shoreface that was periodically inundated by storms. This interpretation is based on the combination of sedimentary structures including upward bundling ripples, swaley cross stratification, combined flow ripple cross lamination and planar cross stratification.

Walk upriver and cross the small access stream before ascending up to the field (while it is possible to walk in the shallow channel and view the stratigraphy, for efficiency with a large group we will ascend up to the field, walk northward and descend to the river at various points. WARNING: old, difficult to see barbed wire is present in the woods. Be careful!).

Stop 2B (UTM Z18 NAD83: 0613688 4964712) Mudstone

This portion of the Altona stratigraphy, between 62-65 meters in the Altona composite section (Figure 12), exposes Lithofacies 4, a heterolithic unit dominated by mudstone but containing sandstone, siltstone, and dolostone. Note the interbedded nature of the sandstones and mudstones as well as the sedimentary structures found within the sandstones. Mudstones are red and grey in color with mm scale laminations. Trace fossils are present but rare. Sandstones are poorly sorted, fine to coarse-grained, and contain planar cross beds and ripple cross lamination. Slightly thicker and finer-grained sandstone beds contain structures resembling hummocky cross stratification (HCS). Planar cross beds have erosional bases, are occasionally graded, and change thickness laterally over ~50 meters from 4 to 30 cm. Ripple cross laminations are present with cosets less than 10 cm thick and are either form concordant or discordant. Siltstones contain 1 cm thick ripple cross lamination and locally there are 1–2 cm thick lenses or nodules of dolostone.

Lithofacies 4 is interpreted to record deposition of offshore muds near the transition from the lower shoreface to offshore zones. The intercalated beds of sand are interpreted as tempestite deposits; episodically high energy deposition in an overall lower energy, further offshore setting. Transitions between lithologies are abrupt; there are no mud-rich dolostones, sandstones or muddy siltstones that would be expected on a graded shelf. This suggests the possibility that the deposition of mud represents a salinity controlled discharge-related event from hypopycnal flow.

Figure 11. Lithofacies 1 of the Altona Formation at Atwood Farm (Stop 2A).

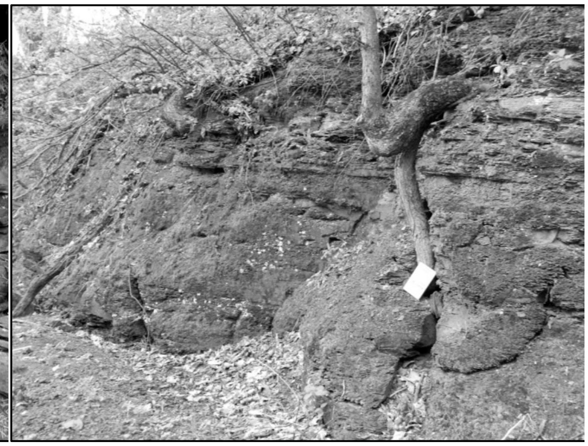

Figure 12. Lithofacies 4 (mudstone) of the Altona Formation at Atwood Farm (Stop 2B).

Stop 2C: (UTM Z18 NAD83: 0613633 4964839). Dolostone bench

A prominent dolostone bench forms a small waterfall between 67-69 meters in the Altona composite section (Figure 13). Dolostone beds may contain disseminated sand-sized clastic material but the majority of beds are carbonate. Thin section analysis has not revealed fossils, sedimentary structures or fabrics that can be used to interpret paleoenvironments as there is evidence of multiple dolomitization events. The carbonate material may be shallow water (photic zone) algal in origin or it may be a chemical precipitate (“whitings”). The shoreline setting suggested for the clastic lithofacies of the Altona suggests that the near shore clastics may have passed offshore into more clear water carbonate ramp deposits. During sea level highstands, clastic material would be trapped in terrigenous fluvial systems which allowed carbonate deposition to commence. The interbedding of sandstone/mudstone and dolostone would record discharge events rather than sea level fluctuations. Dolostone beds containing clastic material frequently exhibit graded bedding of the sand, which may represent punctuated mixing during storm events. Dolostones containing fine sand disseminated throughout the carbonate may record eolian input of clastics.

Stop 2D: (UTM Z18 NAD83: 0613533 4964930) Poorly exposed uppermost Altona

This portion of the Altona stratigraphy, 81-84 meters in the Altona composite section, is poorly exposed but includes Lithofacies 5, a poorly sorted, feldspathic fine to medium-grained sandstone (Figure 14). 50 cm thick beds appear to be graded with faint ripple cross laminations. Due to its graded nature, stratigraphic position interbedded with dolostones, and stratigraphic position (overlain by Lithofacies 6), this lithofacies is interpreted to have been deposited under conditions of waning flow velocities associated with discharge events in the adjacent terrestrial fluvial system (Ausable Fm.). This lithofacies is interpreted to represent “event beds”: siliciclastic sediment washed onto the carbonate ramp following a runoff event (storm). This lithofacies may represent the nearshore component of the event beds represented by the graded planar cross bedded sandstones of Lithofacies 4.

