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Epeirogenic transgression near a triple junction: the oldest (latest early–middle Cambrian) marine onlap of cratonic New York and Quebec

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Abstract – The discovery of a fossiliferous interval (Altona Formation, new unit) under the Potsdam Formation requires a new geological synthesis of a large part of the northeast Laurentian craton. Potsdam sandstones can no longer be regarded as the oldest sedimentary unit on the middle Proterozoic Grenville orogen in northern New York and adjacent Quebec and Ontario. The thickest Potsdam sections (to 750 m) in the east Ottawa–Bonnechere aulocogen have been explained by deposition with normal faulting possibly associated with Ediacaran rifting (*c.* 570 Ma) that led to formation of the Iapetus Ocean. However, sparse trilobite faunas show a terminal early Cambrian–middle middle Cambrian age of the Altona, and indicate much later marine transgression (*c.* 510 Ma) of the northeast Laurentian craton. Altona deposition was followed by rapid accumulation of lower Potsdam (Ausable Member) sandstone in the middle–late middle Cambrian. The Altona–Ausable succession is probably conformable. The Altona is a lower transgressive systems tract unit deposited on the inner shelf (sandstone, reddish mudstone, and carbonates) followed by aggradation and the deposition of highstand systems tract, current cross-bedded, in part terrestrial(?), feldspathic Ausable sandstone. Unexpectedly late Altona transgression and rapid Ausable deposition may reflect renewed subsidence in the Ottawa–Bonnechere aulocogen with coeval (terminal early Cambrian) faulting that formed the anoxic Franklin Basin on the Vermont platform. Thus, the oldest cover units on the northeast New York–Quebec craton record late stages in a cooling history near an Ediacaran triple junction defined by the Quebec Reentrant and New York Promontory and the Ottawa–Bonnechere aulocogen.

Keywords: Cambrian, Laurentia, trilobites, sequence stratigraphy, epeirogeny, Potsdam Formation, Altona Formation.

1. Introduction

For 150 years, the sandstone-dominated Potsdam Formation (Emmons, 1838) has been regarded as the oldest sedimentary unit deposited over a large part of the northeast Laurentian craton. In eastern New York and adjacent Quebec and Ontario, the Potsdam rests nonconformably on high-grade metamorphic (granulite-facies) and igneous rocks of the middle Proterozoic Grenville orogen (*c.* 1.0 Ga), and is overlain by the carbonate-rich formations of the Beekmantown Group (Clarke & Schuchert, 1899). The Potsdam records the beginning of a long interval of passive margin deposition on the craton that ended in the Late Ordovician with the onset of the Taconian Orogeny (e.g. Lavoie, Burden & Lebel, 2003; Landing, 2007).

Several questions involving the geological significance of the Potsdam have long remained unanswered. These include the reason(s) for the Potsdam's abrupt thickening in its northeastern outcrop belt in the New York–Quebec border region, as well as the age of the Potsdam's feldspathic, nonfossiliferous, lower interval (Ausable Member) that has been variably assigned to the Ediacaran through late Cambrian in recent reports. Our recognition of a surprisingly thick (about 80 m), fossiliferous, mudstone-dominated, marine-deposited formation under the Potsdam allows the first determination of the age of the lowest Potsdam in the New York–Quebec border region. Our study of this newly recognized and named Altona Formation suggests that rapid subsidence of the Ottawa–Bonnechere aulocogen and accumulation of the thick Potsdam successions in northeast New York and adjacent Quebec were related to dramatic terminal early–middle Cambrian epeirogenic activity on the easternmost platform. Biostratigraphically important trilobites from the new sub-Potsdam unit demonstrate that marine onlap of the Laurentian craton on the south side of the Ottawa–Bonnechere aulocogen occurred late in the Cambrian, and was unrelated to Ediacaran–earliest Cambrian rifting and initial formation of the Iapetus Ocean.

2. Geological setting

The siliciclastic sandstone of the Potsdam Formation does not occur in the folded and thrust sequences of the Appalachian Mountains, where its apparent

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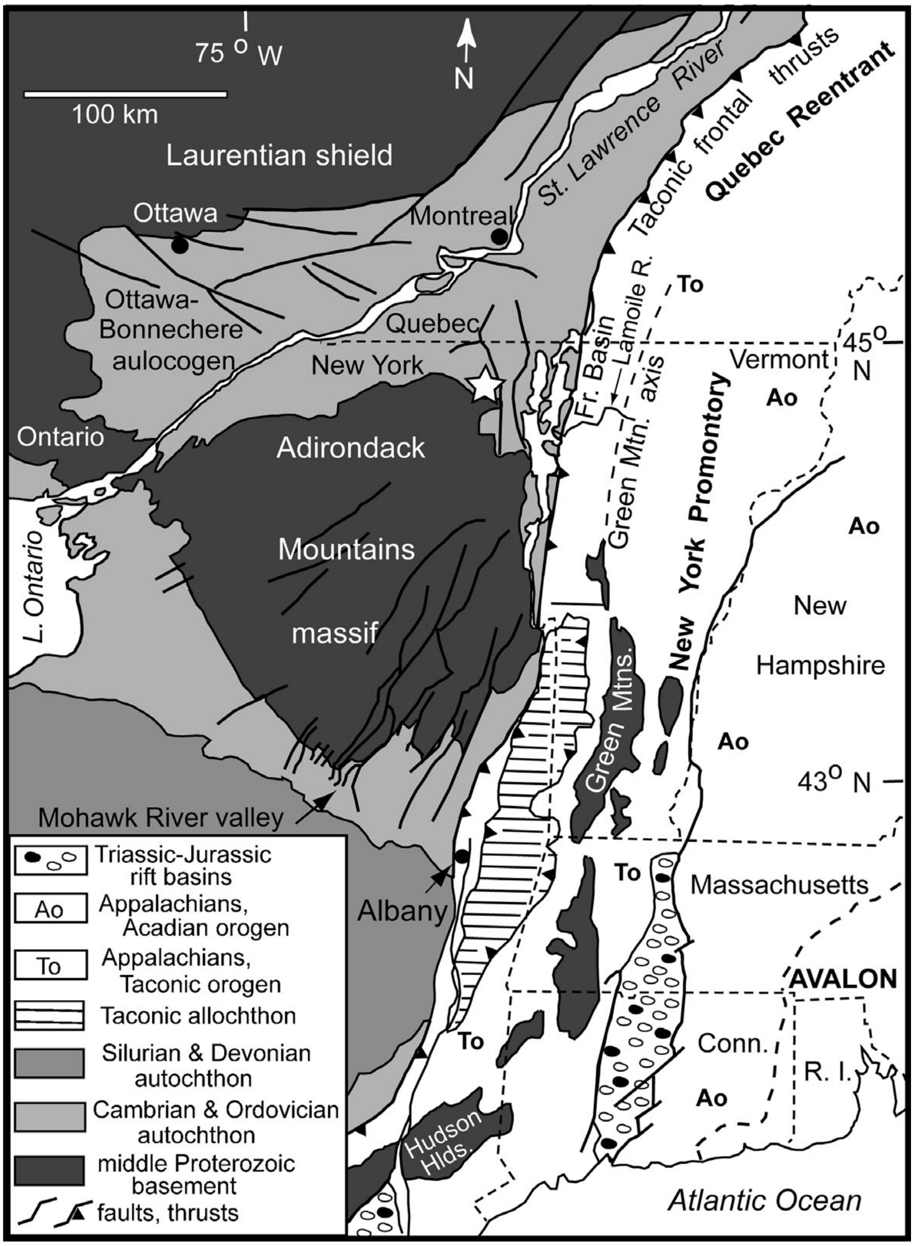

Figure 1. Regional geological map showing location of field area (white star). Abbreviations: Conn. – Connecticut; Fr. Basin – Franklin Basin; R. I. – Rhode Island; Hudson Hlds. – Hudson Highlands. Figure modified from Landing (2007, fig. 1).

correlative is the mixed dolostone and quartz arenite of the nonfossiliferous Danby Formation west of the Green Mountain axis in Vermont (Fig. 1; e.g. Cady, 1945; Landing, 2007, p. 11). The thickest Potsdam sections reach 750 m in thickness, and are limited to a belt that extends from the northeast Adirondack Mountains massif into the subsurface of Quebec southwest of Montreal in the eastern Ottawa–Bonnechere aulocogen (e.g. Clark, 1966; Lewis, 1971). The Ottawa–Bonnechere aulocogen is the failed arm of a triple junction that formed with late Ediacaran rifting (*c.* 570 Ma) of this part of Rodinia. This rifting led to formation of the Iapetus Ocean with extension along the active arms of the Quebec Reentrant and New York Promontory (Kumarapeli & Saull, 1966; Thomas, 1977; Kumarapeli, 1985; Cherichetti, Doolan & Mehrtens, 1998).

The thick Potsdam successions in northeast New York–Quebec consist of two divisions. The lower is a feldspathic, current cross-bedded sandstone unit up to 610 m thick that is thought to represent, at least in part, terrestrial environments. The upper is a quartz arenite-dominated unit (to 150 m thick) with locally abundant marine trace and body fossils (e.g. Walcott, 1912; Clark, 1966, 1972; Fisher, 1968, 1977; Lewis, 1971; Bjerstedt & Erickson, 1989). Further west near Ottawa, Ontario, and south along the eastern and southern margins of the Adirondack Mountains, the Potsdam thins to less than 50 m, or is absent. Where present, only the quartz arenite-dominated unit occurs, as the oldest cover unit on the Grenville (e.g. Wilson, 1946; Fisher, Isachsen & Rickard, 1970; Selleck, 1978; Wolf & Dalrymple, 1984; Dix, Salad Hersi & Nowlan, 2004).

