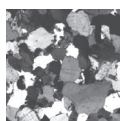# Sedimentology and petrography of a lower Cambrian transgressive sequence: Altona Formation (Potsdam Group) in northeastern New York

Ryan Brink, Charlotte Mehrtens & Henry Maguire

The Altona Formation, the oldest unit in Potsdam Group, is a heterolithic shallow marine deposit recording fair weather and storm deposition in a marginal marine setting associated with the onlap of the Laurentian Craton in the latest early Cambrian (*Olenellus* Zone) to middle middle Cambrian (*Bathyuriscus-Elrathina* Zone). Six lithofacies are recognized within the Altona Formation including non-marine sheet flood, nearshore bay/estuary, and upper and middle shoreface. These lithofacies occur in the stratigraphy in response to relative sea level change and sediment supply. Onlap of Precambrian Grenville basement represents initial transgressive systems tract deposition which was succeeded by highstand deposition, and with it, diminished terrigenous input and the onset of carbonate deposition. Renewed input of terrigenous sand in the upper third of the Altona resulted in shoreline progradation followed by a second cycle of transgressive and highstand systems tract deposition. The overlying Ausable Formation marks the transition to falling sea level and onset of non-marine deposition. Analysis of gamma ray log data confirms that terrigenous sediment input varied through the stratigraphy, which is interpreted as a response to rising sea level trapping sediment on the coastal plain. Predominantly compositionally immature sandstone, the Altona also contains arenaceous dolostone, dolostone and silty shale. Modal analysis of the sandstones indicates an arkosic composition for the sandstones, with an accessory mineral suite including apatite, ilmenite, rutile, and zircon. This accessory suite, along with detrital zircon ages, indicates an Adirondack massif source rock. • Key words: Cambrian, *Olenellus*, *Elhmaniella*, sedimentology, shoreface, systems tracts, gamma ray log, Sauk II.

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As a result of recent revisions to the stratigraphic nomenclature and ages of the basal sandstone units that outcrop in the St. Lawrence lowlands and Champlain Valley of New York, Quebec, Ontario and Vermont, (*e.g.*, Landing *et al.* 2009, Sanford & Arnott 2010, Lowe *et al.* 2017) there is a need for detailed description and interpretation of the stratigraphy that records the onlap of the Laurentian Craton in the Cambrian. While Landing *et al.* (2009) identified fossils and generally described the Altona Formation as a shallow marine deposit, the greater detail of section measurement and description in this study permit more refined environmental interpretations. This study presents detailed compositional and sedimentologic descriptions and interpretation of the Altona Formation, the basal transgressive unit in the Cambrian sequence in the region northeast of the Adirondack Massif. We hope our data will shed light on regional paleogeographic questions, such as provenance and sediment transport patterns and regional correlations.

Regional stratigraphy and geologic setting

The Altona Formation outcrops within in the south-western-most portion of the Quebec Basin (Fig. 1), a major reentrant in the rifted Laurentian margin, the main axis of which lay to the east in Vermont. The ocean affinity of latest Precambrian mafic volcanic rocks in southern Quebec and Vermont that form the basement beneath the Cambrian stratigraphy there confirm their tectonic significance, and radiometric dates of these units constrain rifting to 615 to 554 (+10/−8) Ma (Abdel-Rahman & Kumarapeli 1999, Malka *et al.* 2000, Coish *et al.* 2012). The large-scale promontory-reentrant geometry of the rifted North American margin has long been known (*e.g.*, Thomas 1977), however variation in the smaller-scale along-strike geometry that controlled thickness and facies of syn- and post-rift strata has only more recently been described (*e.g.*, Cherichetti *et al.* 1998, Mehrtens & Brink 2015). The tectonic and structural relationship between
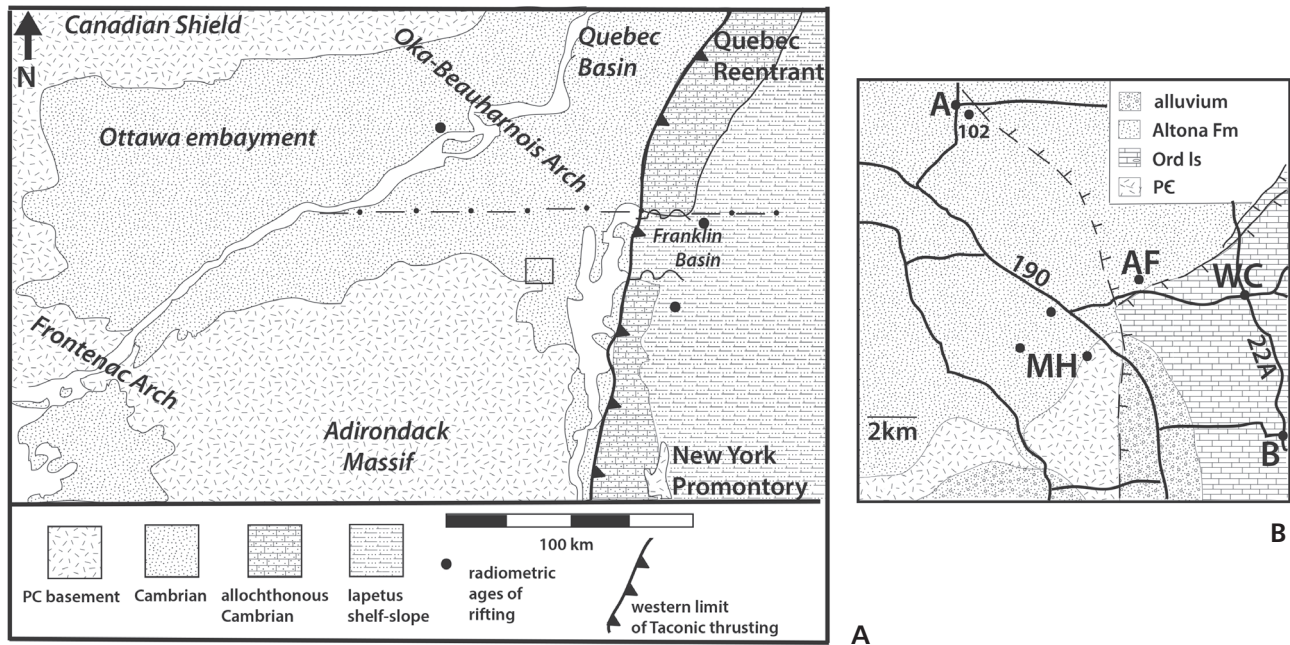
Figure 1. A – location of the study area and major physiographic and geologic features. Radiometric ages for MORB-affinity rift basalts are shown by dots. The location of the Franklin Basin in northernmost Vermont is indicated. • B – detailed geologic map of key outcrops used in this study to construct the composite stratigraphic column for the Altona Formation. Abbreviations: B – Beekmantown; A – Altona; WC – West Chazy; MH – Murtaugh Hill; AF – Atwood Farm. The location of the fault shown is from Lowe (personal communication).

the Ottawa-Bonnechere Graben (Kay 1942), which lays to the north and west of the study area and the main axis of rifting to the east in Vermont is not clear. Improved understanding of possible links between the sedimentary succession in the western basin and the main Iapetus shelf margin in Vermont may help clarify this.

The paucity of body fossils in the Altona Formation make precise age determinations difficult, however better dated overlying strata (summarized in Hagadorn & Belt 2008) provide constraints on its youngest possible age and radiometric dates on rift-related dikes intruding Adirondack basement provide a maximum age ~590 Ma but may be as young as ~554 Ma (Kumarapeli 1993).

Stratigraphic relationships in the Potsdam Group in New York and the Cambrian succession in Vermont are presented in Fig. 2. The stratigraphic nomenclature of the basal sedimentary sequence on the Laurentian Craton has been in revision for several years by stratigraphers (*e.g.*, Clark 1966, Clark & Lewis 1971, Sanford 2007, Lowe *et al.* 2017) and only a brief review is presented here. Historically, in New York the stratigraphic names "Ausable" and "Keeseville" Sandstones have been applied to the lower and upper members within the Potsdam Sandstone (*e.g.*, Fisher 1955). Sanford's (2007) comprehensive synthesis of Cambrian stratigraphy in Ontario, Quebec and northern New York solidified the use of the term "Potsdam Group" to describe the genetically related package of Cambrian to Lower Ordovician strata

in this region. In this scheme the Ausable and Keeseville Sandstones were elevated to formation status within the Potsdam Group. Most recently, Landing *et al.* (2009) described fragments of an *Olenellid* trilobite as well as specimens of *Ehmaniella* from a heterolithic unit which lies below the Ausable Sandstone. The discoveries of these fossils led Landing *et al.* (2009) to suggest that the older horizons should be recognized as a separate unit termed the Altona Formation. Sanford & Arnott (2010) applied the name "Jericho Member" of the Ausable Formation for this same group of rocks but this study adopts the terminology suggested by Landing and his coworkers.

The fauna retrieved from the Altona by Landing *et al.* (2009) indicates an older age for the base of the Potsdam Group than previously recognized (no older than Series 2 of the Cambrian). Landing *et al.* (2009) reported that faunal remains retrieved from the overlying non-marine facies of the Potsdam in northern New York have yielded a *Crepicephalus* Zone fauna (Series 3). Hagadorn & Belt (2008) also reported the presence of a trilobite fauna indicating an uppermost middle Cambrian (Series 3) as present in the middle and upper horizons of the Keeseville and Ausable Formations. This data provides a minimum age for the uppermost Altona Formation.

Biostratigraphic studies of fauna contained in the Cambrian strata in northern New York–southern Quebec Basin (Landing *et al.* 2009 and references therein) and western Vermont (Palmer & James 1979, Mehrtens &

Gregory 1984 and references therein; Fig. 2) indicate that the age of post-rift, marine shelf deposits in Vermont are significantly older than those in the northern New York–southern Quebec Basin, reflecting the westward transgression of the Iapetus seas onto Laurentia. Thus, the initial Sauk transgression (Sloss 1963) onto the Laurentian Craton occurred earlier in Vermont, younging westward into northern New York.

Study area and methodology

The study area is in northeastern New York State, approximately 15 km northwest of Plattsburgh (Fig. 3) in Clinton County. Outcrops of the Altona Formation are limited in number beneath the more well-exposed overlying units of the Potsdam Group. In assembling the composite stratigraphic column of the Altona Formation (Fig. 4)

this study focused on five outcrops and one well log drill core which determined that the Altona in this region is approximately 84 meters thick. As documented by Lowe *et al.* (2017) the Altona thins to the north into the Quebec Basin to approximately 36 meters in thickness.