Figure 13. Dolostone bench in the Altona Formation at Atwood Farm (Stop 2C).

Figure 14. Lithofacies 5 (feldspathic fine to medium-grained sandstone) of the Altona Formation at Atwood Farm (Stop 2D).

Ascend up to the fields and walk south back to the vehicles, which need to turn around to retrace the route back to the Military Turnpike.

Distance (miles)		
Cumu-lative	Point to Point	Route Description
14.6		
14.8	2.0	Atwood Road to intersection with Rt. 190 (Military Turnpike), go right.
28.6	13.8	Near Ellenburg turn left to continue onto Rt. 190 (Military Turnpike)
29.0	0.4	Turn Right onto Rt. 190 (Star Road)
30.4	1.4	Turn R onto Cashman Road
30.5	0.1	Park in the angler’s parking or onto shoulder STOP 3

STOP 3: Great Chazy River, North Branch Near Ellenburg: The Ausable Formation

Location Coordinates: (UTM Z18 NAD83: 0589017 4970697)

Park at the angler’s parking along Cashman Road. Walk south almost to the intersection of Cashman Road and Rt 190 (Star Road) and work your way down to the river. The section is continuous on the east side of the river from beneath the bridge southwards for some distance upriver. The section at this stop is along a river and waterproof footwear may be needed, depending on the current water level. **Watch your step, as rocks are strewn across the riverbed and may be slippery.**

This stop showcases the lithofacies and architectures of braided fluvial strata of the Middle Cambrian Ausable Formation, stratigraphically beneath the Keeseville but above the Altona. We are now on the foot wall of the east-dipping normal Havelock fault upon which lower potions of the Potsdam succession are exposed on the axis of the Oka-Beauharnois Arch (Figures 1 and 4), but nevertheless the Altona –Ausable contact is probably several hundred meters in the subsurface at this location. Strata here records deposition of pebbly arkose by braided rivers in a humid climate setting. The braided rivers flowed roughly SE and had nearby hinterlands 70 – 150 km to the NW. These rivers drained into a ~N-S trending sub-basin that covered ca. ~10,000 - 15,000 km^2 in this region, resulting in the deposition of ~300 – 400 m of braided fluvial arkose that occurs from Montreal south to Plattsburgh (Figure 6a).

Most of the section consists of ~5 – 15 cm thick cross-stratified sets of moderately sorted upper medium to very coarse-grained pebbly sandstone formed by 2D or 3D dunes in shallow high energy steady unidirectional currents; although thicker (~15 – 45 cm) planar-tabular sets are interpreted to have been deposited by simple downstream-accreting solitary bars (i.e. unit bars, see Bridge, 2003; Reesink and Bridge, 2011) (Figure 15). Architectural analysis reveals that dunes and unit bars coalesced to form larger-scale accretional elements (bounded by the red lines in Figure 15) where in which sets and cosets bounded by accretion surfaces dip at low angles in the downstream direction. These accretional elements are interpreted as the deposits of low relief compound braid bars in shallow braided rivers, ubiquitous components of modern and ancient braided fluvial environments. Other features include 4 – 10 cm thick pebble conglomerates that record energetic bar-top deposition and ~ 1.5 – 6 cm thick argillaceous fine-grained sandstone beds and associated local rip-up clasts. In thin section the latter beds are shown to contain preferentially degraded feldspars, swollen biotite and eluvial clay and silt (Figure 16) recording preferential weathering (mostly by hydrolysis) and illuviation, and are therefore interpreted as overbank floodplain deposits.

Relatively thick (~1.3 – 2.5 m) repetitive successions usually capped by thin overbank deposits are recognized here and elsewhere (bounded by heavy black lines in Figure 15) and interpreted as channel belt successions. At this outcrop the at least one entire channel belt succession is exposed, over- and underlain by parts of others.

Return to the vehicles, which need to turn around to retrace the route back to the Star Road (Rt. 190).

Distance (miles)		
Cumu-lative	Point to Point	Route Description
30.5		
30.6	0.1	Turn cars around and proceed south to T junction with Star Rd (Rt. 190), turn right
38.8	8.2	At Brainardsville turn right onto Rt. 374 (Lake Road)
42.8	4.0	Turn left onto Pulp Mill Rd
43.7	0.9	Turn right onto Jerdon Rd
43.9	0.2	Turn right into the High Falls Campground parking, DRIVE SLOWLY. STOP 4A