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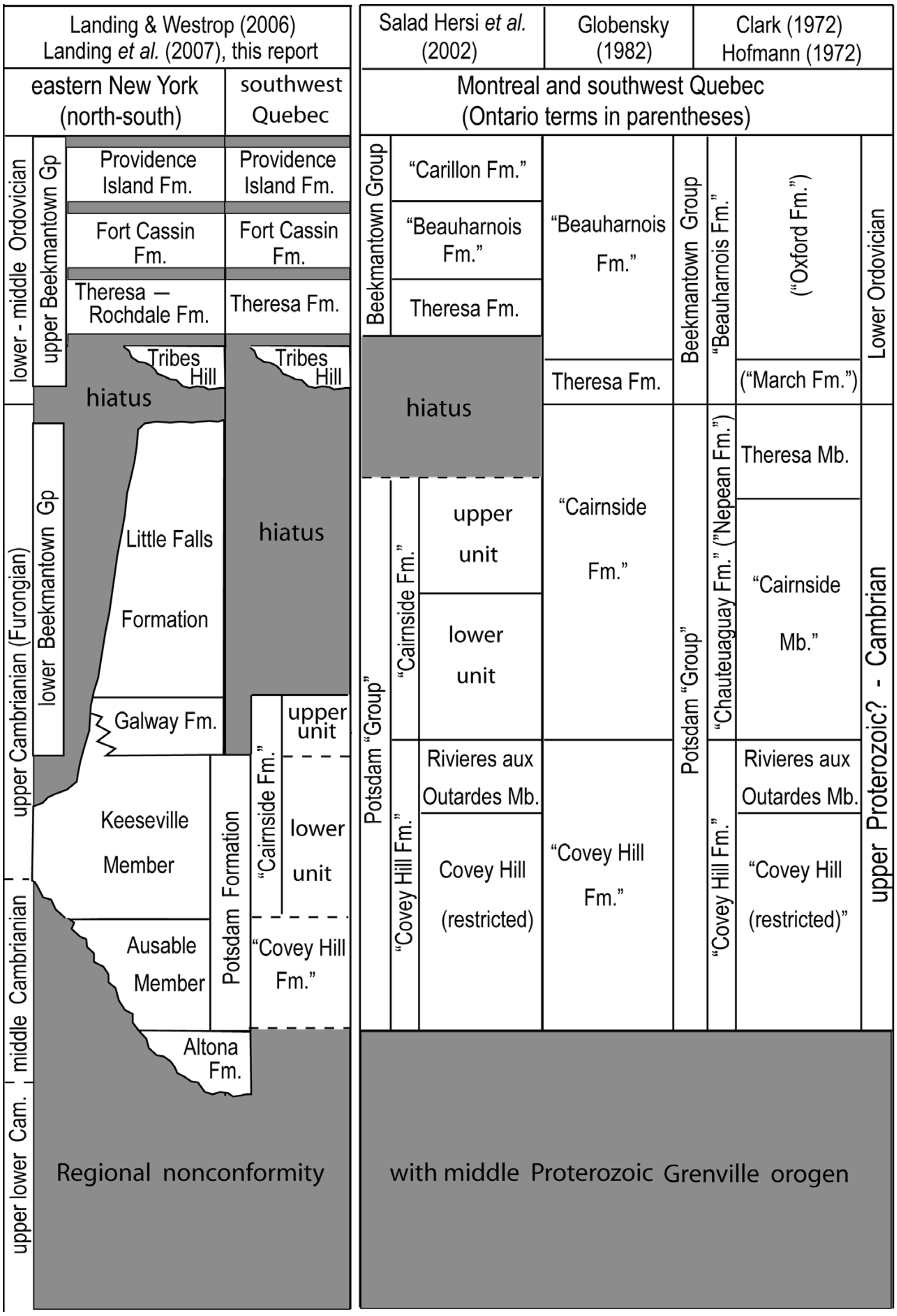

Figure 2. Nomenclature and correlation of Potsdam Formation and associated units.

2.a. Stratigraphic terminology

The oldest stratigraphic designations for the two divisions of the Potsdam are based on the New York sections, and include the Ausable Member (Alling, 1919) for the lower feldspathic sandstones and Keeseville Member (Emmons, 1841) for the quartz arenite unit (Fig. 2; see Fig. 3 for location of Ausable River and Keeseville). A complex stratigraphic nomenclature has developed for Potsdam sandstones, and a number of synonyms exist for parts of the formation in Ontario, Quebec and New York (Appendix 1). The proliferation of synonymous terms for parts of the Potsdam has worked to obscure lithologically comparable units, and clouds the early geological history of the Ottawa–Bonnechere aulocogen.

2.b. Age of lowest Potsdam Formation and geological implications

Terminal middle Cambrian *Crepicephalus* Zone trilobites are known from the lowest Keeseville Member where it rests on the Grenville at the southeast margin

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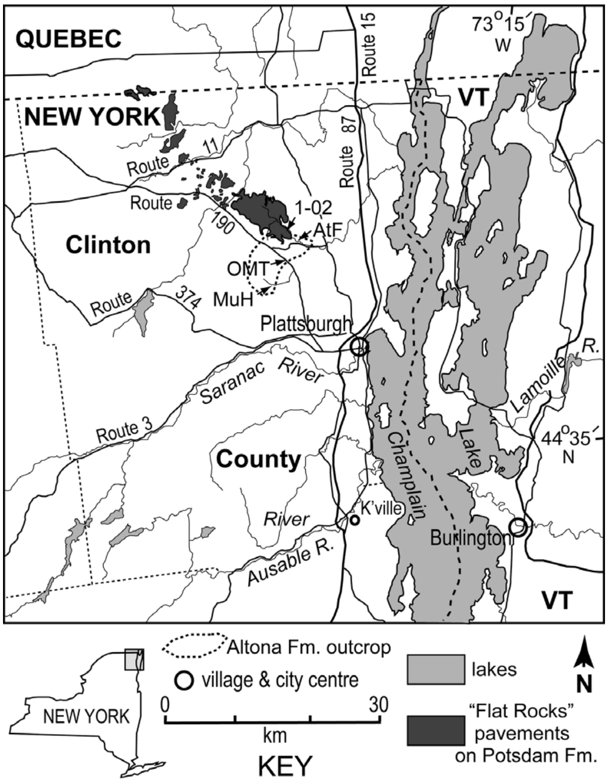

Figure 3. Field area in Clinton County, northwestern New York; figure shows Atwood Farm (AtF), Murtagh Hill Road (MuH) and Old Military Turnpike (OMT) localities and location of subsurface well 1-02. Abbreviations: K'ville – Keesville village; VT – Vermont.

of the Adirondacks (Flower, 1964, p. 156; Landing *et al.* 2007, p. 30). A *Crepicephalus* Zone assemblage is also reported from the Keeseville Member 160 km further north at Ausable Chasm just downstream from Keeseville village (Lochman, 1968; Fig. 3). (see Peng *et al.* 2004 for international consensus that the traditional, Laurentian 'upper Cambrian' *Cedaria* and *Crepicephalus* Zones are referable to the third series of the Cambrian (that is, middle Cambrian)).

These *Crepicephalus* Zone trilobites only provide an upper age bracket on the lower feldspathic (Ausable Member) sandstones, and the age of the lowest Potsdam has long remained unknown. It has been considered early–middle Cambrian (Walcott, 1891; Fisher, 1968; Sandford, 1993; Lavoie, Burden & Lebel, 2003; Sandford, 1993) or even Ediacaran (Fisher, 1956, 1977; Kirchgasser & Theokritoff, 1971; McRae, Johnson & Johnson, 1986; Bjerstedt & Erickson, 1989). Other reports have simply referred the entire Potsdam to the 'upper Cambrian' (Otvos, 1966; Lewis, 1971; Hersi & Lavoie, 2000).

Normal faulting has typically been assumed to control both the accumulation of the thick Potsdam successions and the development of the Ottawa–Bonnechere aulocogen (C. Dufresne, unpub. M.Sc. thesis, McGill Univ. Montreal, 1947; Wiesnet & Clark, 1966; Kumarapeli & Saull, 1966). If the feldspathic lower Potsdam is Ediacaran, then, as discussed above, it accumulated with formation of the Ottawa–Bonnechere aulocogen during break-up of Rodinia and initial opening of the Iapetus Ocean. However, if the Ausable Member accumulated significantly later in the Cambrian, then a different tectonic model is required to explain the normal faulting and deposition of the thick succession of feldspathic sandstones in the eastern part of the aulocogen.

3. Field localities and age of sub-Potsdam Altona Formation (new)

3.a. Study area

New information on the age and tectonic significance of the thick Potsdam successions in northern New York and adjacent Quebec is now available from sub-Potsdam sedimentary rock on the northeast margin of the Adirondack Mountains massif (Fig. 1). We investigated an outcrop area that Wiesnet (1961, pp. 7, 11, fig. 2) noted as 'dominantly red shale and siltstone' that is 'unique for the Potsdam' (Fig. 3). The outcrop area (about 30 km^2) contains distinctly non-Potsdam lithologies, and overlies Grenville gneiss and underlies Ausable Member feldspathic sandstone. This red and purple mudstone-dominated interval with weakly feldspathic quartz arenites and dolostones is designated a new formation-level unit termed the 'Altona Formation' (see Appendix 2).

The easily eroded Altona Formation is locally exposed as a result of scouring by catastrophic break-out floods from proglacial lakes in the Lake Ontario and St Lawrence River lowlands in the late Pleistocene. These floods also created a discontinuous belt of broad pavements on the Potsdam, or Flat Rocks, in northeastern New York (Fig. 3) (e.g. Franzi *et al.* 2002; Rayburn, Knuepfer & Franzi, 2005). Outcrops of the Altona Formation are limited in its type area of Clinton County, New York, by Pleistocene drift and low topographic relief. Where overlying drift deposits are absent, the distribution of the Altona Formation can be inferred from the red soils that develop on it, a distinctive feature as soils are typically grey or brown in northern New York. The limited surface outcrops were complemented by a nearby borehole (Fig. 3, well 1-02) that records a complete downward succession from the lower Ausable Member, through the Altona Formation, and into the Grenville basement. Without this well, the thickness of the Altona could not have been determined because the unit is otherwise known from short, isolated outcrops. In addition, determination of its stratigraphic thicknesses is confounded by a dense network of post-Ordovician normal faults that cross-cut this area of northeast New York (e.g. Wiesnet, 1961; Fisher, 1968).