Outcrops were measured and described at the centimeter scale with particular attention to sedimentary structures, which include cross lamination, hummocky cross stratification, oscillatory ripples, graded bedding, trough and planar cross stratification, herringbone cross stratification, horizontal laminations, and bioturbation. Although not numerous when available, measurements were taken of cross bedding to provide data on paleoflow direction. Covered intervals were measured by surveying. In addition to outcrop data, chips from one well drilled through the Altona (drill chips provided to the authors from David Franzi, S.U.N.Y. Plattsburgh) were also examined. Gamma-ray log data from the same well and details

Figure 2. Correlation chart for Cambrian to Lower Ordovician strata in western Vermont and northwestern New York. Abbreviations: Pc – Parker conglomerate; RB – Rugg Brook conglomerate; RL – Rockledge conglomerate. Radiometric ages on the Cambrian-Ordovician boundary from Landing *et al.* (2000) and the Precambrian–Cambrian boundary from Gradstein *et al.* (2004).
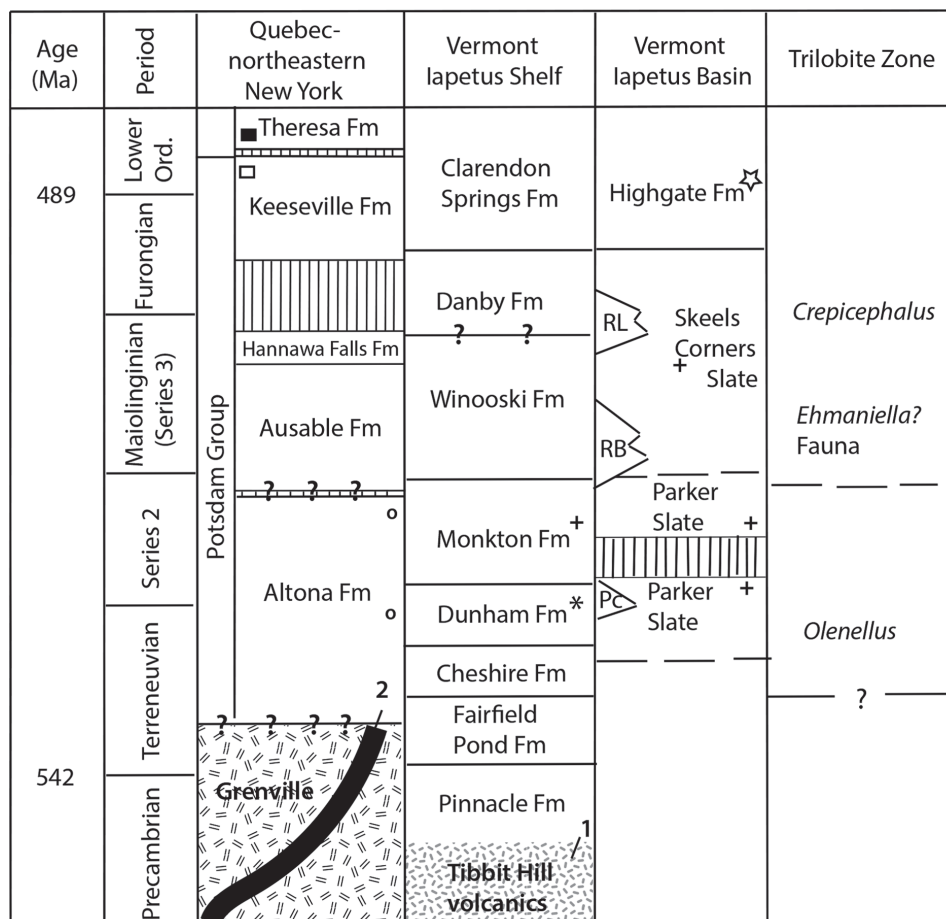
Key: RL = Rockledge Cong; RB = Rugg Brook Cong; 1= radiometric age from Malka *et al.* (2000); 2 = radiometric age from Kumarapeli *et al.* (1989); o = Landing *et al.* (2009); * = Mehrtens & Gregory 1981); + = Palmer & James (1979 and references therein); ✡ = Landing (2007); □ = Nowlan (2013); ■ = Brand & Rust (1977); vertical lines represent unconformities
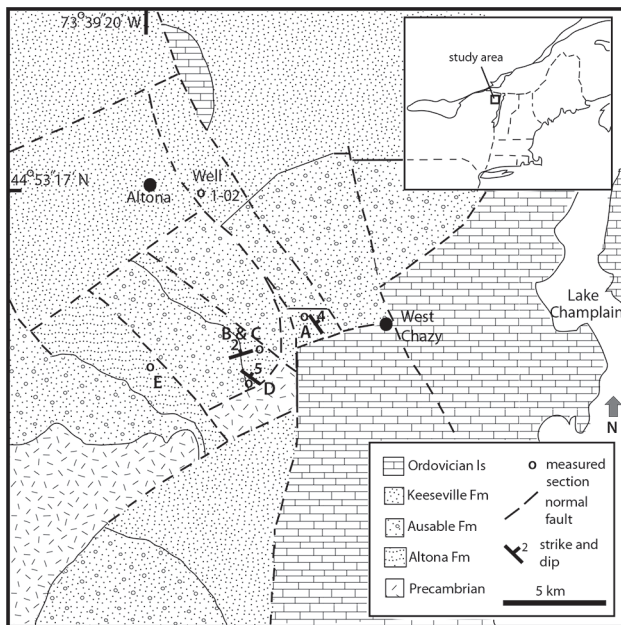
Figure 3. Geologic map of the study area, including unpublished data provided to the senior author by David Lowe. See also Lowe *et al.* (2015). Locality A – Atwood Farm (UTM Zone 18: 0613737 E, 4964653 N); B and C – McKinney Farm (UTM Zone 18, 0611758 E, 4962606 N); D – lower Murtaugh Hill stream (UTM Zone 18: 0611739 E, 4961998 N); E – top of Murtaugh Hill (UTM Zone 18: 0610762 E, 4960784 N). The location of well 1-02 at is shown (UTM Zone 18: 0612713 E, 4965740 N).

of the well log and cycle interpretation were collected by Edwin Romanowicz (S.U.N.Y. Plattsburgh) and are reported in Maguire *et al.* (2018). Samples were collected throughout all sections for hand sample and petrographic examination.

Uranium–lead data from zircons in the Altona were provided by Chiarenzelli *et al.* (2010) from Altona samples collected near Potsdam, N.Y., to the west of present study's field area. Their results are discussed below.

Compositional data was obtained from thin sections. The fine grain size and hematite staining made it necessary to examine thin sections with a scanning electron microscopy with EDS and cathode luminescence. Thin sections from each of the lithofacies were examined. Multiple transects across thin sections confirmed grain size measurements made from transmitted light microscopy and provided the basis for grain identification and point count data. The composition of mudstones was determined by Xray diffraction.

Results

Construction of the composite section

While we acknowledge that it is possible that irregular Precambrian topography could produce thickness dif-

ferences in the Altona Formation, the composite section presented here is based on the total unit thickness of 84 meters between basement and the overlying Ausable Formation retrieved from well 1-02. A composite stratigraphic section was constructed from three of the five outcrops (Atwood Farm: Fig. 5, McKinney Farm: Fig. 6, and lower Murtaugh Hill: Fig. 6). Neither the base nor top of the Altona was exposed at the Purdy Mills outcrop (Fig. 6), so its position in the composite section cannot be placed with any certainty. The exposure at the top of Murtaugh Hill, although close to exposures of overlying younger Potsdam strata, likewise cannot be placed accurately in the stratigraphy but lithologies and sedimentary structures suggest that it is near the top of the Altona. The lower Murtaugh Hill stream channel exposure off Route 190 contained the contact of the Altona with basement. The Atwood Farm exposure did not extend down to basement but reached the upper contact with the overlying Ausable Formation. The McKinney Farm section overlapped a portion of the Atwood Farm section.

Depositional Facies

Hampson (2000, tab. 1) described four subdivisions of shelf to shoreface environments. This include: (1) offshore shelf/ramp, (2) distal lower shoreface and inner shelf/ramp, (3) proximal lower shoreface and (4) upper shoreface. Hampson's (2000) upper shoreface includes sediments deposited above fair-weather wave base; his lower shoreface environments represent deposition above storm wave base but below fair-weather wave base and the offshore shelf environment represents sediment deposited below storm wave base. As noted by Rey & Hidalgo (2004), along shorelines where tidal processes are a factor, a fifth setting, the subtidal to intertidal environment of the foreshore/shoreface, is also important to identify.

The key attributes of grain size, sedimentary structures, sorting, bed thickness, bedding contacts and discontinuity surfaces used to distinguish wave-dominated environments are well described (Elliot 1986 and references therein, Walker & Plint 1992 and references therein, Pattison 1995) and are not repeated here. These attributes form the basis for the identification of six lithofacies in the Altona Formation (Tab. 1 and Figs 7–12). A depositional model for the distribution of lithofacies is shown in Fig. 13.