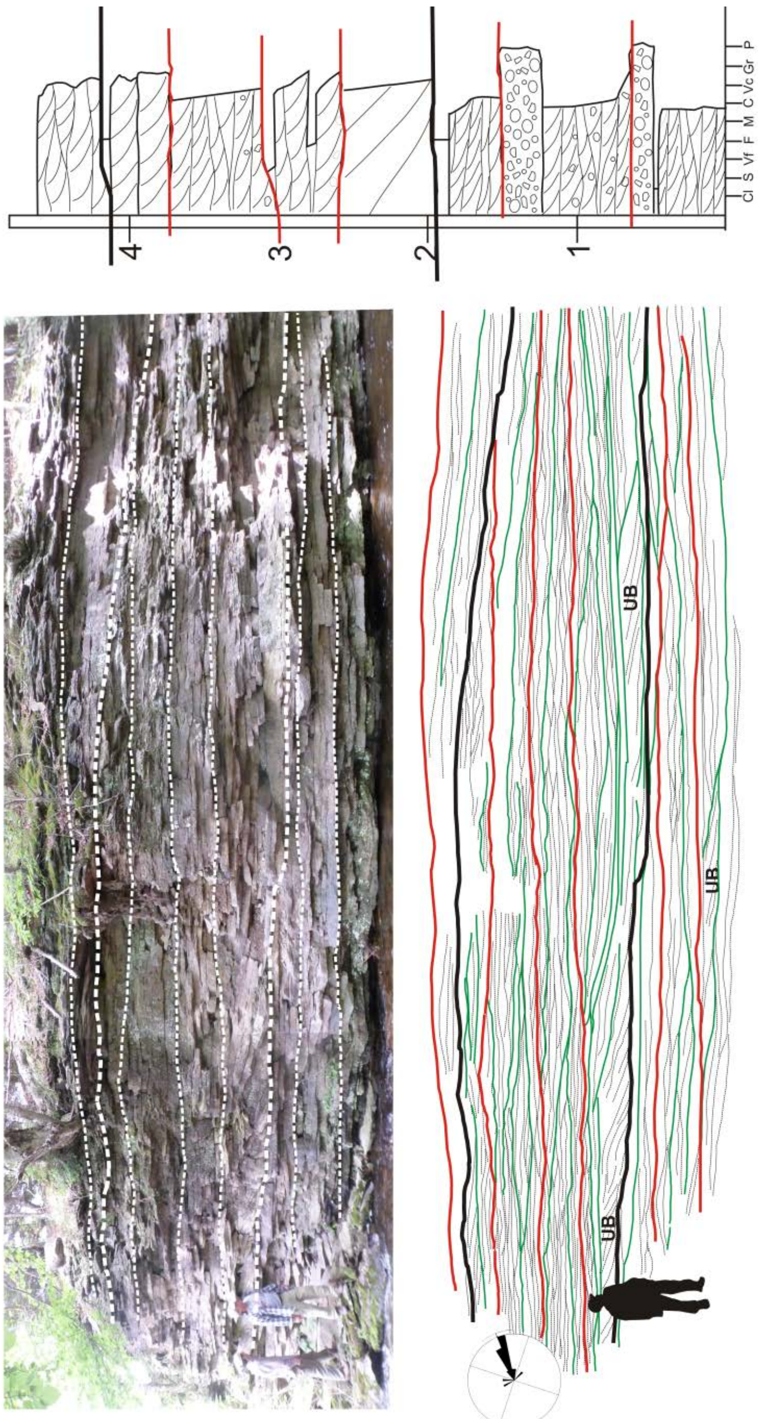

Figure 15: Outcrop photo, log and interpretation of architectures from Stop 3, just north of the bridge. Numerous orders of bounding surfaces exist (green, red and black) that record deposition of different orders of braided fluvial elements: from dunes/unit bar (UB) cross-strata, to compound braid bar deposits (outlined in red) and finally channel belt deposits (outlined by heavy black line).

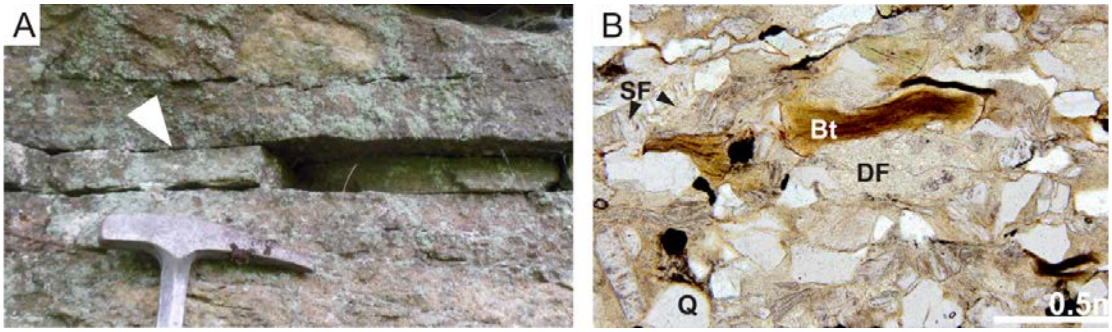

Figure 16: A) an argillaceous fine-grained sandstone bed interpreted as a thin overbank deposit (outlined by bedding planes, indicated by arrow). B) thin section photomicrograph of same bed. Eluviated matrix is common as are skeletal and degraded feldspar grains (SF and DF), hydrated biotite (Bt) and quartz grains (Q).

STOP 4: Chateguay Chasm: the Keeseville Formation

Location Coordinates: (UTM Z18 NAD83: 0571974 4972971)

While entering the High Falls campground parking lot please DRIVE SLOWLY. After parking, proceed to the main building. Access to the lower falls (stop 6A) will cost $2 per person. Leave the building through the back door and proceed along the marked trail and stairs to the High Falls viewpoint. The section is wonderfully exposed all the way down the stairs and also father north along the trail that follows the Chateguay River.