3.b. Old Military Turnpike and Murtagh Hill Road section

The lower Altona Formation is exposed in a drainage ditch and low road-cuts on the southwest side of Old Military Turnpike (Rte 190) where it rises to the

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northwest to cross the northeast slope of Murtagh Hill (Fig. 3, locality OMT). A 7.5 m covered interval separates low outcrops of Grenville gneiss at the foot of the hill (612 064 E, 4962 371 N*) from a gently dipping (about 3° NW) section in the Altona Formation. (*Here and below, localities are reported as UTM, Zone 18, NAD 1983, grid coordinates.)

As exposed in 2007, the 48.5 m thick Old Military Turnpike section consists of light brown-weathering, pink to whitish coloured, feldspathic quartz arenites with red to purple mudstone interbeds (Fig. 4). Investigation suggests that the covered intervals are probably developed on weathered mudstones. Most of the sandstones are medium-grained. The coarsest beds have granule- and small pebble-sized quartz and feldspar grains in the lower 1.4 m of the exposed section. Primary sedimentary features in the sandstones include scattered burrows, synaeresis cracks and wave-rippled surfaces, with trough cross-beds showing WSW-flowing currents in the top 9.0 m of the section (0611655 E, 4962681 N). A second, 2.0 m thick outcrop in this sandstone-rich part of the Altona Formation was exposed in Summer 2008 in a newly dug drainage ditch on the west side of Murtagh Hill Road (Fig. 3, locality MuH). No body or trace fossils were found in the flat-lying sandstone outcrop on Murtagh Hill Road. The short Murtagh Hill Road section consists of 1.0 m of thin-bedded, current cross-bedded, medium-grained sandstone overlain by 1.0 m of trough cross-bedded coarse-grained sandstone deposited by a WSW-flowing current. The Murtagh Hill Road section lies about 55.5 m above the highest Grenvillian (metagabbro) outcrops that we observed (about 300 m elevation), and its trough cross-bedded facies resembles the upper 9 m of the Old Military Turnpike section.

3.c. Old Military Turnpike fossils and age

Isolated horizontal (*Planolites*) and unidentifiable (that is, incomplete) vertical trace fossils occur at several horizons in the Old Military Turnpike succession, but provide little evidence on age or depositional environments. Disarticulated, moldic trilobite debris was found in a burrow-mottled, reddish weathering, light grey, dolomitic quartz arenite 12.5 m above the highest exposure of Grenville gneiss (Fig. 4, sample OMT-12.5).

The trilobites are very significant: they occur below the unfossiliferous Ausable Member of the Potsdam Formation, and show that the oldest sedimentary deposits on the Grenville orogen in northeast New York craton are marine. Because precise U–Pb zircon geochronology indicates that trilobites (at least skeletalized forms) appeared no earlier than half way through the Cambrian (Landing *et al.* 1998), the lower Altona Formation trilobites indicate that earlier proposals that the overlying Ausable Member may be Ediacaran or earliest Cambrian are no longer supportable.

Although the trilobite remains are fragmentary and were comminuted before burial, an exfoliated,

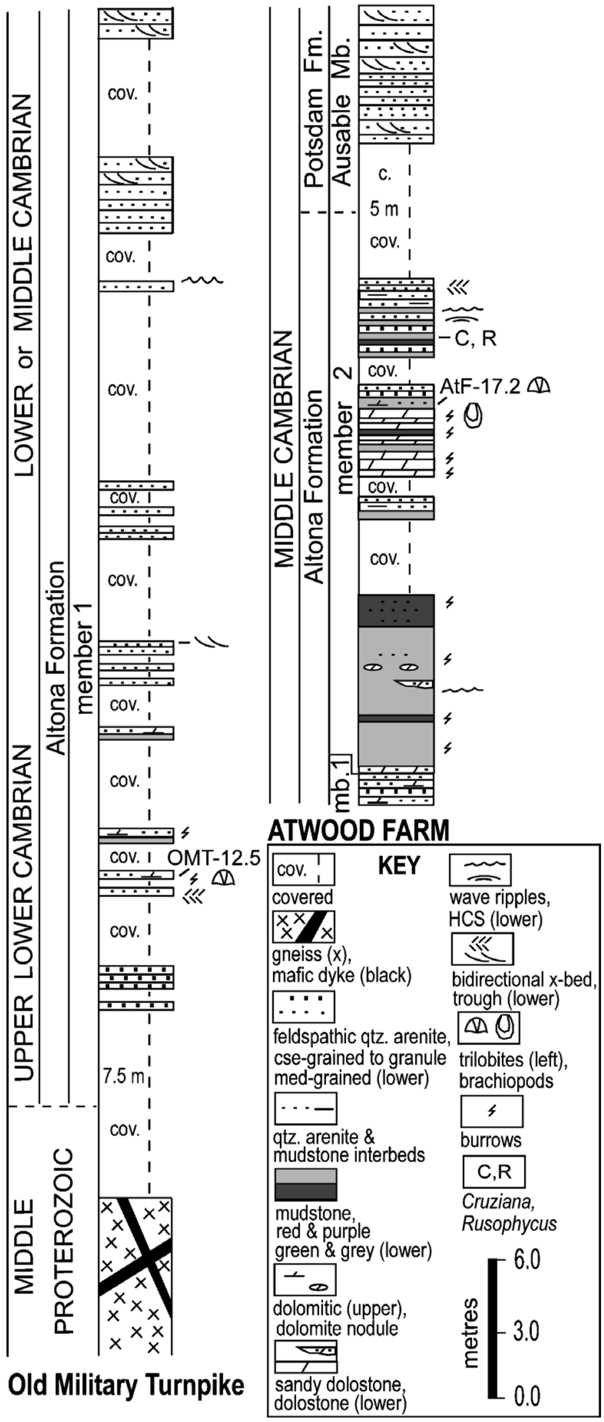

Figure 4. Sub-Potsdam sections in the Altona Formation, Clinton County, New York. Abbreviation 'HCS' is 'hummocky cross-stratified'

extraocular area of an olenellid was recovered in sample OMT-12.5 (Fig. 5). With its relatively large size, high convexity, large elongate eye, raised brim, and a genal spine that originates slightly anterolaterally of the posterolateral margin of the cheek, the specimen bears a strong resemblance to the fixed cheeks of several *Olenellus* species illustrated from the Parker and Monkton formations in the easternmost Appalachian Mountains just across Lake Champlain in Vermont (e.g. Walcott, 1890, pls 82, 83; Kindle & Tasch, 1948, pls 1,

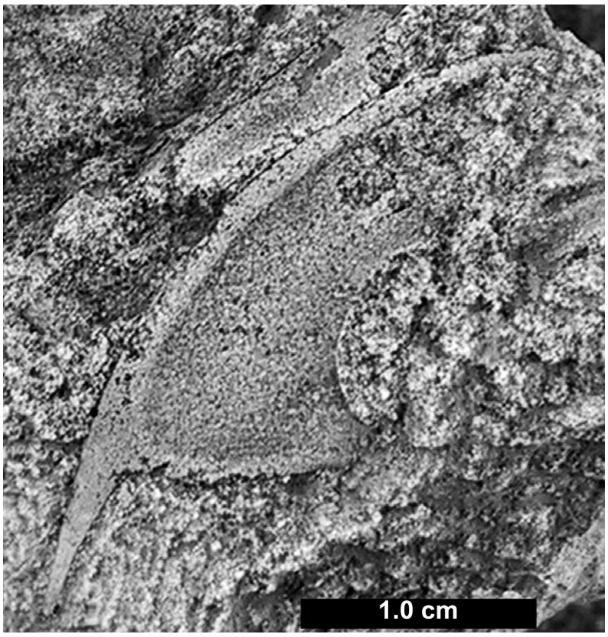

Figure 5. Unidentified olenellid from lower Altona Formation in roadcut on Old Military Turnpike, sample OMT-12.5; NYSM 17247.

2; Shaw, 1955, pl. 75). The presence of this olenellid shows that the lowest Altona Formation is upper lower Cambrian in terms of Laurentian chronostratigraphy.

3.d. Atwood Farm section

The upper Altona Formation crops out in cut-banks along the south bank of the Little Chazy River on the Atwood Farm. The Atwood Farm buildings are just north of Atwood Road (Fig. 3, see unlabelled east–west road that connects Route 190 and locality AtF). The base of the Atwood Farm section is 350 m north of the farm buildings, and located where a foot bridge with heavy stone footings crosses the Little Chazy River (613737 E, 4964660 N).

Feldspathic quartz arenites comparable to those of the OMT section form the lower 1.5 m of the Atwood Farm section (Fig. 4), and also crop out in the pasture southwest of the base of the Atwood Farm sequence. However, most of the Atwood Farm succession is purple and red mudstone-dominated, and has dolostones and feldspathic sandstones. Arenaceous dolostones (Fig. 4, 1.5–1.7 m) mark the change from the sandstone- to a mudstone-dominated succession. The lower 19.7 m of the section dip west, with dip increasing upstream (4–8°). The Atwood Farm succession forms a broad syncline as the top beds (Fig. 4, 19.1–22.5 m) show a reversal of dip to 4° NE. A distance of 120 m separates the lower and upper parts of the Atwood Farm section. However, a coarse-grained sandstone interbedded with red and grey mudstones (19.1–19.7 m) can be traced upstream in the bed of the Little Chazy River, and forms the base of the uppermost beds of the Altona Formation on the west side of the syncline.

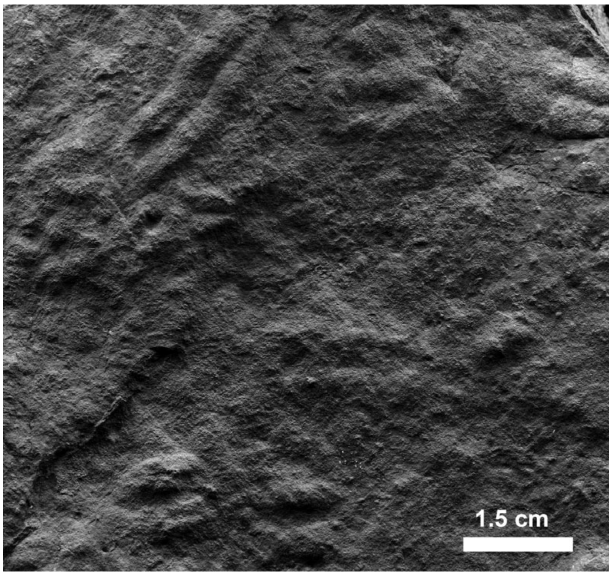

Figure 6. Current-effaced *Cruziana* and *Rusophycus* specimens from Altona Formation, horizon AtF-20.0, stored as *Rusophycus* sp. under NYSM 17688.