Lithofacies 1: non-marine to marginal marine

Lithofacies 1 (Fig. 7) consists of a medium to coarse-grained poorly-sorted arkosic sandstone. Sandstone beds 10–20 cm in thickness contain 10–15 cm thick isolated
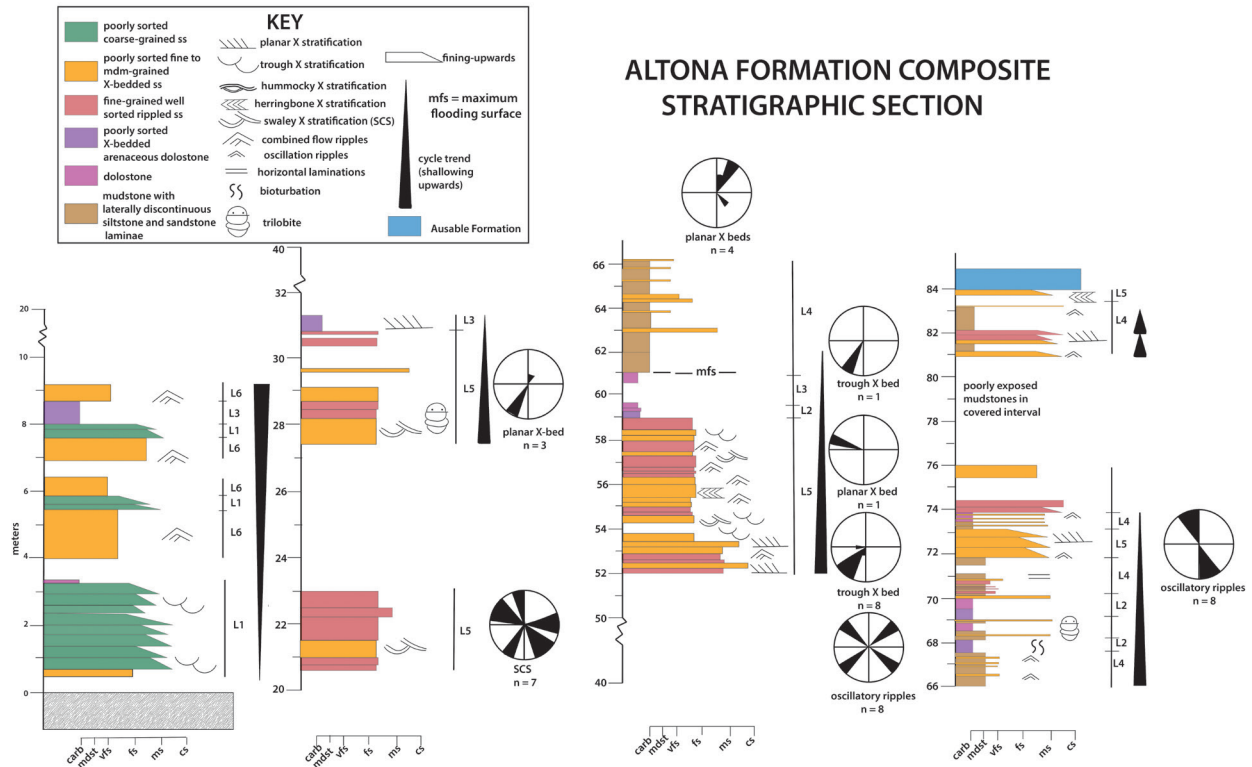
**Figure 4.** Composite stratigraphic section of the Altona Formation. Scale is in meters. Abbreviations: SCS – swaley cross stratification; carb – carbonate; mdst – mudstone; vfs – very fine-grained sandstone; f – fine-grained sandstone; ms – medium-grained sandstone; cs – coarse-grained sandstone.
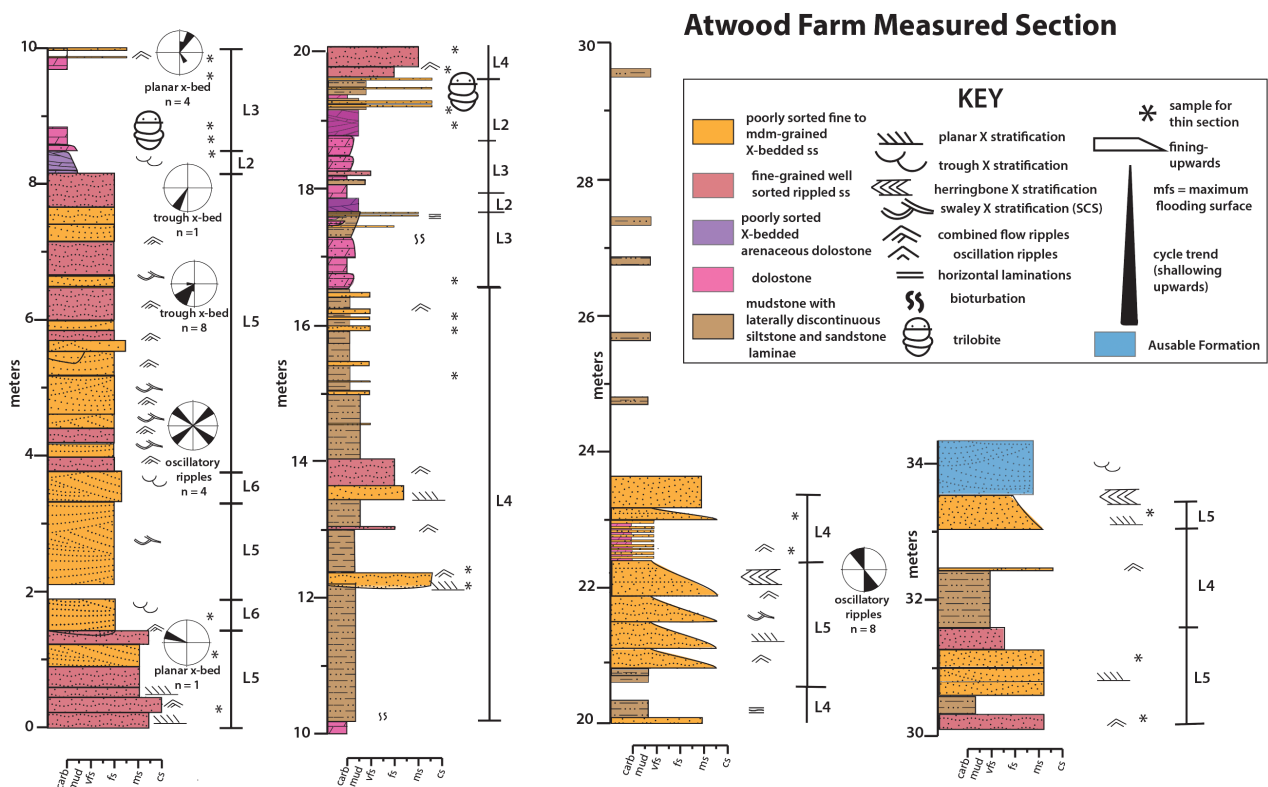
Figure 5. Measured section from Atwood Farm. Vertical scale in meters. Key to symbols for Figs 6–12.

Table 1. Summary of lithofacies.

Lithofacies	Description	Interpretation	Representative stratigraphy
1	medium to coarse-grained poorly sorted sandstone with rare gravel horizons; trough and planar cross stratification	fluvial (sheetflow) to marginal marine	on PC basement
2	dolostone and arenaceous dolostone with siltstone. Coarse-tail graded bedding and cross lamination, bioturbation	nearshore carbonate pond	middle of Atwood Farm
3	arenaceous dolostone containing poorly sorted medium-grained sand exhibiting graded bedding and cross lamination	nearshore shelf adjacent to terrigenous source with periodic 2D and 3D bedload deposition	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; bioturbation	nearshore estuarine/bay quiet water with periodic tempestite deposition	Atwood Farm, Purdys Mills
5	poorly sorted medium-grained feldspathic ss, trough, planar, swaley and hummocky cross stratification, graded bedding and cross lamination	2D and 3D dunes nearshore wave reworked fairweather and tempestite deposits	lower third and top of Atwood Farm
6	fine to medium-grained well sorted ss. Upward-bundling ripples, combined flow ripples, erosional surfaces are common	2D and 3D wave-generated ripples on storm-influenced upper-middle shoreface	middle of Atwood Farm
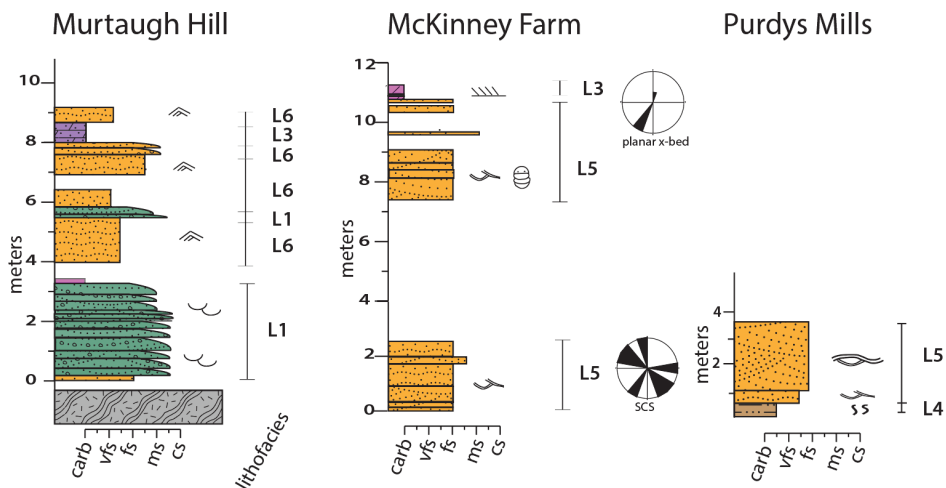
Figure 6. Measured sections from Murtaugh Hill, McKinney's Farm and Purdys Mills. Vertical scale is in meters. Rose diagrams represent paleoflow data from swaley (SCS) and planar cross stratification. Key to symbols as shown in Fig. 5.

sets of trough cross stratification and stacked sets which may be capped by 2D and 3D ripple cross lamination. The bases of beds are very sharp and bed thickness is constant across limited lateral exposure. Coarse-tail grading is present. This lithofacies lies at the base of the Altona, above Precambrian basement at the lower Murtaugh Hill exposure.

Sedimentary structures present in this lithofacies are not unique to any depositional environment; however the coarse grain size and poor sorting suggest rapid deposition from sediment-laden high velocity flows. Single sets of cross beds present in this lithofacies represent sediment deposited as bedload as sinuous-crested migrating

bedforms (3D ripples of Harms *et al.* 1982) and stacked sets record the migration of three dimensional ripple fields.

Taken together, the stratigraphic position of this lithofacies immediately above Precambrian basement suggests that it records deposition in a fluvial to marginal marine setting, possibly from sheetflood deposition which may have subsequently experienced reworking by currents. Sand-dominated sheetflood deposits have been described by many authors (*e.g.*, McKee *et al.* 1967, Bull 1972, Collinson 1978, Tunbridge 1981). They are interpreted as laterally extensive sand bodies which frequently form on the distal reaches of alluvial

Figure 7. Lithofacies 1. • A – measured section from lower Murtaugh Hill. The covered interval above the Precambrian basement is approximately 0.3 m thick succeeded by several meters of cross bedded sandstone. • B – outcrop photograph from above the Precambrian contact on lower Murtaugh Hill. • C – thin section photomicrograph of sample AF 13-20 illustrating the poorly sorted texture of a sandstone. • D – bipolar flow directions produced from cosets of planar cross stratified sandstone. Pencil for scale. • E – arrows point to a pebble horizon at the top of a poorly sorted, cross stratified coarse-grained sandstone. The black scale bar is 2 cm.
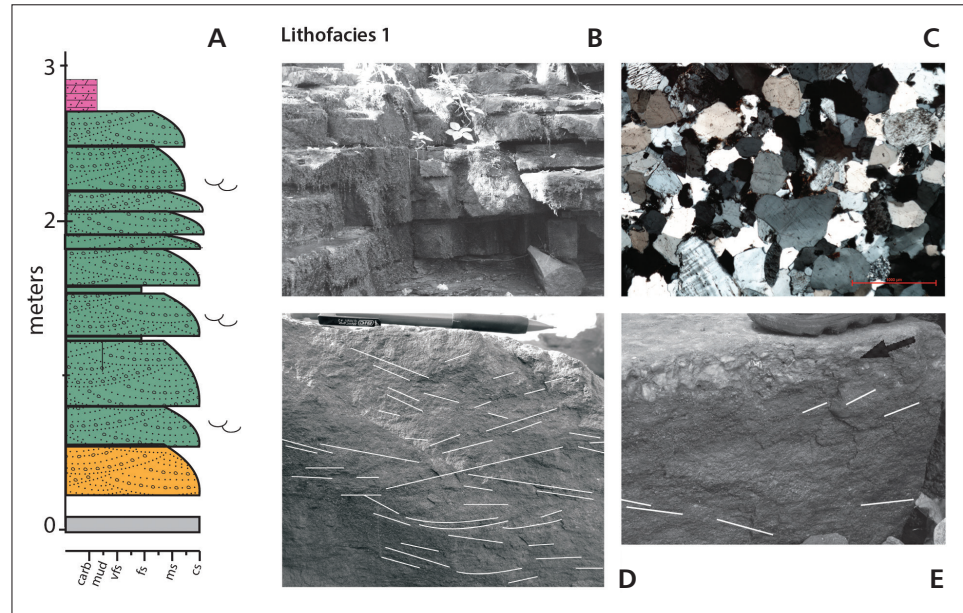
Figure 8. Lithofacies 2 is a dolostone to arenaceous dolostone in composition containing poorly sorted medium grained sand, cross stratification and ripple cross laminations. • A – an interval of the Atwood Farm stratigraphy where this lithofacies is exposed in contact with Lithofacies 4. • B – dolostone bed at Atwood Farm that grades upwards into red silty mudstone. Hammer for scale. • C – thin section photomicrograph of siltstone. • D stadial rod in front of an outcrop of interbedded dolostone and mudstone at Atwood Farm. • E – color mottling in the fabric of dolostone is interpreted to represent the effects of bioturbation.
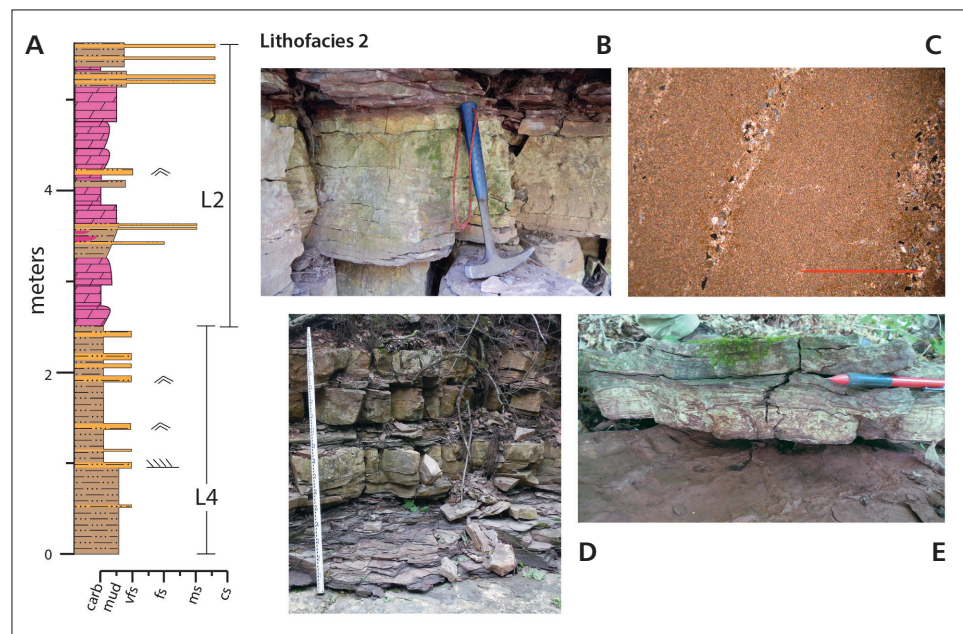
fans. At the lower Murtaugh Hill exposure, 2.5 meters of this lithofacies is overlain by Lithofacies 3 – dolomitic sandstone.