Stop 4A.

This very thick section exposes a sharp but conformable contact between two distinct parts of the Upper Cambrian quartz arenitic Keeseville Formation (Figure 17). The lower part was deposited in a coarse-grained sandy braided fluvial setting and exhibits large-scale cross-stratification formed by large dunes and unit bars with ~westward paleoflow. Although in the past this lower unit has been correlated to the Ausable Formation due to similarity in sedimentary lithofacies, its detrital composition, detrital zircon ages and its westward paleoflow instead suggest that this is a part of the Keeseville Formation. The upper part of the section exhibits a planar-tabular character. Based on lithofacies analysis it is interpreted to have been deposited mostly by unconfined terminal ephemeral sheet floods in an arid or semi-arid terrestrial environment (i.e. ephemeral fluvial). Each sheet flood deposit was largely deflated and reworked by the wind during the long recurrence intervals between flooding, which resulting in a generally tabular architecture with abundant windblown deflation lags. In places, particularly near the top of the section, upstream,-migrating scour-filling features are exposed and interpreted as supercritical chutes-and-pools or cyclic steps. These features, particularly cyclic steps, are better exposed and thus described at stop 6B.

The sharp contact separating the braided and ephemeral fluvial strata records a shift in climate of from humid to semi-arid. This climate shift is correlated to a global Late Cambrian climate fluctuation at around ~494 Ma recorded by numerous isotopic and lithofacies indicators and attributed to orbital forcing (Cherns et al., 2013).

Figure 17: Contact between mostly cross-stratified braided fluvial and planar-stratified ephemeral fluvial sandstones of the Keeseville Formation at the lower part of the Chateauguay Chasm (Stop 4A).

Return to the parking lot, where we will proceed back to Jerdon Road and make our way to the section above the High Falls that exposed the ephemeral fluvial unit.

Distance (miles)		
Cumu-lative	Point to Point	Route Description
43.9	-	Exit High Falls parking, turn right on Jerdon Rd.
44.1	0.2	Turn left on Pulp Mill Rd.
44.2	0.1	Turn right onto La Plant Rd.
44.2	0.02	Park along the shoulder of La Plant Rd.

Stop 4B.

After leaving the High Falls parking lot, turn left (south) on to Jerdon Road. Then turn left (east) on to Pulp Mills Road, cross the bridge and turn right (south) on to La Plant Road. Park along La Plant Road and walk back to Pulp Mill Road and turn left (west). Cross the bridge and then make a right and walk north along a beaten path towards the Chateguay River. The outcrop is continuous along both sides of the river. From this (the east) side the finer detail of the ephemeral fluvial deposits can be seen, while spectacular large-scale features, including cyclic steps, can be seen by looking across to the other side of the river.

Most of the section along the west side of the river consists of planar-stratified medium to very coarse grained sandstone (Figure 18). Many if not most planar laminations are inversely graded and record deposition by the migration of wind ripples. Many planar layers are capped by coarse- to very coarse-grained deflation lags. Bedding surfaces are either featureless or expose low relief regular or irregular features suggesting adhesion and/or microbial processes. Sand Grains, although coarse, are rounded with common pits and bulbous edges, suggesting aeolian processes. Eluvial silt and clay is common along grain margins, indicating illuviation of fine-grained windblown material. Scours and low angle cross-stratified sets, probably formed by antidunes under energetic sheet floods, are common (as in Figure 18). Altogether this association records episodic deposition by terminal sheet floods (i.e. terminal splays) followed by long periods of aeolian deflation and reworking in an ephemeral fluvial environment. Most of these features can be observed close-up while walking north along the exposed sections. Farther north, pink colored apatite-cemented layers occur in lower parts of the section. These preserve high primary intergranular volumes and prohibit silica overgrowths present elsewhere (Figure 19) and thus are early intergranular cements. The origin of the phosphate is unknown, but was most likely derived from phosphate-bearing brines from underlying basement rocks.

As we walk back along the outcrop to Pulp Mill road, a large scour-filling feature can be seen on the other side of the river. This feature (outlined in Figure 20) is interpreted as a cyclic step deposit. Cyclic steps form under high energy and shallow supercritical flows in which the formation of hydraulic jumps permits the buildup and upstream-migration of cross-stratified sandstone (see Figure 20). This scour records the upstream-migration of the erosional trough of a cyclic step bedform. On the upstream side of the trough the flow accelerated causing erosion, while further downflow the flow expanded under a stable hydraulic jump resulting in stoss-side deposition (e.g. Cartigny et al. 2014). The sets are bounded by erosion surfaces that record natural fluctuations in the quasi-stable hydraulic jump during the same flood event. The final position of the cyclic step trough and its subsequent fill under subcritical flow conditions is recorded by the symmetrical scour immediately upstream of cyclic step sets, which contains downstream-migrating dune cross-stratified sandstone (Figure 20). Thus this features records high energy sheet flood conditions, perhaps during an atypically voluminous high energy flood or a flood closer to the source of overland drainage (such as a nearby isolated storm cell or front). The erosion and filling of cyclic step troughs (the scour) are crucial to the preservation of these features from subsequent aeolian reworking/deflation.