About 5 m of cover separate the highest exposed beds of the Altona Formation from the Ausable Member. These uppermost beds of the Altona in the Atwood Farm section (613130 E, 4964950 N) feature a transition from lower-energy marine mudstones to higher-energy, sandstone-dominated units, with hummocky cross-stratification and trough cross-beds appearing near the top of the exposed Altona. Indeed, the highly feldspathic, cross-bedded, pink sandstones at the top of the Altona outcrop (Fig. 4, 22.0–22.5 m) represent a lithology common in the Ausable Member. These limited data, which are complemented by data from a nearby borehole (discussed in Section 3.f), suggest that a lithologically transitional, conformable contact exists between the Altona and Ausable.

3.e. Atwood Farm fossils and age

Fossils are common through the Atwood Farm section, but are primarily limited to small, *Planolites*-like burrows in the mudstones. Current-effaced, small *Cruziana* and *Rusophycus* specimens were found at the base of a 1.0 cm thick sandstone in mudstones near the top of the section (Fig. 6). By comparison, the thick-bedded, white-weathering dolostones (Fig. 4, 13.9–15.5 m) are heavily burrow-churned, with bedding surfaces and slabbed sections recording large endichnia up to 5 cm in diameter. The abundance and large size of the traces suggest that the dolostones were deposited as limestones under normal marine salinities. The carbonate beds are pervasively dolomitized, and contain small vugs filled with saddle dolomite, druses of malachite, and small quantities of galena and sphalerite as insoluble residues. These mineral associations may be related to hydrothermal fluid movement along faults that extend into the Grenville orogen in northern New

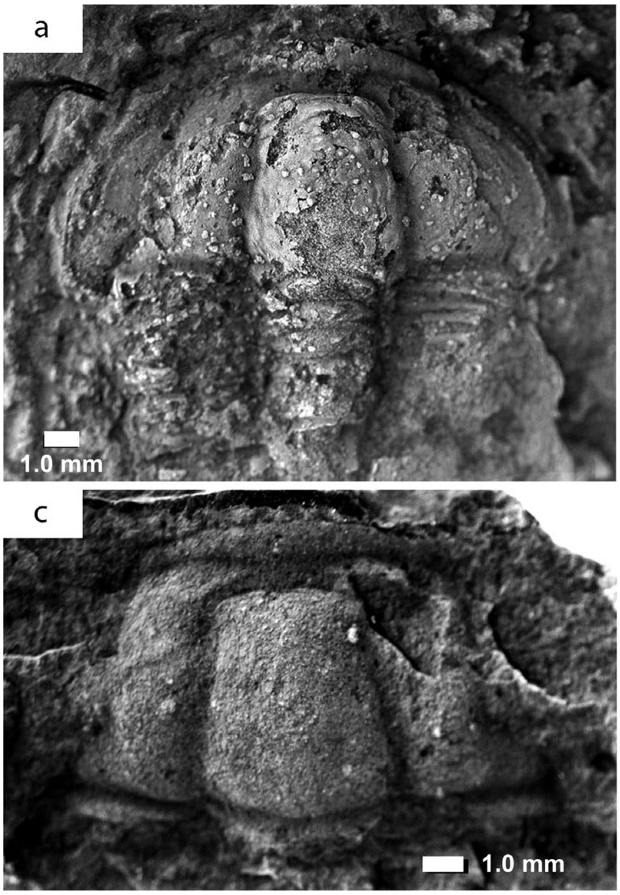

Figure 7. *Ehmaniella*? sp. from upper Altona Formation along Little Chazy River on Atwood Farm, hypotype specimens. (a) NYSM 14195, mostly exfolilated cephalon and partial thorax in dorsal view; (b) NYSM 14196, exfoliated cephalon; (c) NYSM 14197, exfoliated cranidium; (d) NYSM 16999, external mold of cranidium, latex cast illustrated.

York, and were re-activated during the Late Ordovician Taconic Orogeny or later orogenies (Landing, Westrop & Knox, 1996; Benison & Lowenstein, 1997; Landing, 2007, p. 10).

Body fossils are limited in the Atwood Farm succession. Dissolution of five 6 kg dolostone samples from the middle of the section (13.9–17.1 m) yielded no acid-resistant fossils. Ghosts of calcareous brachiopods were noted in cut slabs of a dolostone bed (horizon AtF-15.5), but calcareous or phosphatic brachiopod remains were not recorded from any other horizon.

Of far more significance was the discovery of trilobites in a slightly dolomitic red mudstone (Fig. 4, sample AtF-17.2). The trilobites comprise a monospecific assemblage of moldic to dolomite-replaced isolated sclerites to partially articulated specimens of *Ehmaniella*? sp. (Fig. 7).

Ehmaniella Resser, 1937 is widespread in Laurentian successions, and provides a biostratigraphic bracket on the upper Altona Formation and basal Ausable Member. The genus is known from the eastern Laurentian platform (Alabama, Georgia, Tennessee and Virginia: see Resser, 1937, 1938), the western platform in the Great Basin of eastern Nevada–western Utah and the Pentagon Shale of Montana (see Sundberg, 1994), as well as in deep-water facies in western Laurentia (British Columbia: Fritz, 1971).

Sundberg (1991) reported *Ehmaniella* to be characteristic of a low-diversity, ptychopariid biofacies. This middle Cambrian biofacies ranged from mixed carbonate–siliciclastic sequences deposited inboard of platform-margin carbonate banks to more proximal, mudstone–siltstone sequences of the inner platform. Deeper-water occurrences of *Ehmaniella*, probably transported specimens, are in the Burgess Shale of British Columbia (Fritz, 1971). All of these studies report the genus from the traditional Laurentian middle middle Cambrian (‘*Bathyuriscus–Elrathina* Zone’).

Sundberg (1994) reported a comparable middle middle Cambrian range of *Ehmaniella* and regarded it as appearing in his ‘*Ehmaniella* Subzone’ and persisting into an overlying *Altiocculus* Subzone. Unfortunately, he proposed the *Ehmaniella* Subzone as the third of four successive subzones of an ‘*Ehmaniella* Zone’ that ranged well down into the lower middle Cambrian. However, bio-, litho- and chronostratigraphic units require distinctive names that cannot also be used as names for their lower-order subdivisions (North American Commission on Stratigraphic Nomenclature, 1983). Consequently, we regard *Ehmaniella*? sp. as indicating a middle middle Cambrian age for the upper Altona Formation, as elsewhere in Laurentia, and do not assign it to a biostratigraphic zone/subzone.

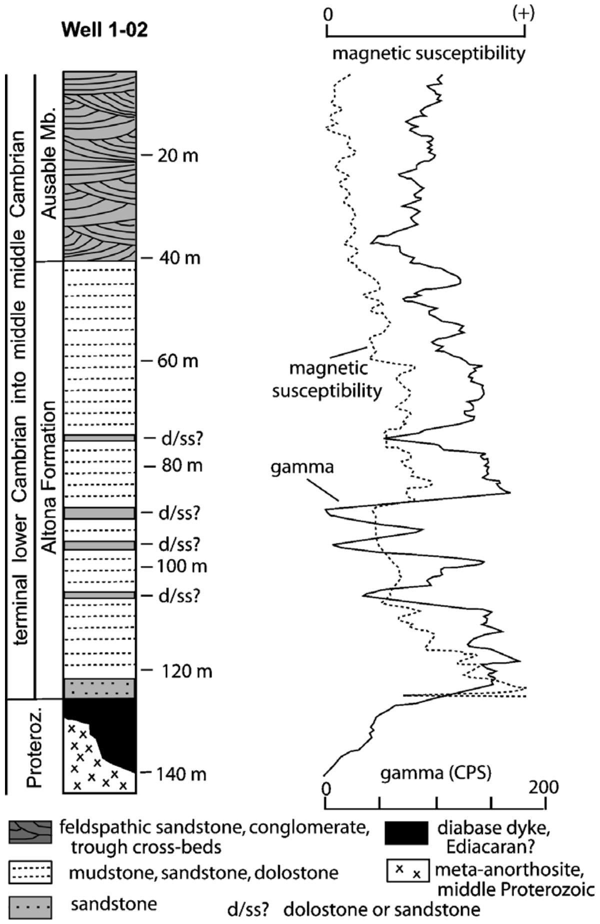

Figure 8. Geophysical characteristics and generalized lithology of Well 1-02 at Altona Flat Rock (see Fig. 3). Data courtesy of J. H. Williams, U.S. Geological Survey, Water Resources Division, Troy, NY (modified from Landing *et al.* 2007, fig. 11).

3.f. Well at Altona Flat Rock

Long outcrop sections through the Altona Formation do not exist in Clinton County, and a borehole near the Atwood Farm succession was invaluable in demonstrating the unit's thickness. Well 1-02 (612713 E, 4965740 N) is 1.5 km northwest of the top of the Atwood Farm sequence and close to the southeast margin of the large pavement on the Potsdam Formation known as Altona Flat Rock (Fig. 3). The deepest of the hydrogeological research wells drilled in this region, well 1-02 first penetrated trough cross-bedded and ripple-marked feldspathic sandstones and conglomerates of the lower Ausable Member (Fig. 8). Increases in gamma radiation and magnetic susceptibility at about 42 m are used to mark the base of the Ausable Member, and suggest a transition from sandstone into finer-grained siliciclastics. Cuttings from this depth also indicate a downward gradation into reddish brown or maroon mudstone, siltstone and fine-grained sandstone lithologies that are known from the Altona Formation in the Atwood Farm succession. Decreases in gamma radiation at 75, 88, 96 and 104 m and an associated decrease in magnetic susceptibility may indicate dolostone or well-sorted and -cemented sandstone beds. The nonconformity of the Altona with the Proterozoic basement rocks is at 126 m, with the borehole first cutting a mafic dyke (126–135 m) and then penetrating meta-anorthosite (135–142 m).