Lithofacies 2: nearshore carbonate

Lithofacies 2 is a heterolithic unit containing dolostone, siltstone, and fine-grained sandstone exhibiting cyclic transitions between lithologies. Figure 8 illustrates the variety of lithologies and cyclic nature of interbedding of lithologies. Dolostone beds range in thickness from 1 cm up to 0.5 m thick and are occasionally silty with some

evidence of graded bedding and cross bedding. Thin beds containing terrigenous sediment may exhibit ripple cross lamination. Some beds appear bioturbated. Dolostone beds have no apparent stromatolites, mudcracks, rip up clasts, or other shallow water features, however Lowe (personal communication, 2015) reported finding cryptalgal structures in thin section. This lithofacies is located in the middle of the Atwood Farm section and is associated with Lithofacies 4. This lithofacies yielded specimens of *Ehmaniella* trilobites (Landing *et al.* 2009).

The carbonate sediment of Lithofacies 2 is interpreted to be the result of biomineralization from calcareous algae. This lithofacies is interpreted to record clear water bio-

genic carbonate deposition in a setting on the shelf adjacent to fine-grained terrigenous material. The fine grain size of terrigenous sediment implies a relatively low energy setting. The mottled fabric of silty dolostones (Fig. 8E) is interpreted to be the result of homogenization of dolostone-siltstone couplets through bioturbation.

Lithofacies 3: upper to middle shoreface

This lithofacies (Fig. 9) consists of dolostone, poorly-sorted, medium-grained dolomitic sandstone, and arenaceous dolostone exhibiting coarse-tail graded bedding. More arenaceous beds contain either decimeter scale sets of trough cross stratification or stacked centimeter-scale sets of unidirectional and oscillatory rippled cross lamination. Dolostones are interbedded with thin (<3 cm) siltstone and sandstone beds which can be cross laminated.

As with Lithofacies 2, the carbonate sediment of this lithofacies is interpreted to be algal in origin and it is interpreted to record clear water biogenic carbonate

deposited on the shelf when terrigenous sediment supply was limited and possibly introduced by eolian processes. The derivation of siliciclastic material and its segregation into "event beds" is characteristic of a punctuated carbonate/siliciclastic mixing model (Mount 1984).

Graded bedding of any terrigenous sediment is thought to reflect resuspension and settling of sediment from the decelerating current flow. Sets of 3D cross strata are interpreted to represent migrating dune deposits from either/both shoreface currents or post-storm relaxation flows. Sets of cross laminae from both unidirectional and oscillatory flow suggest the close temporal association of both unidirectional bottom currents (longshore or rip) and wave processes.

Lithofacies 4: nearshore bay/estuary

Lithofacies 4 consists of interbedded mudstone with lesser amounts of sandstone, siltstone, and dolostone in heterolithic bedding (Fig. 10). Mudstone beds are red
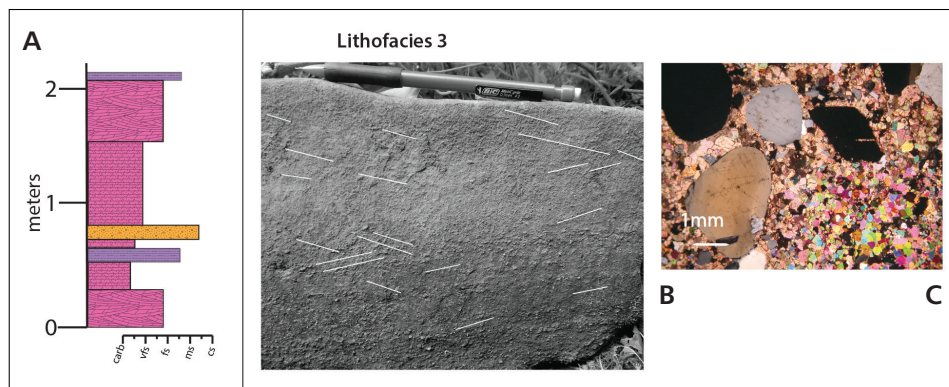
Figure 9. Lithofacies 3. • A – stratigraphic column of L3 from Atwood Farm. • B – field photo of L3 illustrating graded bedding. Thin black lines accentuate inclined foresets of planar cross stratification. Pencil for scale. • C – photomicrograph of L3 showing poorly sorted medium, well rounded sand in an arenaceous dolostone.
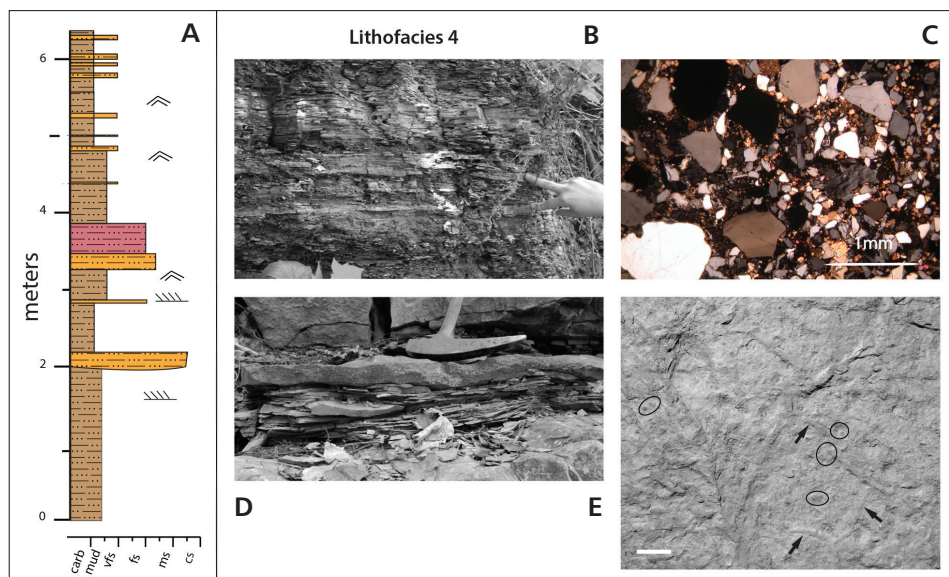
Figure 10. Lithofacies 4. • A – stratigraphic column from Atwood Farm showing the interbedded nature and bed thickness of the mudstone and sandstone. • B – field photo showing mudstone with thin sandstone and dolostone beds that pinch out laterally. • C – photomicrograph of a sandstone under cross-polarized light showing the poorly sorted fine sand grain size. • D – outcrop photo of rippled sandstone in the mudstone at Atwood Farm. Hammer head for scale • E – photograph of *Skolithos* (circled) and *Planolites* (arrow) burrows on a bedding plane from Purdy's Mills. White bar is 1 cm for scale.
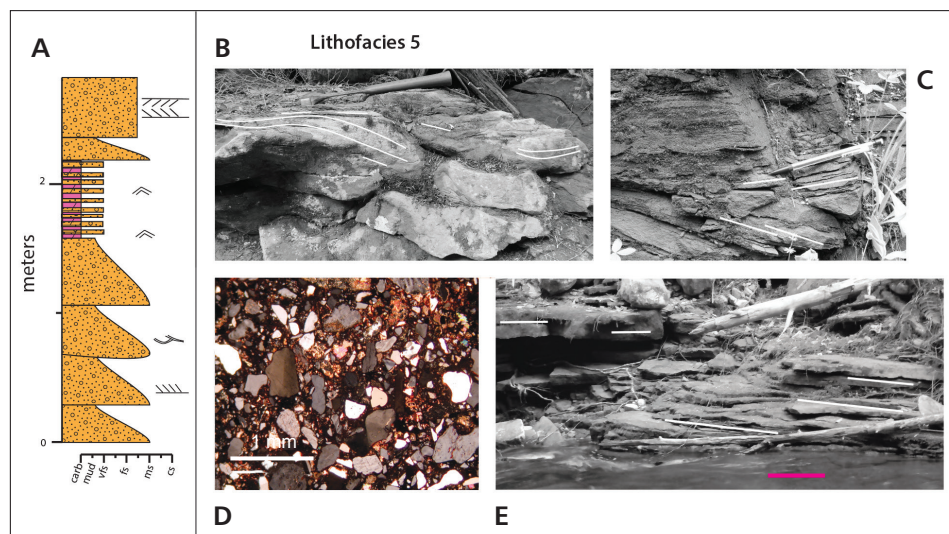
Figure 11. Lithofacies 5. • A – stratigraphic column of L5 in association with dolostones of L2 interbedded with sandstones from Atwood Farm locality. • B – outcrop photograph of swaley cross stratification. Hammer for scale. • C – herringbone cross stratification is not common in the Altona but this example can be seen at the top of Murtaugh Hill. Pencil for scale. • D – thin section photomicrograph of L5 sands under crossed polarized light. Sands are fine to medium grained and are poorly sorted. The highly birefringent grains are dolomite cement. • E – outcrop photograph of low angle planar stratification from the Atwood Farm locality. Thin white lines accentuate dip direction and magnitude of foresets and the black bar in the upper right is 12 cm in length.

and gray in color with mm-scale laminations. Very fine-grained sandstone beds contain 1 cm thick (average) ripple cross lamination. The bases of these beds are characteristically planar and beds are laterally continuous across many meters of outcrop. Other sandstone beds have wavy tops and bases and are more laterally discontinuous. Isolated lenses of sandstone 5–10 cm in length and 103 cm in height occur within the mudstone. The internal structure of these lenses indicates that they consist of uniformly inclined cross laminations. Buff-colored dolostone beds also occur in the mudstone as 1–2 cm thick lenses or laterally discontinuous beds. Landing *et al.* (2009) report occurrences of small *Cruziana* and *Rusophycus* trace fossils from this lithology at Atwood Farm and traces of *Skolithos*, and *Planolites* were identified at the Purdys Mills locality.