Following some discussion/observation, views of the east side can be made from the Pulp Mill Bridge and by a small beaten path on the other side of the bridge. But USE CAUTION the bank is VERY STEEP and quite high on this side. **DO NOT GET TOO CLOSE TO THE EDGE!** From here we can examine the large-scale stratal architecture of these deposits that previously we examined close-up. Most of the upper section is made up of the planar-stratified aeolian-reworked terminal splay deposits we examined close-up, while some parts below are interpreted as scour-filling antidune cross-strata or cyclic step sets (Figure 21).

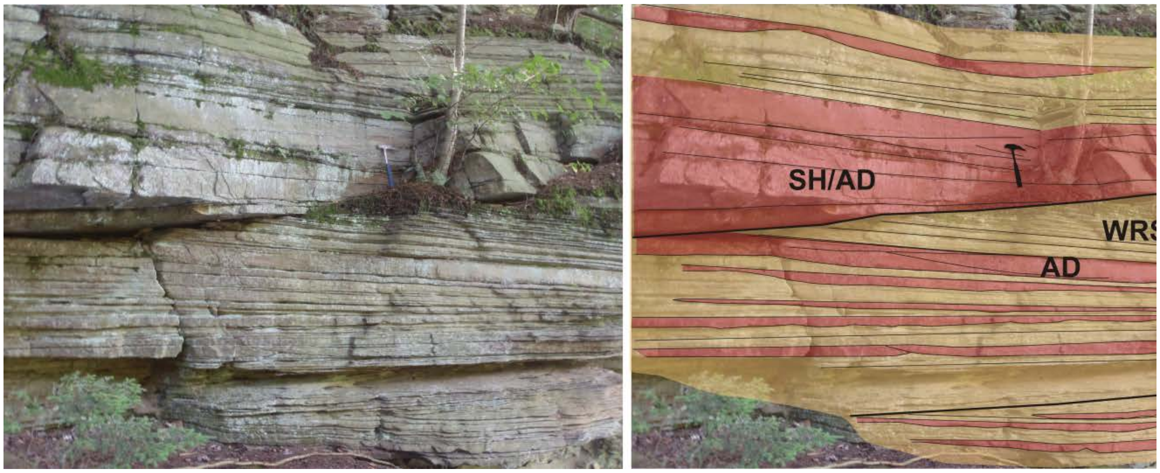

Figure 18: Outcrop photo and lithofacies interpretation of face at Stop 4B (Chateauguay Chasm, upper part). The section consist of interbedded sheetflood (pink) and aeolian (yellow) deposits (AD = antidune cross-strata; SH = massive sheet flood strata; WRS + DF = mainly wind ripple strata with some deflation lags). In this environment, most terminal sheet flood deposits were reworked by wind into aeolian sand sheets. Only the most energetic and therefore thickets sheet flood deposits were preserved. A prominent scour is present at the base of the thickets sheet flood deposit (heavy black line).

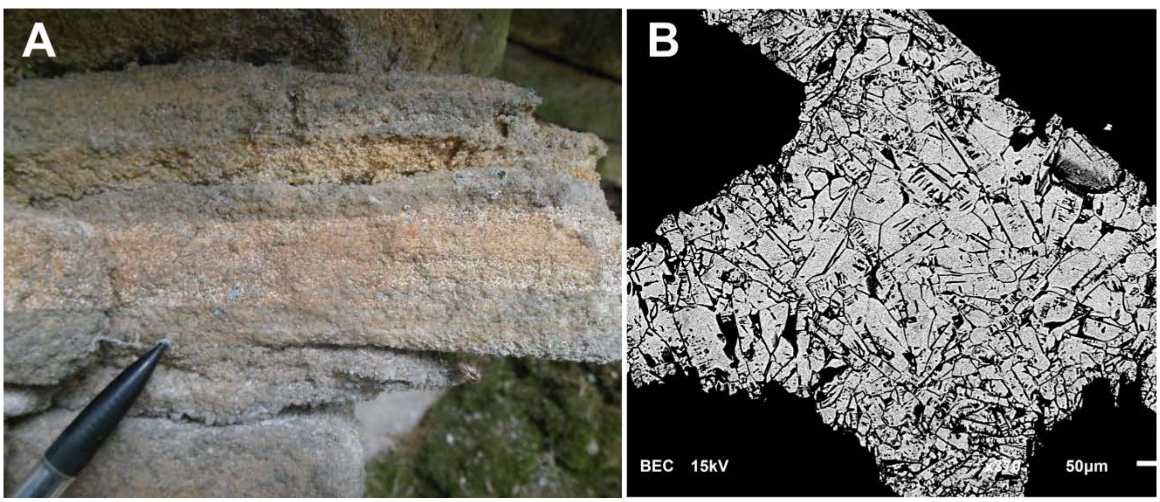

Figure 19: Early apatite cements near the base of the section. A: in outcrop these are identified by pink, roughly planar bands. B: SEM image of intergranular pore space between quartz grains (black) filled with the intergranular apatite cement.