Well 1-02 shows that the Altona Formation is about 84 m thick in the field area. In addition, cuttings from the borehole further support the suggestion of a lithologically gradational Altona–Ausable contact, as indicated by the coarsening-up, higher-energy, mudstone- to sandstone-dominated facies transition in the uppermost Altona Formation in the Atwood Farm section.

4. Discussion

Almost 500 Ma of geological time are unrepresented on the northeast Laurentian craton. This interval follows the *c.* 1.0 Ga Grenville Orogeny, a late stage in the assembly of the Rodinia supercontinent that featured collision of the Amazon Shield with a region that now comprises much of the eastern United States and adjacent Canada (Dalziel, Salada & Gahagan, 1994; Gates *et al.* 2004). Subsequent geological events in northern New York and adjacent Canada are only recorded much later in the Ediacaran with fragmentation of Rodinia, and the development of a triple junction that defined the Quebec Reentrant, New York Promontory, and Ottawa–Bonnechere aulocogen (discussed in Section 2).

The *c.* 570 Ma Tibbit Hill volcanic rocks in the Appalachians are the oldest known cover sequence unit on the Grenville, and are thickest in the area of the triple junction at the headwaters of the Lamoille River in northern Vermont and adjacent Quebec (Figs 1, 3; Cherichetti, Doolan & Mehrtens, 1998). It is possible that the Rand Hill diabase dykes that cut the Grenville basement in the Clinton County field area of this report may reflect coeval early faulting and formation of the Ottawa–Bonnechere aulocogen (Fig. 3, base of Old Military Turnpike section). However, it should be noted that both the tentative Ediacaran–earliest Cambrian age of the Rand Hill dykes and their tectonic interpretation are based on early palaeomagnetic data (see Isachsen *et al.* 1988), and not precise geochronological work based on radioactive isotopes.

'Conventional wisdom' has long maintained that the middle Proterozoic Grenville orogen is nonconformably overlain by terrestrial (at least in part), feldspathic sandstones of the Ausable Member in the thickest sections of the Potsdam Formation on the craton in northeast New York and Quebec. The absence of fossils has led to the suggestion that the Ausable records deposition with normal faulting and subsidence of the Ottawa–Bonnechere aulocogen in the Ediacaran–earliest Cambrian in some reports.

The new information presented in this report is that the base of the cover sequence on the southern margin of the Ottawa–Bonnechere aulocogen in northeast New York is not the Ausable Member, but rather, a surprisingly young, underlying marine unit. An olenellid fragment from the lower Altona Formation represents a trilobite group traditionally assigned to the later part of the early Cambrian in Laurentia (e.g. Geyer & Palmer, 1995). U–Pb geochronology has yielded a 511 Ma date on the upper lower Cambrian (Landing *et al.* 1998). This datum shows that the marine onlap recorded by the lower Altona Formation is far younger, by *c.* 60 Ma, than the early rifting of east Laurentia and extrusion of the Tibbit Hill pillow basalts. Thus, the new information does not support an epeirogenic model that links the lowest cover units in the Ottawa–Bonnechere aulocogen to Ediacaran faulting and subsidence.

An alternative model for explaining deposition of the oldest cover units on the Grenville of the eastern Ottawa–Bonnechere aulocogen may lie outside the field area, and in the northern Appalachians. Dramatic late early Cambrian faulting within the upper part of the temporal range of olenellids is now recognized just outboard of the Ottawa–Bonnechere aulocogen (Landing *et al.* 2007, pp. 57, 58). This faulting took place along an east–west trend that follows the modern Lamoille River in northern Vermont, and led to abrupt local foundering of the early Cambrian carbonate platform and development of the Franklin Basin (Figs 1, 3). The Franklin Basin (Shaw, 1958) featured the abrupt termination of shallow, carbonate platform deposition (Dunham Formation) followed by persistent anoxic/dysoxic deposition in an upper continental slope setting in northwest Vermont through the early Ordovician (Fig. 9). Indeed, the initial faulting and foundering of the Franklin Basin were so geologically abrupt that debris flow blocks of peritidal Dunham carbonates derived from submarine scarp(s) accumulated as the first deposits on the deeply submerged Dunham in the newly formed Franklin Basin (Landing, 2007, pp. 12–14; Landing *et al.* 2007, pp. 48–58).

The growth fault(s) that defined the shelf–slope break at the south margin of the Franklin Basin lies on a trend that connects the southern flank of the Ottawa–Bonnechere aulocogen to an area where the Tibbit Hill pillow basalts are abruptly replaced by coeval, siliciclastic rift facies of the Pinnacle Formation to the south (Cherichetti, Doolan & Mehrtens, 1998; Landing, 2007). This coincidence in trends of major geological features of the northeastern craton and northern Appalachians does not seem to have resulted from or been affected by potential regional rotation or significant lateral (north–south) movement in the Appalachians. Indeed, the north–south trend of Cambrian lithofacies on the Vermont platform still follows the trend of rifting that defined the New York Promontory and early Palaeozoic shelf margin (e.g. Mehrtens, 1987). By contrast, the location of the thickest succession of the Tibbit Hill pillow basalts lies almost precisely at the Ediacaran triple junction, and where an Ediacaran mantle plume may have been located (Landing, 2007).

Marine deposition of the Altona Formation persisted into the middle middle Cambrian, as shown by an

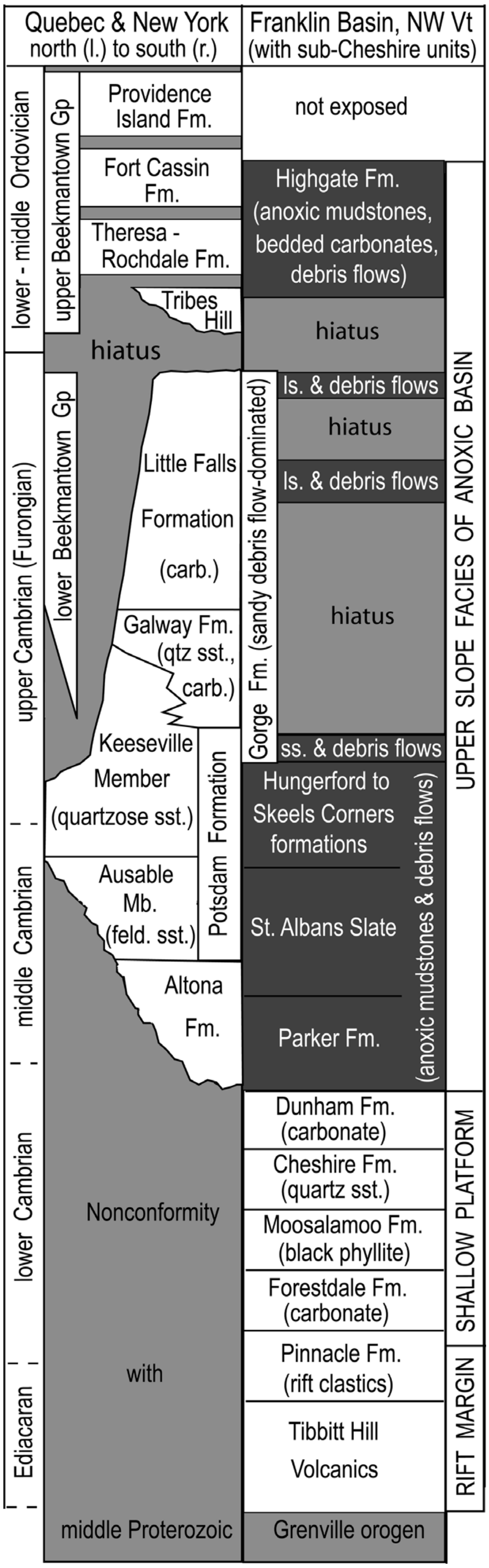

Figure 9. Relationship of Altona Formation to Ediacaran–lower Ordovician succession of the Franklin Basin, northwest Vermont. Cheshire Formation is lowest exposed unit in Franklin Basin in the Rosenburg slice (e.g. Shaw, 1958); thus the Franklin Basin column is a composite section that includes sub-Cheshire stratigraphy in the Hinesburg slice immediately to the east (Clark & Eakins, 1968; Cherichetti, Doolan & Mehrtens, 1998). Abbreviations: carb. – carbonate; feld. – feldspathic; Fm. – Formation; Mb. – Member; sst. – sandstone.

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assemblage consisting of *Ehmaniella*? sp. specimens that appear in inner-platform, mixed siliciclastic mudstone–carbonate facies in the upper part of the formation. A lithologically gradational and likely conformable transition with the Ausable Member is suggested by outcrop and borehole data.

We interpret a conformable Altona–Ausable contact as an upward transition from a lower transgressive systems tract lithosome deposited on the inner shelf (sandstones; oxic, reddish mudstones; carbonates of the Altona). This was followed by aggradation and the deposition of current cross-bedded, perhaps terrestrial, in part, feldspathic Ausable sandstones of the upper highstand facies. Comparable mudstone-dominated (transgressive systems tract) through overlying shallow shelf sandstone (upper highstand facies) sequences may be found elsewhere in the geological record. For example, the upward transition from the anoxic Moosalamoo Phyllite into the peritidal sandstones of the Cheshire Formation in the Early Cambrian of Appalachian Vermont provides another example of a shoaling-up, lithologically transitional succession that culminates with a high-energy (tidalite), proximal facies (Fig. 9). The interesting aspect of both the sandstone-dominated highstand facies of the Cheshire and Ausable is that base-/sea-level continued rising during their deposition, and the Cheshire and Ausable are locally the oldest cover sequence unit on the Grenville orogen (Landing, 2007).