Lithofacies 4 is interpreted to record deposition of nearshore mud in a low energy setting, possibly a bay, lagoon or estuary. Deposition of the mudstone could represent lower energy suspended sediment deposition or it could also record deposition from high mud concentrations associated with a discharge event (McCave 1984, Wilson & Schieber 2014). The presence of bioturbation suggests lower sedimentation rates. Interbedded rippled sandstone beds are interpreted to be tempestites and the heterolithic bedding suggests that these were frequent. The deposition of carbonate sediment would require periodic "clear water" conditions, perhaps reflecting the presence of an adjacent shallow marine carbonate environment. The interbedding of clastic and carbonate lithologies in this lithofacies may reflect the

"facies mixing" process of Mount (1984). Landing *et al.* (2009) interpreted the red coloration of mudstones to reflect oxygenation of the water column, a phenomenon which these authors interpreted to reflect a shallow depositional setting.

Lithofacies 5: middle to upper shoreface

This lithofacies (Fig. 11) is a poorly sorted, feldspathic, fine to medium-grained sandstone with variable amounts of dolomite cement containing a variety of sedimentary structures, including planar, trough, hummocky (HCS), swaley (SCS), and herringbone cross stratification. Sets of planar and trough cross stratification range between 15 and 20 cm in thickness. HCS sets are most commonly ~10 cm in thickness with wavelengths of <1 m however a 70 cm thick set with a wavelength of ~10 m is present at the Purdys Mills locality overlying a swale 20 cm deep and one meter wide. Sandstone beds commonly have planar or erosional bases and are laterally discontinuous, pinching out over 10 meters. Horizons exhibiting cross bedding are frequently topped by 2D or 3D weakly asymmetrical ripple cross laminae in sets 1–3 cm in height. Sandstone beds may exhibit coarse-tail grading.

Based on this suite of sedimentary structures, which record both oscillatory and combined flow processes at a range of scales, Lithofacies 5 is interpreted to represent sediment that accumulated on a wave-dominated shoreface that was periodically inundated by storms. Sets of planar cross stratified sandstone are interpreted to represent

large migrating bars under primarily unidirectional flows under normal fair-weather conditions. Such features are common on the shoreface as a result of longshore and onshore currents (Clifton *et al*. 1979). Sets of 3D cross strata are interpreted to represent migrating dune deposits from either/both rip currents or post-storm relaxation flows. Sets of cross laminae from both unidirectional and oscillatory flow suggest the close temporal association of both unidirectional bottom currents (longshore or rip) and wave processes. The presence of HCS suggests deposition from high energy conditions of either pure oscillatory flow or oscillatory-dominated combined flow conditions (Dott & Bourgeois 1982, Harms *et al*. 1982, Arnott & Southard 1990, Dumas *et al*. 2005). Swaley cross stratification is a bedform that is more indicative of storm and post-storm conditions (Lecki & Walker 1982), which pass vertically into either ripple cross lamination sets or 3D trough cross beds with erosional bases; such features are interpreted to record deposition from either/both rip currents or post-storm relaxation flows on the upper or middle shoreface waning flow following storm conditions (Dumas *et al.* 2005). Flows of this type have been identified by Swift *et al*. (1986) on the Atlantic shelf following storms, where cyclonic flow drives water landward, followed by pressure gradients that drive a bottom return (downshelf) flow. Paleoflow data from this lithofacies (Figs 4, 5) range from SW to NW and such variation can be the result of variation in storm wave energy and variability in wave approach and bottom flow currents.

As noted by Dumas *et al*. (2005), combined flow conditions can be found over a broad range of environments and thus its presence is more indicative of flow conditions than environmental setting. Likewise, 2D and 3D upward bundling ripples are interpreted to represent aggrading bedforms that form in oscillatory flows, a minor unidirectional flow component, and a consistent sediment supply (de Raff *et al*.1977, Harms *et al*. 1982). Graded bedding is interpreted to reflect resuspension and settling of sediment from the decelerating flow of currents.

Lithofacies 6: middle to upper shoreface

Lithofacies 6 (Fig. 12), the most common lithology in the Altona Formation, is a very fine to medium-grained moderately well-sorted sandstone with variable amounts of dolomite cement. Cross laminations, both form concordant and form discordant, are characteristic of this lithofacies. Individual sets range from less than 1 cm in height to 3 cm with wavelengths up to 10 cm. As seen in Fig. 12B, the internal structure of a ripple with a symmetrical profile often contains mm-scale laminations produced from unidirectional flow, a feature that is characteristic of "combined flow" of unidirectional and oscillatory motion. Also common are stacked bidirectional ripple cross laminations ("upward bundling ripples" of de Raff *et al*. 1977). The thickness of beds containing rippled fine-grained sandstone can be up to 50 cm in thickness but this can change laterally (thins) over tens of meters of outcrop. This lithofacies is associated with the cross bedded sandstones of Lithofacies 5 (Fig. 11).

The combination of fine to medium-sand grain size, moderate to good sorting and abundant cross laminations indicates that this lithofacies records bedload deposition on the middle to upper shoreface from migrating 2D and 3D ripples which are often subsequently be reworked by oscillatory wave motion.

Facies Model

Construction of a facies model for the Altona Formation takes into account several features: (1) the stratigraphic occurrence of the unit above Precambrian basement; (2) an abundance of wave-generated sedimentary structures; (3) mixed siliciclastic and carbonate lithologies; (4) the presence of marine ichnofacies and trilobite fragments; and (5) sedimentary structures that record storm-influenced sedimentation. The absence of evidence of subaerial exposure, such as mudcracks, and the relative paucity of tidally-influenced structures such as herringbone cross stratification. While paleocurrent data (Figs 4, 5) indicates bipolar and multi-directional flow often associated with tidal processes (Yang *et al.* 2005 and references therein), these flow directions would also be expected from fairweather and post-storm flow conditions. For these reasons a tidal-flat interpretation for the Altona Formation is rejected.

Based on grain sizes, sedimentary structures and stratigraphic occurrence the six lithofacies of the Altona Formation are interpreted to have formed on a marine shelf (Fig. 13). Except for the basal horizons (L1), interpreted to be sheetflood deposits of sediment shed off Precambrian basement, the remaining lithofacies were deposited on the nearshore, shoreface, and offshore portions of a shelf that experienced episodic discharge from sheetflow or ephemeral streams and deposition from wind-blown sand. The dominance of episodic "flashy" discharge onto the shelf is also supported by climate models for the early Cambrian (Boucot *et al.* 2013) which indicate that the Laurentian margin lay within the sub-equatorial arid belt. Arid conditions would inhibit creation and maintenance of stable fluvial systems that could provide more continuous clastic input to the shelf. The preponderance of sedimentary structures indicates that clastic sediment was reworked by wave and current processes. The sedimentary structures present in dolostone horizons suggests that some carbonate sediment

Figure 12. Lithofacies 6. • A – stratigraphic column showing bed thickness of L6 and their association with beds of L5. • B – field photos of L6 illustration of combined flow ripples above erosional surface. Part of pencil for scale. • C – photomicrograph a L6 under crossed polarized light. This lithofacies is moderately well sorted and is a very fine to medium-grained sand. • D – field photo of a rippled bedding plane at Atwood Farm. • E – photograph of upward bundling cross lamination at McKinney Farm. The black bar in the lower right is 10 cm in length.
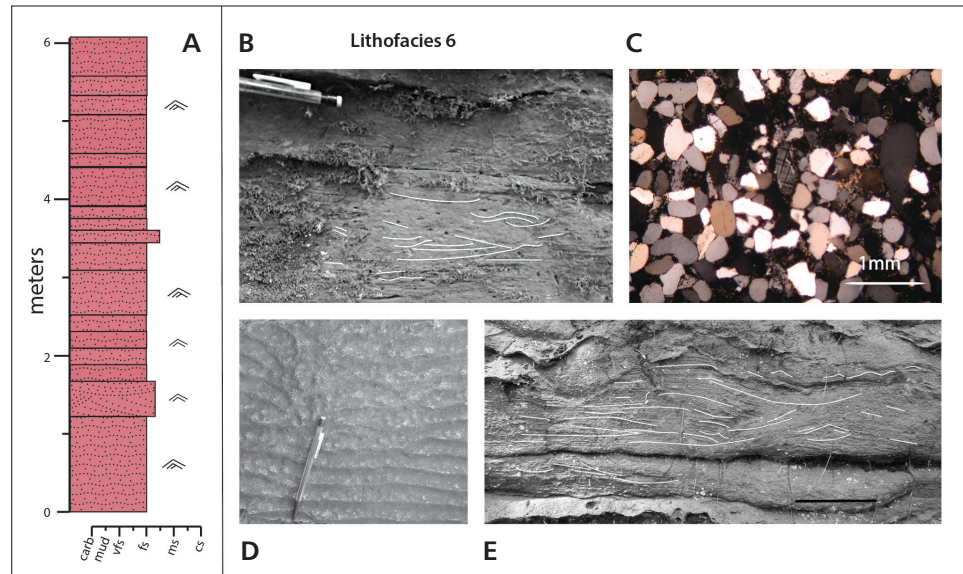
Figure 13. Cartoon illustrating proposed depositional environments for Altona Formation lithofacies. Stream and sheetflow drainage off the Adirondack source area, combined with wind-transported sediment, is deposited in a series of shoreface settings. Laterally adjacent to sheetflood deposits fine-grained clastic and carbonate sediment could accumulate. Further offshore waves rework sediment producing a variety of ripples, dunes and bars.
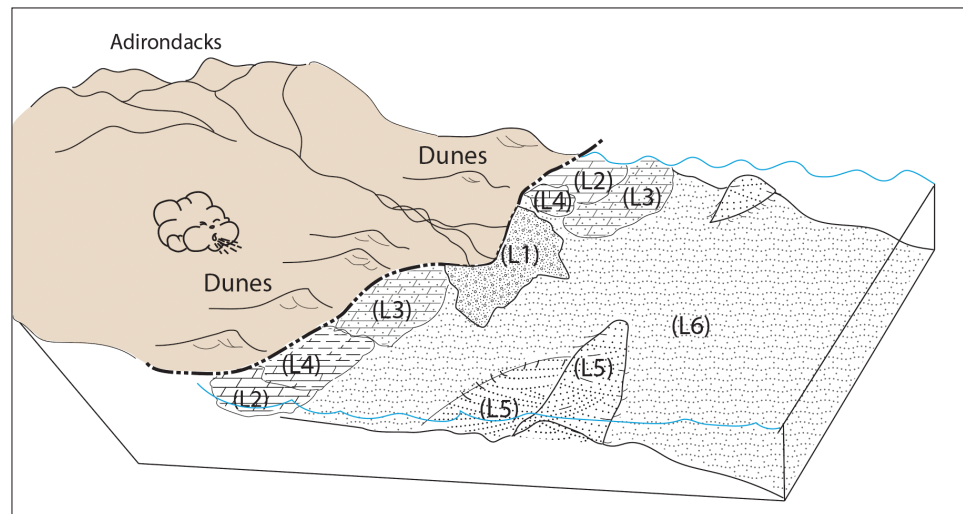