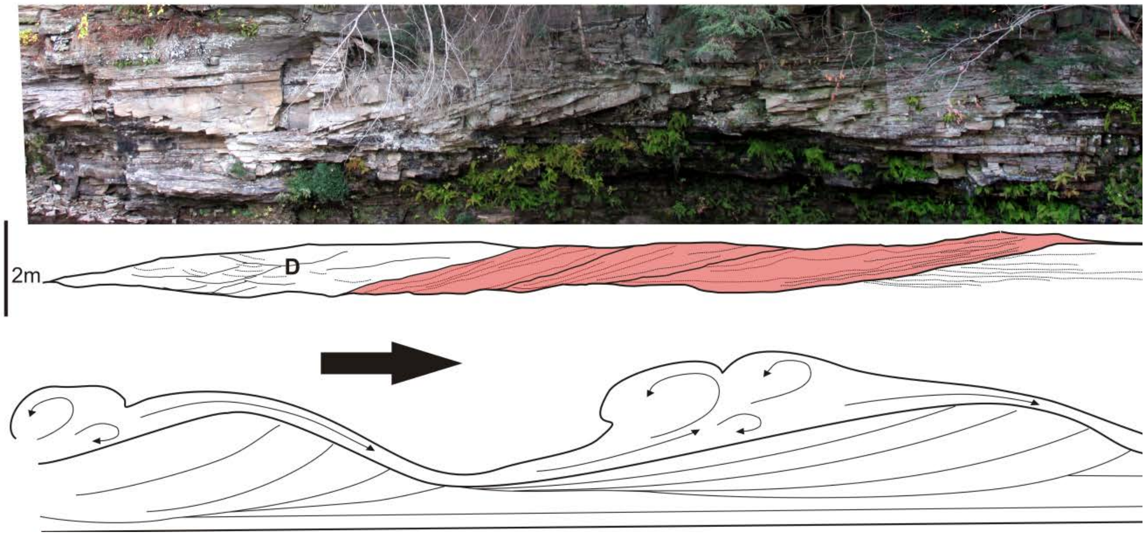

Figure 20: Scour-filling feature interpreted as an upstream-accreted cyclic step deposit that formed under a quasi-stable hydraulic jump in a high energy supercritical flow. Upstream-dipping cyclic step sets (in pink) are separated by erosional contacts caused by fluctuations in the flow/hydraulic jump during the same event. The more symmetrical scour at the upstream end records the final position of the cyclic step through that was subsequently filled by sand dune cross-strata (D) during that later stage of the flood. The line diagram at the bottom is a simplified model for the formation and migration cyclic steps with the arrow indicating the flow direction. Cross-strata only preserved in cyclic step troughs (as in this example).

Ascend the path back to Pulp Mill Rd and return to the vehicles parked on La Plant Road. We must turn the vehicles around and proceed back to the T junction with Pulp Mill Road.

Distance (miles)		
Cumu-lative	Point to Point	Route Description
44.2	0.02	Turn cars around and proceed south to T junction Pulp Mill Rd., turn left
44.3	0.1	Turn left onto Healy Rd.
45.1	0.8	Turn right onto Hartnett/Cook Rd.
48.1	3.0	Turn left onto Quarry Rd.
49.5	1.4	Continue to the end of Quarry Rd. Park just before or just beyond the gate. STOP 5

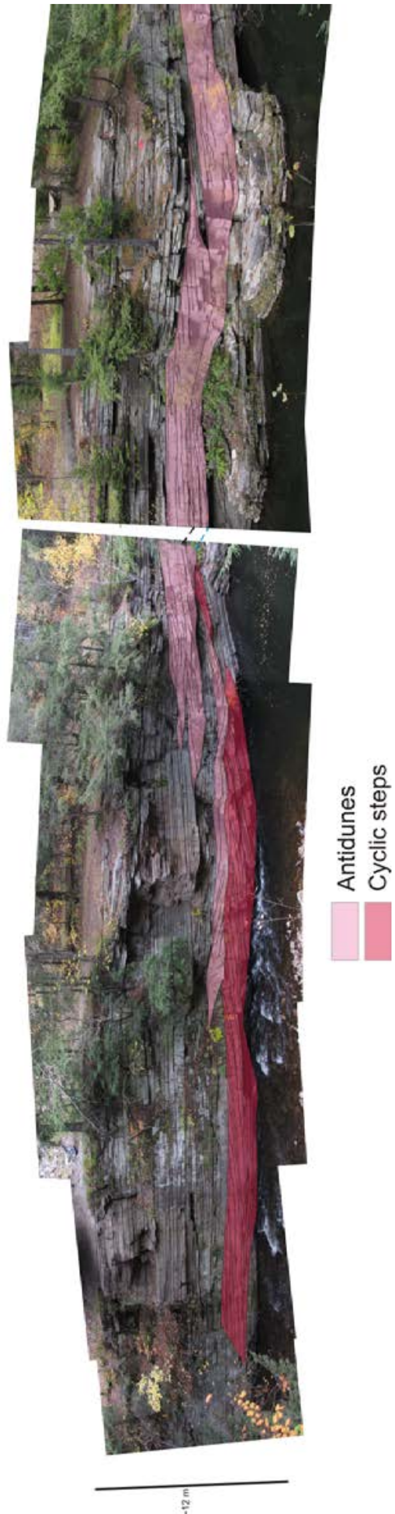

Figure 21: Annotated composite photo of the section on the west side of the upper Chateauguay Chasm section (Stop 4B). Scale bar is ~12 m.