Although a precise geochronology of the terminal middle Cambrian is not yet available, deposition of the thick (up to 610 m) successions of the Ausable Member in the eastern Ottawa–Bonnechere aulocogen must have been relatively rapid. This inference is based upon the facts that the Altona–Ausable contact is only about 5 m above the middle Cambrian *Ehmaniella*? sp. assemblage (Fig. 4), and that upper middle Cambrian (*Crepicephalus* Zone) trilobites are the oldest assemblages in the Keeseville Member. The great thickness and compositional immaturity (that is, feldspathic) composition of Ausable sandstones are consistent with traditional interpretations that relate the unit's deposition in the eastern Ottawa–Bonnechere aulocogen to normal faulting and rapid local subsidence (Wiesnet, 1961; Otvos, 1966; Lewis, 1971).

Additional evidence is available that links Cambrian through early Ordovician deposition in the Ottawa–Bonnechere graben with that of the Franklin Basin. It is tempting to equate the Altona–Ausable succession with a sequestering of sand on the craton and limited off-platform sand transport. Thus, Altona onlap would feature sand deposition in near-shore environments (the lower feldspathic sandstone in Fig. 4 and Appendix 2), while Ausable deposition would be characterized by rapid aggradation and limited off-shelf sand transport. A possible sequestration of sand in the Ottawa–Bonnechere aulocogen during the terminal early–middle middle Cambrian matches developments in the Franklin Basin, where the coeval Parker Formation–St Albans Slate show a limited amount of sand (Fig. 9). Similarly, a transition from the feldspar-rich Ausable into the much more geographically widespread, quartz–arenite-dominated Keeseville Member within the late middle Cambrian (at least by the *Crepicephalus* Chron) is matched in the Franklin Basin by the appearance of abundant quartz sand in the Skeels Corners–Hungerford interval in the slightly older *Cedaria* Chron (e.g. Shaw, 1958). Quartz sand becomes even more abundant and coarser grained in the overlying Gorge Formation, and apparently represents off-platform transport coeval with Keeseville deposition.

Among the most unexpected discoveries in the Ottawa–Bonnechere aulocogen is the presence of a regional unconformity on the Potsdam that separates it from an overlying middle Lower Ordovician Theresa Formation (Salad Hersi *et al.* 2002; Salad Hersi, Lavoie & Nowlan, 2003; Dix, Salad Hersi & Nowlan, 2004). As a consequence, several carbonate-rich, Upper Cambrian and Lower Ordovician units that comprise the lower Beekmantown Group and are prominent further south on the New York Promontory are missing in the Ottawa–Bonnechere aulocogen (Fig. 2). The generally non-fossiliferous strata of the upper Potsdam in the aulocogen do not allow a lower bracket to be placed on this hiatus (Dix, Salad Hersi & Nowlan, 2004). The interbedded dolostones and quartz arenites of the 'upper member' of the 'Cairnside' in Quebec (Salad Hersi, Lavoie & Nowlan, 2003; Fig. 2) resemble those of the Galway Formation at the base of the Beekmantown Group in New York, and suggest the Potsdam near Montreal ranges into the middle upper Cambrian (Fig. 2). Unfortunately, the number and duration of major unconformities in the upper Cambrian–lower Ordovician slope sequences of the Franklin Basin and the long Cambrian–Ordovician hiatus in the Ottawa–Bonnechere aulocogen do not allow an evaluation of the roles of epeirogenic activity and/or sea-level change in latest Cambrian deposition of this region of northwest Laurentia.

5. Systematic palaeontology

Order REDLICHIIDA Richter, 1933
Suborder OLENELLINA Resser, 1938
Family OLENELIIDAE Vogdes, 1893
Olenellid gen. et sp. indet.
Figure 5

Material and occurrence. A single, unassociated cheek from the Old Military Turnpike locality, horizon OMT-12.5.

Description. Cheek quadrate in outline, widest (tr) at base of ocular lobe. Convexity low to lateral border. Lateral margin uniform arc; preserved approximately to mid-line of cephalon. Posterior margin transverse. Ocular lobe crescent-shaped, angled inward anteriorly. Lateral border continuous around lateral and posterior margins; defined by convexity rather than distinct border furrow; very slightly narrower toward anterior, thickened at genal angle, narrower along posterior margin. Genal spine rapidly tapering; length (exsag) about 1/3 length (sag) of cephalon; formed as continuation of lateral border with uniform curvature with lateral margin.

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Genal area in front of ocular lobe not preserved except for lateral border to about mid-line (estimated by change in curvature along anterior margin); facial sutures in lateral border absent. Break at base of ocular lobe directed posterolaterally to posterior margin.

Discussion and comparison. Diagnostic features of the cheek include the large, crescent-shaped eye, a strong, narrow lateral border that continues unbroken anteriorly to the approximate mid-line of the cephalon, the broad distance (tr.) from the ocular lobe to the lateral border, and the long, transverse posterior margin from the genal spine to a break behind the ocular lobe. In corynexochids and most ptychopariids, the anterior branches of the facial suture are divergent or run parallel to the anterior margin. In the few groups in which the lateral border of the cheek extends anteriorly toward the mid-line of the cranidium, the eyes are small and/or the posterior fixigenae extend laterally well beyond the palpebral lobes.

Walcott (1890, pl. 89) observed what he termed 'false facial sutures' in *Elliptocephala asaphoides* Emmons, 1844; *Olenellus gilberti* Meek, 1874 (Walcott, 1890, pls 84–86) and *Olenellus thompsoni* (Hall, 1859) (Walcott, 1890, pl. 83). False facial sutures consist of fractures in the cephalon that extend from the back of the eye postero-laterally across the posterior border and/or cracks that originate at the anterior of the eye and radiate forward to the cephalic margin. Walcott's (1890, pp. 633–4, pl. 89 caption) observations are particularly significant because the breaks are present only in some specimens and when they occur, may be found on only one side of the cephalon. Subsequent illustrations of *Olenellus* specimens from Vermont have shown radiating 'false facial sutures', although these reports have not commented on the commonness of the occurrence of these features (see Kindle & Tasch, 1948, pl. 2, figs 1, 3, 4, where false facial sutures trend posterolaterally from the posterior end of the eye, and Shaw, 1955, pl. 75, fig. 3, who shows a specimen with many cracks in the cranidium, two pairs of which radiate from the anterior and posterior ends of the eye).

The purpose in noting these early reports of 'false facial sutures' is that the olenellid cheek from the Altona Formation shows a comparable, straight suture-like crack that originates at the posterior end of the eye and crosses the brim. Geyer (1996) discussed and illustrated similar cracks in the cuticle of fallotaspid trilobite cranidia that trend from the back of the eye to the posterior margin, as well as fractures that arise at the front of the eye and radiate anterolaterally. Geyer (1996) concluded that the post-burial compaction of thin/weakly calcified cranidia led to the development of these cracks, and proposed that the cracks may trace lines of weakness that presaged the development of sutures characteristic of subsequent redlichiid trilobites.

Order PTYCHOPARIIDA Swinnerton, 1915
Family EHMANIELLIDAE Sundberg, 1994
Genus *Ehmaniella* Resser, 1937

Type species. Crepicephalus (*Loganellus*) *quadrans* Hall & Whitfield, 1877, from the middle Cambrian of Utah.

Ehmaniella? sp.
Figure 7

Material and occurrence. Numerous cranidia and a cephalon with a partial thorax were collected from the Altona Formation at the Atwood Farm locality (sample AtF-17.2).

Description. Cranidium subtrapezoidal, length 65–70 % width; convexity low (sag. and tr.); anterior margin only slightly curved, width about 65 % total width of cranidium across posterior margin; posterior margin behind fixigenae curved backward, directed strongly backward at lateral extremity. Posterior border furrow moderately wide and well impressed on internal molds, curved backward in front of occipital ring, behind fixigenae begins at posterior margin then curves weakly forward to lateral margin. Occipital ring short (sag.), slight posteriorly directed medial swelling. Facial sutures directed nearly straight forward from posterior margin for short distance then curve inward to palpebral lobe; anterior to palpebral lobe, curve only very slightly outward then inward to anterior border furrow; bow outward around margin of anterior border. Palpebral lobes short (sag.), positioned at about mid-length (sag.) of glabella. Glabella subtrapezoidal, narrowing only slightly toward anterior; axial furrows moderately deep, nearly straight; two specimens preserve weak abaxial flexure of furrows at about 70 % glabellar length (sag.) from posterior (Fig. 7a, c); anterior margin of glabella truncated, preglabellar furrow nearly transverse, possibly with slight posterior flexure sagitally (Fig. 7a, b). Lateral glabellar furrows very shallow as seen on internal molds; only p1 and p2 visible; furrows short (tr.), shallow, wide. Preglabellar field short (sag.), nearly equal in length (sag.) to length of anterior border; anterior border slightly wider sagitally, nearly transverse, strongly convex. Anterior border furrow narrow (sag.); moderately deeply impressed; bowed weakly backward medially; arched forward in front of fixigenae. Palpebral ridges moderately expressed on internal molds; originate just behind anterior margin of glabella, directed laterally and slightly backward; terminate at anterior margin of palpebral lobes. Librigenae poorly preserved; width (tr.) appears about equal to width of fixigenae; lateral margins rounded, curve abruptly around genal angle.

Discussion and comparison. Without pygidia, the cranidia and and a cephalon with a partial thorax collected from the Altona at the Atwood Farm locality are difficult to identify below the level of the order. This trilobite is similar to *Elrathina* Resser, 1937, in that the anterior border is slightly narrower than the preglabellar field and the entire frontal area is narrower than the fixigenae at the level of the palpebral lobes (*Elrathina convexa* Deiss, 1939, pl. 15, fig. 2). The anterior margin of the cranidium in the Altona trilobite is nearly transverse with only a slight forward curvature. This is seen in a few species of *Ehmaniella* (*E. clintonensis* Resser, 1938, pl. 8, fig. 54; *E. placida* Resser, 1938, pl. 8, figs 55, 56) and in *Elrathina fecunda* Deiss, 1939 (pl. 15, figs 6, 7, 9). Greater length (sag.) of the anterior border medially is common in species of *Ehmania* Resser, 1935 (see Deiss, 1939), *Ehmaniella* (see Sundberg, 1994), *Elrathia* Walcott, 1924 (see Young & Ludvigsen, 1989), *Elrathiella* Poulsen, 1927 (see Sundberg, 1994), and *Elrathina* (see Deiss, 1939), but this is due to greater curvature of anterior margin sagitally. In the Altona trilobite, the anterior border furrow is flexed backward medially, making the anterior border length greatest sagitally without greater curvature of the anterior margin (Fig. 7b, c). This posterior curvature of the anterior border furrow is seen only in the Altona trilobite and *Elrathina* (*E. fecunda* Deiss, 1939, pl. 15, fig. 7; *E. parallela* Rasetti, 1951; see Young & Ludvigsen, 1989, pl. 9, fig. 10).