did accumulate in a nearshore setting, which implies that it was spatially segregated from siliciclastic input. Mixing of carbonate and clastic sediment occurred via the punctuated and facies mixing models of Mount (1984). There are several modern analogues for the proposed shoreline model, including Puerto Rico (Pilkey *et al.* 1988), where carbonate sediment accumulates spatially removed from a terrigenous point source and clastic and carbonate mixing occurs as a result of storm processes, and the Brazilian shelf, where Testa & Bosence (1998) described a mixed deposition on a coastal ramp where a combination of clastic sediment supply, fluctuating sea level and ocean hydrodynamics spatially segregate sediment types. Because the distribution of facies on modern shelves reflects the interplay between sediment supply and dynamic Quaternary glacio-eustatic sea level changes, like the modern example described by Testa & Bosence (ibid), we would expect the spatial distribution

of environments to change over time as both sediment and sea level reach equilibrium.

Cyclicity and vertical successions

Outcrop

The abundance of covered intervals in the Altona outcrops makes the identification of cyclicity in outcrops difficult but one common occurrence is shown in Fig. 14. Here, cross stratified fine to medium-grained sandstones of Lithofacies 5 (white bar 1) are overlain by fine to very fine-grained cross laminated sandstones of Lithofacies 6 (white bar 2) which are overlain by an erosional surface (base of white bar 3) overlain by another cross stratified unit (Lithofacies 5). Based on the environmental interpretations presented earlier, these cycles are
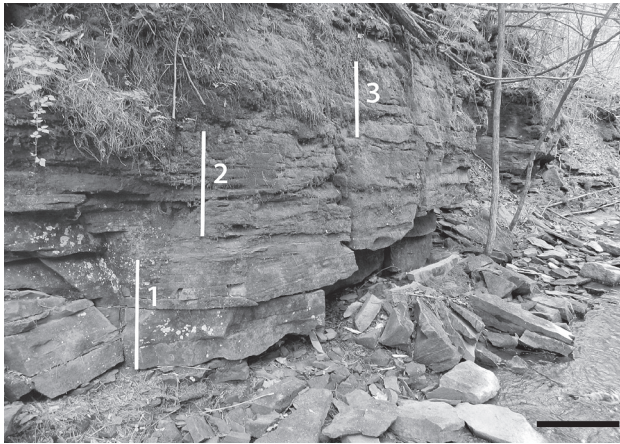
Figure 14. Cycles in the Altona. Numbers 1, 2 and 3 bracket parts of a cycle; 1 is Lithofacies 5 succeeded up (2) section by Lithofacies 6. There is an erosional contact with interval 3, Lithofacies 5. The black bar is 50 cm for scale.

interpreted to be autocyclic in origin, reflecting storm generated inner shelf sand bar migration followed by fair-weather wave reworked shoreface sands.

Gamma Ray Log Analysis

Farrell *et al.* (2013) presents gamma-ray log response patterns from four shelves to shoreface stratigraphies of Cretaceous to Holocene age. They demonstrated that gamma-ray data can complement facies analysis, descriptive field data and sea level history, making it possible to identify characteristic gamma-ray signatures for portions of a shelf to shoreface shallowing-upwards sequences. Such sequences accompany the transition from transgressive systems tract (TST) to highstand systems tract (HST) conditions (systems tract terminology after Catuneanu 2002, Catuneanu *et al.* 2009). Bathymetry and associated hydrodynamic conditions across the shelf to shoreface produce variation in grain size, and gamma-ray emissions are controlled by the concentration of radiogenic elements in compositions (*e.g.*, clay minerals) and grain size [hydraulic sorting of accessory minerals (Trask & Hand 1985)]. Using these relationships, Farrell *et al.* (2013, Fig. 14) summarized the characteristic gamma-ray patterns produced for the upper shoreface, lower shoreface and open shelf environments in a Holocene well log, where sea level history is well known, and used this information to interpret the gamma-ray log patterns in older examples. We use a similar approach in this study.

A condensed, smoothed record of the gamma-ray log data from a well through the Altona Formation and reaching Precambrian basement was presented in Landing *et al.* (2009, Fig. 8) and compared to the stratigraphy they described at Atwood Farm. The data they presented clearly identifies the low gamma-ray value horizons in

the stratigraphy that they interpreted as characteristic of dolostone and arenaceous dolostone beds. However, at the level of resolution they presented no further trends in the data set were evident. The Atwood Farm exposure also does not reach to the base of the unit. In order to determine if the characteristic gamma-ray patterns of shelf and shoreface environments could be identified in the Altona well, and if statistical analysis could reveal cycles, raw gamma-ray log data for the same Altona well 1-02 was processed at a higher level of resolution. The data was statistically analyzed to determine if patterns were identifiable and if so, whether or not the patterns reveal trends or cycles through the Altona stratigraphy. Maguire *et al.* (2018) contains the full gamma emission data set as well as a Mortlet wave analysis of this data, with results which indicate that meter-scale cyclicity is present but poorly developed throughout the entirety of the Altona Formation. Longer period cycles (tens of meters) are present in the lower half of the unit. A portion of their analysis is presented in Figs 15, 16.

In Fig. 15 gamma emission data is plotted at a level of resolution that clearly indicates that the well 1-02 stratigraphy can be viewed as consisting of three intervals with distinct maximum and minimum gamma values and cycle periods: 126 to 107 meters below the well top (0 to 20 meters above the base of the Altona composite stratigraphic section), 107 meters to 87 meters depth in the well (20 meters in the section to 41 meters in the composite section), and above 41 meters (upper Altona and the base of the Ausable Formation). Of these, the second interval is the most distinctly different from other portions of the Altona stratigraphy.

Figure 16 shows gamma emission data through well 1-02 at a much higher level of resolution plotted against the Altona Formation composite stratigraphic section and biostratigraphic data (from Landing *et al.* 2009). The three intervals identified in Fig. 15 are also shown as are two possible sequence stratigraphy interpretations of the data (discussed below). Within Interval 1, the basal 4 meters of Altona stratigraphy (red arrow 1) is represented by the gradually increasing gamma values that records the onlap of Precambrian basement during transgression. This is followed up section with the "sawtooth" gamma emission pattern that Farrell *et al.* (2013) described as characteristic of shoreface successions. Within this "Interval 2" of the stratigraphy, two portions of the data set (red arrows 2 and 3) clearly show examples of cycles produced by the transition from more carbonate-rich sediment with low gamma values (dolostones and arenaceous dolostones) to higher gamma values from carbonate poor (arkosic sandstones), or coarsening-upwards, on the shelf. Cycles between the sand bars (Lithofacies 5) and wave rippled sands (Lithofacies 6) such as those illustrated in Fig. 14 are too small to be seen at this scale. At the top of Interval 2

Figure 15. Cyclic gamma emission pattern in the Altona and lower Ausable Formations. The data falls into three intervals. See text and Fig. 16 for discussion.
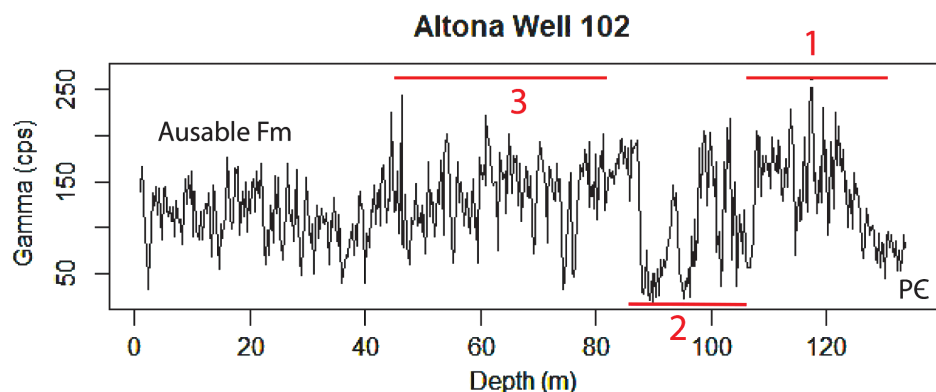
the 11 meter thick section in the well between 97 to 88 meters (31 to 42 meters in the composite section) is characterized by low gamma values which we interpret to record the most dolomitic portion of the Altona stratigraphy (Lithofacies 2). In Interval 3, the gradual decrease in gamma values from 46 to 52 meters and above 76 meters (red arrows 4 and 5) is interpreted to record increasing carbonate content in the sandstones. The uppermost cycle (5), representing increasing carbonate cement content, abruptly terminates at the contact with the overlying non-marine Ausable Formation.

We believe that the interpretation of the intervals of characteristic gamma values (Fig. 15) and the details of cycles (Fig. 16) can best be interpreted by applying the concepts of sequence stratigraphy. In sequence stratigraphy Posamentier & Vail (1988) suggested that packages of sediment termed "systems tracts" are associated with variations in sea level and sediment supply and which are bounded by surfaces of non-deposition or erosion termed sequence boundaries.

Applying these concepts, Fig. 16 illustrates two possible sequence stratigraphy interpretations (A and B) of the Altona stratigraphy. In both A and B, the basal 4 meters of stratigraphy records the onlap of Precambrian basement during transgression as part of a Transgressive Systems Tract (TST). This is followed up section with the "sawtooth" gamma emission pattern that is the characteristic of shoreface successions that Farrell *et al.* (2013) recognized as characteristic of the Highstand Systems Tract (HST). Carbonate-rich horizons, such as those seen between 60 and 72 meters in the composite section (Fig. 15), would occur above marine flooding surfaces (representing rapid sea level rise) with clastic deposition subsequently accumulating in the accommodation space produced by the rise. The low gamma values that characterize Interval 2 (31 to 42 meters in the composite section) we interpret to record the most dolostone-rich portion of the Altona stratigraphy and in sequence stratigraphy this would be associated with maximum sea level highstand and the trapping of clastic sediment in the hinterland. Differences between the two

interpretations begin with this carbonate-rich interval. In option A, the carbonate strata between 31 and 42 meters represent a change in the rate of sea level rise; with clastics temporarily unable to enter the shoreline system, and a condensed sequence produced. Above 42 meters in the stratigraphy the return to higher gamma values with the "sawtooth" pattern of the shoreface interpreted to represent the re-equilibration of sea level and sediment supply and a resumption of clastic deposition in the late stage of highstand. An alternative interpretation (option B) suggests that the highstand recorded between 31 and 42 meters includes the transgressive surface overlain by a thin transgressive interval between 40 and 41meters in the stratigraphy, represented by rapidly increasing gamma values. As with interpretation A, above 42 meters the gamma pattern is characteristic of shoreline stratigraphy and above 76 meters a downward trend in gamma values begins as the contact with the overlying non-marine Ausable Formation, is approached. The Ausable, non-marine sandstone, would represent deposition in a Falling Stage Systems Tract (FSST) as sea level fell and broad unconformities are generated across the shelf. The contact of the Altona with the Ausable would be a sequence boundary and it is recognized in the gamma log by the rapid transition to shorter wavelength, higher amplitude variation in gamma values.