STOP 5: Rainbow Quarry: The Keeseville Formation

Location Coordinates: (UTM Z18 NAD83: 0567998 4968956)

Park at or just beyond the quarry entrance. The best section is exposed in the southwest corner of the Quarry. Here relatively thick (~4-6 m) sets and cosets of cross-stratified medium grained sandstone are present and are interpreted to have been formed by the migration of large aeolian dunes in a generally dry aeolian erg setting (Figure 22). Close examination of the cross beds reveals inverse graded grain flow deposits in foreset strata and inversely-graded wind ripple laminations in the toe sets. At this location and at a similar quarry ~1.6 km southwest of here the aeolian dune sets are separated by generally planar stratified sandstone underlain by horizontal surfaces erosion that most likely record dry to damp interdune erosion and deposition of interdune sand flats (see Hagadorn et al. 2008 for more details). Aeolian erg strata here are interpreted to be coeval to the ephemeral fluvial strata at the top of the previous stop (Chateauguay Chasm) and most likely accumulated by the deflation and downwind transport of the ephemeral fluvial splay deposits at the Chateauguay Chasm. This correlation is supported by similarities in detrital zircon ages.

Figure 22: Large-scale cross-stratified sets formed by the migration of aeolian dunes in an arid erg setting at Stop 5. Arrow points to book bag for scale.

Turn vehicles around and proceed northward along Quarry Road.

Distance (miles)		
Cumu-lative	Point to Point	Route Description
49.5		
50.8	1.3	Drive to T junction with Cook Rd. Turn left
51.3	0.5	Turn left onto Flynn/Willis Rd (Rte. 36). Continue through sharp turns.
54.7	3.4	At T junction with Brainardsville Rd. (Rte. 24) turn left
60.1	5.4	At Brainardsville continue straight onto Rte. 190 (Star Rd.)
69.8	9.7	At T junction near Ellenburg turn left onto Rte. 190 (Military Turnpike)

70.2	0.4	At T junction near Ellenburg turn right onto Rte. 190 (Military Turnpike)
78.9	8.7	Turn left onto Devils Den Rd.
80.7	1.8	Turn left into Feinberg Park. STOP 6

STOP 6: Lasalle Dam, Altona NY: The Keeseville Formation

Location Coordinates: (UTM Z18 NAD83: 0606129 4970511)

Park at the Feinberg Park and walk south along Devils Den Road across the bridge. The outcrop is along both sides of the river, and the section is continuous upriver to the abandoned McGregor Powerhouse. Following some discussion on the south side of the river, the north side can be accessed directly from Feinberg Park.

This section exposes a part of the Upper Cambrian Keeseville Formation which underlies the surrounding area in Altona north of the Flat Rock State forest (Figure 4). Here the Keeseville consists of a sheetflood-dominated ephemeral fluvial facies association that was deposited on a Late Cambrian coastal plain inboard of the paleo-shoreline located at or somewhere south of the Ausable Chasm section, ca. 40 km to the south, which was mostly a coastal sabkha throughout the Late Cambrian. A good modern approximation for such a setting might be the coastal plain of the Skeleton Coast of Northern Namibia in which ephemeral rivers discharge directly into the Atlantic forming ephemeral fluvial “deltas”.

Most of this section consists of beds of slightly inclined (≤ 10^{o}) or horizontal planar-stratified medium grained quartz arenite usually truncated by low angle or horizontal surfaces (Figure 23). Internally these beds consist of finely-interlaminated shallow water (depth-limited orbital ripples, upper plane bed, rare current ripples) and aeolian (wind ripple and adhesion) lithofacies recording alternating wet and dry conditions. Coarse-grained deflation lags are common and desiccation cracks are also present but rare. These beds are interpreted terminal splay lobes in an ephemeral fluvial setting, and were built up over time by the accretion of episodic flood deposits. Flood deposits were largely reworked by the wind between episodic floods, resulting in common aeolian and adhesion features. Features such as oscillation ripple marks, parting lineations and adhesion ripples and warts immediately catch the eye on the bedding planes of these terminal splay lobes but belie the aeolian influence on deposition. Keep an eye out for less obvious features, such as inversely-graded laminations or low relief step-like features on bedding planes attributed to wind ripple stratification, coarse-grained deflation lags, or featureless planar laminations and surfaces most probably recoding the adhesion of windblown sand onto damp surfaces (i.e. adhesion stratification: Hunter, 1980; Kocurek and Fielder, 1982). Infiltrated matrix is also present in these strata and can be seen in thin section, and record the infiltration of clays into the vadose zone by illuviation, probably during rainstorms.