Although the features discussed above (width (tr.) of the frontal region relative to the fixigenae at the level of the palpebral lobes, curvature of the anterior margin of the cranidium, course of the anterior border furrow) suggest assignment to *Elrathina*, other diagnostic features are present only in species of *Ehmaniella*. The preglabellar furrow in the

Altona trilobite is transverse with a weak backward deflection medially. The preglabellar furrow in *Ehmaniella angustigena* Sundberg, 1994 (fig. 33.1, 3) is nearly as transverse and is nearly identical in *Ehmaniella fronsplanata fronsplanata* Sundberg, 1994 (fig. 34.1, 2). The blunt anterior margin of the glabella in the Altona trilobite also has a very slight medial indentation, which is also present in *E. fronsplanata fronsplanata* and *E. fronsplanata concava* Sundberg, 1994 (fig. 36.1, 2), and is developed to a greater degree in *E. fronsplanata convexa* Sundberg, 1994 (fig. 35.1, 2, 4). Finally, a very slight abaxial deflection of glabellar furrows just posterior to palpebral ridges is seen in the Altona trilobite and *E. fronsplanata convexa*.

Sundberg (1994) erected the family Ehmaniellidae to include trilobites with glabellae that are blunt anteriorly (as well as other features). Genera assigned to this family include *Altiocculus* Sundberg, 1994; *Ehmania*; *Ehmaniella*; *Elrathia*; *Elrathiella*; *Parehmania* Deiss, 1939; *Proehmaniella* Sundberg, 1994; *Pseudoalokistocare* Sundberg, 1994; *Pseudomexicalla* Sundberg, 1994; *Schopfaspis* Palmer & Gatehouse, 1972; *Trachycheilus* Resser, 1935 and *Tympanuella* Sundberg, 1994. *Elrathina* is excluded from the Ehmaniellidae based on pygidial features, which we are unable to assess for the Altona trilobites without additional material. Although there are similarities in cranidial morphology with *Elrathina*, we tentatively assign the Altona trilobites to the Ehmaniellidae.

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References

Alling, H. L. 1919. Geology of the Lake Clear region. *New York State Museum Bulletin* 207–208, 111–45.

Benison, K. C. & Lowenstein, T. K. 1997. Carbonate-hosted mineralization of the Lower Ordovician Ogdensburg Formation: evidence for a Paleozoic thermal anomaly in the St. Lawrence Lowlands of New York and Ontario. In *Basin-wide fluid flow and associated diagenetic patterns: integrated petrologic, geochemical, and hydrologic considerations* (eds I. Montanez, K. Skelton & J. Greggs), pp. 207–18. SEPM Special Publication no. 57.

Bernstein, L. 1992. A revised stratigraphy of the Lower–Middle Ordovician Beekmantown Group, St. Lawrence lowlands, Quebec and Ontario. *Canadian Journal of Earth Sciences* **29**, 2677–94.

Bjerstedt, T. W. & Erickson, J. M. 1989. Trace fossils and bioturbation in peritidal facies of the Potsdam–Theresa Formations (Cambrian–Ordovician), northwest Adirondacks. *Palaios* **4**, 203–24.

Cady, W. M. 1945. Stratigraphy and structure of west-central Vermont. *Geological Society of America Bulletin* **56**, 515–58.

Chadwick, G. H. 1915. Post-Ordovician deformation in the St. Lawrence valley, New York. *Geological Society of America Bulletin* **26**, 287–94.

Chadwick, G. H. 1920. The Paleozoic rocks of the Canton quadrangle. *New York State Museum Bulletin* 217–218, 60 pp.

Cherichetti, L., Doolan, B. & Mehrtens, C. 1998. The Pinnacle Formation: a late Precambrian rift valley fill with implications for Iapetus rift basin evolution. *Northeastern Geology and Environmental Sciences* **20**, 175–85.

Clark, T. H. 1966. Châteauguay area – Châteaugay, Huntingdon, Beauharnois, Napierville, and St. Jean counties. *Ministère des Richesses Naturelles du Québec, Rapport Géologique* **122**, 63 pp.

Clark, T. H. 1972. Montreal area. *Ministère des Richesses Naturelles du Québec, Rapport Géologique* **152**, 244 pp.

Clark, T. H. & Eakins, P. R. 1968. The stratigraphy of the Sutton area of southern Quebec. In *Studies of Appalachian Geology: Northern and Maritime* (eds E. Zen, W. S. White, J. B. Hadley & J. B. Thompson, Jr), pp. 163–73. New York: Interscience Publishers.

Clarke, J. M. & Schuchert, C. 1899. The nomenclature of the New York series of geological formations. *Science* **10** (new series), 876, 877.

Cushing, H. P. & Ruedemann, R. 1914. Geology of Saratoga Springs and vicinity. *New York State Museum Bulletin* **169**, 177 pp.

Cushing, H. P., Fairchild, H. L., Ruedemann, R. & Smyth, C. H. Jr. 1910. Geology of the Thousand Islands region – Alexandria Bay, Cape Vincent, Clayton, Grindstone and Theresa quadrangles. *New York State Museum Bulletin* **145**, 194 pp.

Dalziel, J. W. D., Salada, L. H. D. & Gahagan, L. M. 1994. Paleozoic Laurentian–Gondwana interaction and the origin of the Appalachian–Andean mountain system. *Geological Society of America Bulletin* **106**, 243–52.

Deiss, C. 1939. Cambrian stratigraphy and trilobites of northwestern Montana. *Geological Society of America Special Papers* **18**, 135 pp.

Dix, G. R., Salad Hersi, O. & Nowlan, G. S. 2004. The Potsdam–Beekmantown Group boundary, Nepean Formation type section (Ottawa, Ontario): a cryptic sequence boundary, not a conformable transition. *Canadian Journal of Earth Sciences* **41**, 897–902.

Emmons, E. 1838. Report of the Second Geological District of the State of New York. *New York State Geologist Second Annual Report*, pp. 185–252.

Emmons, E. 1841. Report of the Second Geological District of the State of New York. *New York State Geologist Fifth Annual Report*, pp. 113–36.

Emmons, E. 1844. *The Taconic system*. Pamphlet 4. Albany, NY (publisher unnamed), 67 pp.

Emmons, E. 1860. *Manual of Geology*. Philadelphia (publisher not named), 290 pp.

Fisher, D. W. 1956. The Cambrian System of New York. In *El Sistema Cambrico, su paleogragrafia y el problema de su base* (ed. J. Rodgers), pp. 321–51. 20th International Geological Congress Symposium, Part II, Mexico City.

Fisher, D. W. 1968. Geology of the Plattsburgh and Rouses Point, New York–Vermont quadrangles. *New York State Museum Map and Chart Series* **10**, 37 pp.

Fisher, D. W. 1977. Correlation of the Hadrynian, Cambrian, and Ordovician rocks in New York State. *New York State Museum Map and Chart Series* **25**, 75 pp.

Fisher, D. W., Isachsen, Y. W. & Rickard, L. V. 1970. Geologic map of New York – Adirondack sheet.*New York State Museum Map and Chart Series* **15**.

FISHER, D. W., ISACHSEN, Y. W. & RICKARD, L. V. 1971. Generalized tectonic–metamorphic map of New York. *New York State Museum Map and Chart Series* **16**.

FLOWER, R. 1964. The nautiloid order Ellesmeroceratida (Cephalopoda). *New Mexico Bureau of Mines and Mineral Resources Memoir* **12**, 234 pp.

FRANZI, D. A., RAYBURN, J. A., YANSA, C. H. & KNUEPFER, P. N. K. 2002. Late Wisconsinan lacustrine and marine history of the Champlain Lowland and its paleoclimate implications. In *Joint meeting of the New England Intercollegiate Geological Conference (94th Annual Meeting) and New York Geological Society (74th Annual Meeting)* (eds J. McLelland & P. Karabinos), pp. A5/1–A/512. Guidebook for Field Trips in New York and Vermont, Union College, Schenectady, New York.

FRITZ, W. H. 1971. Geological setting of the Burgess Shale. *Proceedings of the North American Paleontological Convention* **2**, 1155–70.

GATES, A. E., VALENTINO, D. W., CHIARENZELLI, J. R., SOLAR, G. S. & HAMILTON, M. A. 2004. Exhumed Himalayan-type syntaxis in the Grenville orogen, northeastern Laurentia. *Journal of Geodynamics* **37**, 337–59.

GEYER, G. 1996. The Moroccan fallotaspid trilobites revisited. *Beringeria* **18**, 89–199.

GEYER, G. & PALMER, A. R. 1995. Neltneriidae and Holmiidae (Trilobita) from Morocco and the problem of Early Cambrian intercontinental correlation. *Journal of Paleontology* **69**, 459–74.

GLOBENSKY, Y. 1982. Région de Vaudreuil. *Ministère de l'Énergie et des Ressources, Québec, Rapport Géologique* **199**, 63 pp.

GLOBENSKY, Y. 1987. Géologie des Basses-Terres du Saint-Laurent. *Ministère de l'Énergie et des Ressources, Québec, Rapport* **MM85-02**, 63 pp.

HALL, J. 1859. New American trilobites from the Hudson River Group of Vermont. *Canadian Journal, New Series* **4**, 491–3.

HALL, J. & WHITFIELD, R. P. 1877. Paleontology: fossils of the Potsdam Group. *U.S. Geological Exploration of the 40th Parallel Report* **4**, 199–231.