Biostratigraphic data does not favor one interpretation over the other. Figure 16 shows the stratigraphic distribution of trilobite material collected from the Altona by Landing *et al.* (2009) against the Altona composite stratigraphic section. Collections of *Ehmaniella* spp. are found in the upper third of the unit, above the carbonate-rich Interval 2. If *Ehmaniella* is characteristically associated with a middle Cambrian (mid-Miaolingian) trilobite fauna, then the upper third of the Altona is significantly younger than the *Olenellid*-bearing (Cambrian Series 2, Stage 4) lower Altona strata. While these findings do not require an unconformity in the Altona stratigraphy it is plausible that the carbonate-rich Interval 2 is related either to the production of a condensed interval or the transgressive surface.

Altona Composite Section with Gamma Log
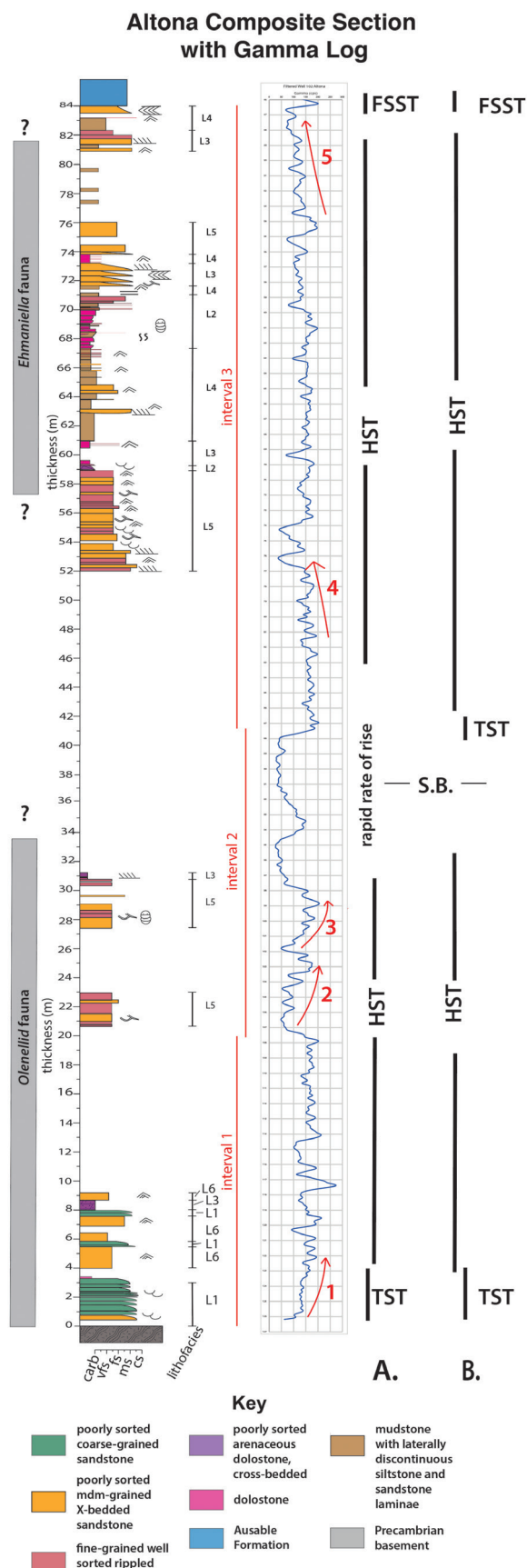
Identification of systems tracts and sequence boundaries in Potsdam Group strata is not a novel approach. In order to transcend some of the confusion regarding regional differences in stratigraphic terminology Lowe *et al.* (2017) applied sequence stratigraphy concepts to the study of the Potsdam Group in northern New York, southern Quebec and southern Ontario. Lowe *et al.* (2017) identified strata as "allounits" based on their position between sequence boundaries. These authors interpreted the Altona Formation as "Allounit 1." The present study suggests that, based on age differences between the base and top of the unit and the identification of intervals or packages of strata with distinctly different gamma emission patterns in the stratigraphy, "Allounit 1" of Lowe *et al.* (2017) can be subdivided into two allounits consisting of lower Altona (0 to 42 meters) and upper Altona (42 to 76 meters) with the overlying Ausable Formation representing a third.

Compositional Analysis of Sandstones

Altona Formation sandstones are arkose to quartz arenite in composition with variable amounts of dolomitic cement. As described in each lithofacies, several other compositions are present in the unit, including arenaceous dolostones, dolostone, and mudstone. Of the entire measured section 63% is sandstone (including dolomitic sandstone), 21% is dolostone (including arenaceous dolostone) and 16% is mudstone (with intercalated sandstone and siltstone). Table 2 and Fig. 17 summarize compositional data of the sandstones that were point counted. Using Folk's (2000) sandstone classification of the sandstones, 70% are arkose, 20% subarkose and 10% are quartz arenite.

Figure 16. Composite stratigraphic column of the Altona Formation with smoothed gamma log and interpreted sequence stratigraphy. The basal 4 meters of section show the rising gamma emissions associated with coarsening-upwards of the Transgressive Systems Tract. This is followed up section with a "sawtooth" pattern that is characteristic of shoreface successions in the Highstand Systems Tract (HST) however two intervals (red arrows 2–3) represent cycles produced by the transition from more carbonate-rich sediment (dolostones and arenaceous dolostones) to carbonate poor (arkosic sandstones). Low gamma values between 31 and 42 meters record the most dolomitic portion of the Altona stratigraphy associated with sea level highstand and the trapping of clastic sediment in the hinterland. Above 42 meters the peak in gamma values suggests that sea level and sediment supply has equilibrated and returned to clastic deposition. Red arrow 4 represents another "sawtooth" pattern of the shoreface HST, however above 76 meters begins the downward trend in gamma values as the contact with the overlying non-marine Ausable Formation is approached (Falling Stage Systems Tract FSST). The contact is recognized in the gamma log by the rapid transition to shorter wavelength, higher amplitude variation in gamma values.

Quartz grains are monocrystalline to polycrystalline rounded to sub-rounded with quartz overgrowths. Detrital feldspar grains are both potassium rich and calcium rich and many show perthitic textures. Differences in luminescence reveal the presence of authigenic feldspar grains and overgrowths. Lithic fragments have been identified and are primarily sedimentary (dolostone, mudstone and very fine-grained siltstone) in composition. Dolostones are composed of dolomite grains which are non-planar, unimodal, and void-filling, (terminology after Sibley & Gregg 1987). The XRD analysis on mudstones indicates that they are composed primarily of very fine silt-sized grains of orthoclase and muscovite clay.

Accessory minerals represent 1–5% abundance of detrital grains and the Altona accessory mineral suite is composed of primarily apatite, ilmenite, rutile, and zircon (Tab. 2).

Origin of the red color

As noted by Palmer & James (1979) many of the regressive sandstones in the northern Appalachians of late lower Cambrian age are red in color (*e.g.*, Monkton and Rome Formations). Using SEM backscatter imaging and EDS analysis the origin of the red color in the Altona was found to be the result of the formation of iron oxide-rich aluminosilicate clays by the early diagenesis of the iron-rich accessory minerals (ilmenite, magnetite) in the unit (Fig. 18). These iron-rich clays are disseminated through the sandstones in early kaolinite cement interlayered with early carbonate cement (which is now dolomite). While many detrital feldspar grains appear fresh, others have undergone early diagenesis to produce *in situ* aluminiosilicate clays. Iron-oxides were incorporated into these early clay and carbonate cements.

Provenance Analysis

Dickinson & Suczek (1979) pioneered the approach of plotting proportions of detrital framework grains to determine provenance types which are in turn, influenced by plate tectonic settings. An excellent review paper by Johnsson (1993) cautioned that the various controls on sandstone composition, such as recycling, weathering intensity and duration, transport processes and diagenesis, can all complicate the provenance interpretation of detrital modes. Paleoclimate models for the early Cambrian (Boucot *et al.* 2013) suggest that the Iapetan margin sat near the 30° +/− the equator arid belt and in this climate the dominance of physical over chemical weathering would explain the fresh state of the feldspars in the Altona sandstones. Based on the textural immaturity of sand grains, which suggests limited transport and physical
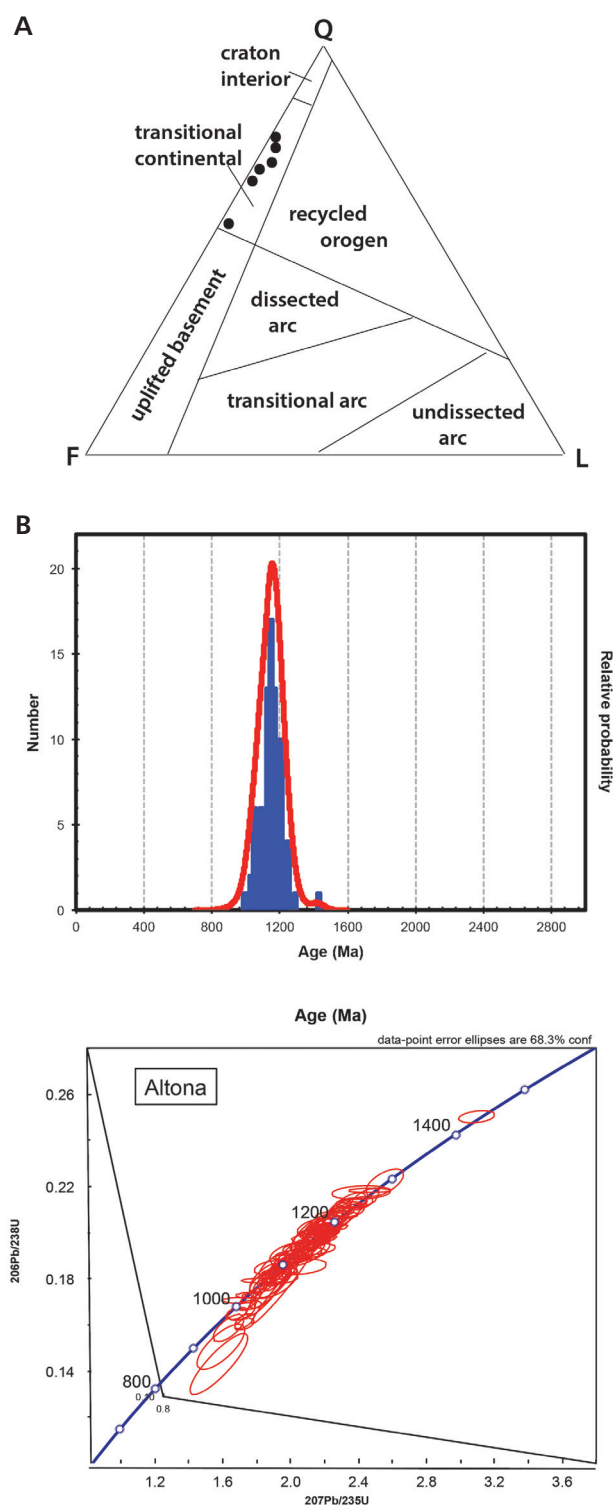
Figure 17. A – Altona modal analysis data plotted on a QFL ternary diagram (after Dickinson & Suczek 1979). See text for discussion. • B – U-Pb detrital zircon relative abundance age spectrum from cores of zircons from the Altona Formation. This shows a single age spectrum indicating a single source of sediment of the same age between 1000 to 1300 Ma with a peak centered at 1160 Ma. Data from Chiarenzelli *et al.* (2010).