Upper medium to coarse-grained antidune cross-stratification is also present at this section and record high energy, probably more proximal, waning shallow sheet flood conditions. Antidune strata are recognized by low angle symmetrical trough-cross stratified bottom sets and convex-up low angle symmetrical formsets with wavelengths in the order of ~25 cm – 1 m (Figures 23 and 24). It has a very similar structure to HCS, something noted from numerous fluvial deposits (Cotter and Graham, 1991; Rust and Gibling, 1990; Fielding, 2006) and also from experimentally produced antidune cross-stratification (Alexander et al., 2001; Cartigny et al., 2014). However, several features including the small thickness and wavelengths of sets and formsets, its 2D form on bedding planes, its relatively coarse grain size and lack of association with bioturbated lower shoreface deposits rules out classic HCS.

Also present near the base of the section are erosionally-based and crudely channelized trough cross-stratified sandstone formed by the migration of subaqueous dunes. These strata record the filling of an erosional distributary channel (like an arroyo or wadi) that had previously funneled energetic flood waters to terminal splays, probably during the late stages of lower energy floods leading to the abandonment of this particular distributary channel.

Isolated *Proticnites* trackways formed by arthropods have been observed at this location, but are rare.

Return to vehicles in Feinberg Park and exit right onto Devils Den Rd.

Distance in miles		
Cumu-lative	Point to Point	Route Description
	0.0	Turn right onto Devils Den Rd.
	1.8	Turn left onto Rte. 190 (Military Turnpike)
	13.9	Turn left onto Tom Miller Road.
	2.5	Turn right onto Prospect Rd.
	0.8	Turn left onto Broad Street.
	0.0	Turn left on Beekman street and immediate left into Hudson Hall parking lot.

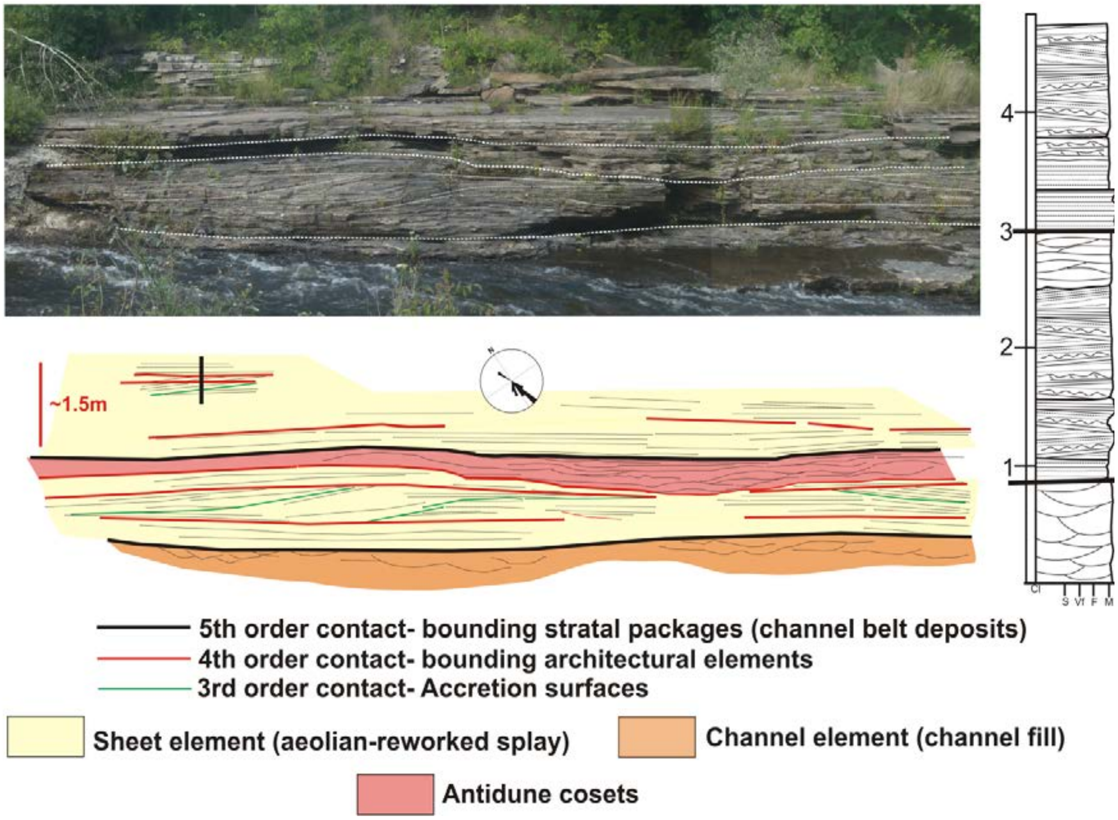

Figure 23: outcrop photo, log and sketch of section at Lasalle Dam (Stop 6). See text for more details.

Figure 24: Hummocky-looking antidune stratification at the Lasalle Dam section (Stop 6).

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