Table 2. Summary of petrography.

sandstone composition	percent of samples
arkose	70.00
subarkose	20.00
quartz arenite	10.00

Abbreviations: n – number of samples; Q – quartz; F – feldspars; L – lithic fragments; A – apatite; I – ilmenite; M – magnetite; R – rutile; Z – zircon.

sample	lithofacies	mean grain size	n	QnFnLn	accessories
092013-4	1	very fine sand	309	$Q_{19}F_{81}$	A, M, R, I
AF13-22	1	mdm sand	165	$Q_{92}F_8$	
AF13-23	1	fine sand	322	$Q_{36}F_{63}L_1$	A, R, M
AF13-14	2	coarse sand	202	$Q_{77}F_{22}L_1$	I, A, R
AF13-13	2	fine sand	325	$Q_{69}F_{31}$	A, R, M
MT 1-7	3	dol (mdm sand)	260	$Q_{95}F_5$	I, R, Z
AF 13-2	3	dol (mdm sand)	230	Q_{100}	
AF13-18	4	fine sand	312	$Q_{71}F_{28}L_1$	I, A, Z
AF13-19	4	fine sand	306	$Q_{69}F_{31}$	A, I, R, Z
AF13-15	5	fine sand	319	$Q_{56}F_{44}$	A, I, R, M
AF13-18	6	mdm sand	312	$Q_{73}F_{25}L_2$	I, R, Z
092013-1	6	mdm sand	330	$Q_{62}F_{38}$	R, I, A

weathering intensity, and the abundance of more labile components, such as feldspar and dolostone lithics, which infer little to moderate chemical weathering, the major framework constituents of quartz, feldspar and lithic fragments were interpreted for provenance determination. As shown in Fig. 17, the sandstone compositions all plot in the "transitional continental" QFL field, a regime that describes sediment derived from fault-bounded uplifted basement such as offset segments along a rifted continental margin. The presence of low quantities of sedimentary lithics suggests the erosion of sedimentary cover on basement or possibly intraformational-derived material. The abundance of feldspar (potassium and plagioclase), the presence of both monocrystalline and polycrystalline quartz, and accessory minerals such as apatite and muscovite mica all suggest a granitic/gneissic source.

The geology of Precambrian basement of northern New York, thought to be the provenance of the Altona Formation, is complex, consisting of a wide range of metamorphic rocks that formed between 1350 and 1000 Ma in the Grenville Cycle of McLelland *et al.* (1996). Detrital zircon geochronology of the Altona Formation west of this study area by Chiarenzelli *et al.* (2010) yielded a symmetric unimodal U-Pb peak between the ages 1000–1300 Ma centered at 1160 Ma (Fig. 10B). This age is compatible with that of many metamorphic rocks in the Adirondacks, including the associated mangerite-charnockite-granite rocks (AMCG suite), which have

yielded intrusion ages of 1158 +/−5 (McLelland *et al.* 2001). Although its perthitic feldspar-ilmentite-magnetite-apatite rich mineral suite matches that of the Altona Formation, the Lyon Mountain granite, in close geographic proximity to present day exposures of the Altona, is too young to be the its source, having yielded an age of 1040 Ma (Valley *et al.* 2007).

Discussion – regional implications

A goal of this study was to combine sea level history for the Altona Formation with biostratigraphic data in order to refine correlations of the Altona Formation to other Cambrian strata along the Iapetus margin and to use such correlations to shed light on the paleogeography of the margin.

As seen in Fig. 2, biostratigraphic relationships indicate that the Altona is at least partially correlative to the Monkton Quartzite in western Vermont. The Monkton is a non-marine to tidally-influenced shallow marine prograding sandstone (Rahmanian 1981, Goldberg & Mehrtens 1998, Maguire *et al.* 2018). But, unlike the Altona, which onlaps Precambrian basement, the Monkton is one unit within a shelf sequence many hundreds of meters thick; it overlies carbonates of the *Salterella*-bearing lower Cambrian Dunham Dolostone which in turn overlies the poorly fossiliferous Cheshire Quartzite. Locally, the basal Monkton consists of sandstones and
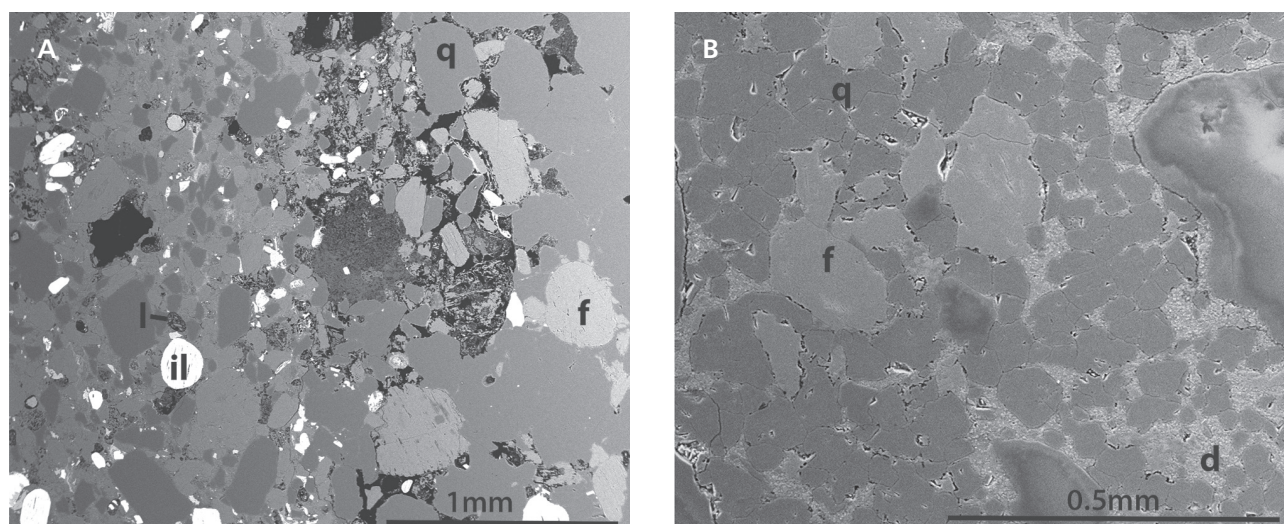
Figure 18. SEM backscatter images of two Altona thin sections. • A – quartz (q), feldspar (f), lithic fragments (l) and accessory minerals (il = ilmenite) in a sample of Lithofacies 1. • B – quartz and feldspar grains are sitting in a cement of intergrown carbonate and iron-rich clay, which under BSE is bright white; the intergrown fabric produces a "salt and pepper" luminescence; Lithofacies 4. Abbreviation: d – dolomite.

pebble conglomerates which pass upward and into more than 300 meters of mixed siliciclastic and carbonate facies, all of which were deposited during the Sauk II transgression (Goldberg & Mehrtens 1998, Maguire *et al.* 2019). Thermal subsidence along the Iapetus margin produced accommodation space for this thick package of sediment and siliciclastic sediment supply kept pace or exceeded sea level, triggering basinward progradation of tidally influenced facies. Maguire *et al.* (2019) have interpreted the upward thinning in parasequence thickness as recording the loss of accommodation space as the rate of sea level rise slowed through Monkton deposition.

The Monkton Formation pinches out to the north on the edge of the Franklin Basin where the shales and conglomerate/breccia horizons of the Parker Slate accumulated. Analysis of the trilobite fauna within these rocks by Shaw (1958) and Palmer & Holland (1971) documented a significant disconformity within the basinal sequence with the lowest horizons of the Parker Slate containing a lower Cambrian (Series 2, Stage 4) *Olenellus* fauna while upper horizons contain trilobites of the middle Cambrian (Miolingian) *Bolaspidella* Zone. The Monkton Formation itself contains fragmental *Olenellid* material (Palmer & James 1979, Palmer personal communication). Palmer & James (1979) suggested that this unconformity represented an Iapetus-wide event which they termed the Hawke Bay Event. According to Palmer & James (1979) the disconformity within the Parker Slate corresponds to regressive sandstone deposition (the Monkton Formation) on the shelf.

Using sequence stratigraphy, we interpret the onlap of Precambrian basement in New York and deposition of the lower Altona Formation as having occurred during the latest, slowest stage of rising sea level that Maguire *et al.*

(2019) documented in the upper horizons of the Monkton Formation in western Vermont. Onlap of the Vermont shelf and deposition of the bulk of the Monkton Formation occurred earlier than in New York and the decreasing rate at which accommodation space formed in Vermont would be represented in New York by the basal 30 meters of the Altona Formation.

Karlstrom *et al.* (2018) presented detrital zircon dates that they used to calibrate the timing of Sauk II transgression in the Cambrian Tonto Group of the Grand Canyon (505–500 Ma). Applying the same technique to the fauna from the Potsdam Group in New York, they suggested that these strata represented also represent a short interval of time (510–505 Ma) for onlap of this portion of the eastern margin of Laurentia. The much thicker Cambrian stratigraphy in western Vermont indicates that regional variation is significant. Several hundred meters of pre-Monkton Formation stratigraphy (Dunham Dolostone and Cheshire Quartzite) suggests that Sauk I sediments were either not deposited in eastern New York, or were deposited and removed prior to deposition of the Altona Formation.

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Appendix. Locality information in Universal Transverse Mercator (UTM) coordinates.

Atwood Farm, located in West Chazy on the Atwood Road along the banks of the Little Chazy River (UTM Zone 18: 0613737 E, 4964653 N). The McKinney Farm site is located along the Military Turnpike Road (Rt. 190) from south of the road (UTM Zone 18: 0611758 E, 4962606 N), in drainage ditches along Rt. 190, and continuing up through the farm field on the side of Murtagh Hill. The lower Murtaugh Hill section is a stream bed exposure on the Palmer Family Maple Sugar Farm off Route 190 (UTM Zone 18: 0611739 E, 4961998 N). The upper Murtagh Hill site is located 1.5 miles up the Murtagh Hill Road off of Route 190 in a drainage ditch on the south side of the road (UTM Zone 18: 0610762 E, 4960784 N). The Purdy Mills locality is in Jericho in a stream bank off of Rand Hill Road (UTM Zone 18: 0605143 E, 4962508 N).