HOFMANN, H. J. 1972. *Stratigraphy of the Montreal area. 24th International Geological Congress, Montreal, Field Trip Guidebook* **B-03**, 34 pp.

ISACHSEN, Y. W., KELLY, W. M., SINTON, C., COISH, R. A. & HEITZLER, M. T. 1988. Dikes of the northeast Adirondack region – introduction to their distribution, orientation, mineralogy, chronology, magnetism, chemistry and mystery. *New York State Geological Association, 60th Annual Meeting, Field Trip Guidebook*, pp. 215–44.

KINDLE, C. H. & TASCH, P. 1948. Lower Cambrian fossils of the Monkton Formation of Vermont. *Canadian Field-Naturalist* **62**, 133–9.

KIRCHGASSER, W. & THEOKRITOFF, G. 1971. Precambrian and Lower Paleozoic stratigraphy, northwest Saint Lawrence and north Jefferson counties, New York. *New York State Geological Association, Annual Meeting, Field Trip Guidebook*, pp. B1–B24.

KRYNINE, P. D. 1948. Possible Algonkian in New York State. *Geological Society of America Bulletin* **59**, 1333–4.

KUMARAPELI, P. S. 1985. Vestiges of Iapetus rifting in the craton west of the northern Appalachians. *Geosciences Canada* **12**, 54–9.

KUMARAPELI, P. S. & SAULL, V. A. 1966. The St. Lawrence valley system: a North American equivalent to the East African rift valley system. *Canadian Journal of Earth Sciences* **3**, 639–58.

LANDING, E. 1983. Highgate gorge: upper Cambrian and lower Ordovician continental slope deposition and biostratigraphy, northwestern Vermont. *Journal of Paleontology* **57**, 1149–87.

LANDING, E. 2007. Ediacaran–Ordovician of East Laurentia – geologic setting and controls on deposition along the New York Promontory region. In *Ediacaran–Ordovician of East Laurentia – S. W. Ford memorial volume* (ed. E. Landing), pp. 5–24. New York State Museum Bulletin no. 510.

LANDING, E., BOWRING, S. A., DAVIDEK, K., WESTROP, S. R., GEYER, G. & HELDMAIER, W. 1998. Duration of the early Cambrian: U–Pb ages of volcanic ashes from Avalon and Gondwana. In *Cambrian subdivisions and correlations* (ed. E. Landing), pp. 329–38. *Canadian Journal of Earth Sciences* **35**.

LANDING, E., FRANZI, D. A., HAGADORN, J. W., WESTROP, S. R., KRÖGER, B. & DAWSON, J. C. 2007. Cambrian of East Laurentia: field workshop in eastern New York and western Vermont. In *Ediacaran–Ordovician of East Laurentia – S. W. Ford memorial volume* (ed. E. Landing), pp. 25–80. New York State Museum Bulletin no. 510.

LANDING, E. & WESTROP, S. R. 2006. Early Ordovician faunas, stratigraphy, and sea-level history of the middle Beekmantown Group, northeastern New York. *Journal of Paleontology* **80**, 958–80.

LANDING, E., WESTROP, S. R. & KNOX, L. A. 1996. Conodonts, stratigraphy, and sea-level changes of the Tribes Hill Formation (lower Ordovician, east-central New York). *Journal of Paleontology* **70**, 656–80.

LAVOIE, D., BURDEN, E. & LEBEL, D. 2003. Stratigraphic framework for the Cambrian–Ordovician rift and passive margin succession from southern Quebec to western Newfoundland. *Canadian Journal of Earth Sciences* **40**, 177–205.

LEWIS, D. W. 1971. Qualitative petrographic interpretation of the Potsdam Sandstone (Cambrian), southwestern Quebec. *Canadian Journal of Earth Sciences* **8**, 853–82.

LOCHMAN, C. 1968. *Crepicephalus* faunule from the Bonneterre Dolomite (upper Cambrian) of Missouri. *Journal of Paleontology* **42**, 1153–62.

MARCOU, J. 1888. The Taconic of Georgia and the report on the geology of Vermont. *Proceedings of the Boston Society of Natural History* **4**, 105–31.

MCRAE, L. E., JOHNSON, G. D. & JOHNSON, N. M. 1986. Temporal reevaluation of late Hadrynian non-marine facies in the Adirondack border region, New York State, southeastern Ontario, and southwestern Quebec. *Geological Society of America Abstracts with Programs* **18**(1), 54.

MEEK, F. B. 1874. Report on invertebrate fossils. In *Preliminary Geographic and Geologic Exploration and Survey west of the 100th Meridian* (ed. C. A. White), pp. 6–34. U.S. Geological Survey.

MEHRTENS, C. J. 1987. Stratigraphy of the Cambrian platform in northwestern Vermont. In *Centennial field trip guide. Volume 5* (ed. C. J. Roy), pp. 229–32. Geological Society of America, Northeastern Section.

NELSON, A. E., WIESNET, D. R., CARSWELL, L. D. & POSTEL, A. W. 1956. Geologic map of the Chateaugay quadrangle, New York. *U.S. Geological Survey Miscellaneous Geologic Investigations, Map* **I-168**.

NORTH AMERICAN COMMISSION ON STRATIGRAPHIC NOMENCLATURE. 1983. North American Stratigraphic Code. *American Association of Petroleum Geologists Bulletin* **67**, 841–75.

Otvos, E. G. Jr. 1966. Sedimentary structures and depositional environments, Potsdam Formation, upper Cambrian. *Bulletin of the American Association of Petroleum Geologists* **50**, 159–85.
Palmer, A. R. & Gatehouse, C. G. 1972. Early and middle Cambrian trilobites from Antarctica. *U.S. Geological Survey Professional Paper, Report* **P 0456-D**, 37 pp.
Peng, S. C., Babcock, L. E., Robison, R. A., Lin, H. R., Rees, M. N. & Saltzman, M. R. 2004. Global standard stratotype-section and point (GSSP) of the Furongian Series and Paibaian Stage (Cambrian). *Lethaia* **37**, 365–79.
Postel, A. W., Wiesnet, D. R. & Nelson, A. E. 1959. Geologic map of the Malone quadrangle, New York. *U.S. Geological Survey Miscellaneous Geologic Investigations, Map* **I-167**.
Poulsen, C. 1927. The Cambrian, Ozarkian, and Canadian faunas of northwest Greenland. *Meddelelser om Grønland* **70**, 233–343.
Rasetti, F. 1951. Middle Cambrian stratigraphy and faunas of the Canadian Rocky Mountains. *Smithsonian Miscellaneous Collections* **116**, 1–277.
Rasetti, F. 1963. Middle Cambrian ptychoparoid trilobites from the conglomerates of Quebec. *Journal of Paleontology* **37**, 575–94.
Rayburn, J. A., Knuepfer, P. L. K. & Franzi, D. A. 2005. A series of late Wisconsinan meltwater floods through the Champlain and Hudson valleys, New York. In *Re-assessing the role of meltwater processes during Quaternary glaciations* (eds T. G. Fisher & A. J. Russell), pp. 2410–19. *Quaternary Science Reviews* **24**.
Resser, C. E. 1935. Nomenclature of some Cambrian trilobites. *Smithsonian Miscellaneous Collections* **93**(5), 1–46.
Resser, C. E. 1937. Third contribution to nomenclature on Cambrian trilobites. *Smithsonian Miscellaneous Collections* **95**(22), 59 pp.
Resser, C. E. 1938. Cambrian System (restricted) of the southern Appalachians. *Geological Society of America Special Paper* **15**, 140 pp.
Richter, R. 1933. Crustacea. *Handwörterbuch der Naturwissenschaften*, **2**, pp. 840–64. University of Jena.
Salad Hersi, O. & Lavoie, D. 2000. Pre-Cairnside Formation carbonate-rich sandstone: an evidence for a Cambrian carbonate platform in southwestern Quebec? *Current Research, Geological Survey of Canada* **2000-D**, 1–10.
Salad Hersi, O., Lavoie, D., Mohamed, A. H. & Nowlan, G. S. 2002. Subaerial unconformity at the Potsdam–Beekmantown contact in the Quebec Reentrant: regional significance for the Laurentian continental margin. *Bulletin of Canadian Petroleum Geology* **50**, 419–40.
Salad Hersi, O., Lavoie, D. & Nowlan, G. S. 2003. Reappraisal of the Beekmantown Group sedimentology and stratigraphy, Montreal, southwestern Quebec: implications for understanding the depositional evolution of the lower–middle Ordovician Laurentian passive margin of eastern Canada. *Canadian Journal of Earth Sciences* **40**, 149–76.
Sandford, B. V. 1993. St. Lawrence platform – geology. In *Sedimentary cover of the craton in Canada* (eds D. F. Scott & J. D. Aitken), pp. 723–86. Geological Survey of Canada, Geology of Canada, No. 5.
Selleck, B. W. 1978. Paleoenvironments of the Potsdam Sandstone and Theresa Formation of the southwestern St. Lawrence Lowland. In *New York State Geological Association Field Trip Guidebook, 50th Annual Meeting, St. Lawrence University*, pp. 173–83.
Shaw, A. B. 1955. Paleontology of northwestern Vermont. V. The lower Cambrian fauna. *Journal of Paleontology* **29**, 775–805.
Shaw, A. B. 1958. Stratigraphy and structure of the St. Albans area, northwestern Vermont. *Geological Society of America Bulletin* **69**, 519–68.
Sundberg, F. A. 1991. Paleogeography of western Utah and eastern Nevada during the *Ehmaniella* Biochron (middle Cambrian). In *Paleozoic paleogeography of the western United States, II* (eds J. D. Cooper & C. H. Stevens), pp. 387–99. Society of Economic Paleontologists, Pacific Section, 67.
Sundberg, F. A. 1994. Corynexochida and Prychopariida (Trilobite, Arthropoda) of the *Ehmaniella* Biozone (middle Cambrian), Utah and Nevada. *Contributions in Science, Natural History Museum of Los Angeles County* **446**, 137 pp.
Swinnerton, H. H. 1915. Suggestions for a revised classification of trilobites. *Geological Magazine (New Series)* **2**, 407–96, 538–45.
Thomas, W. A. 1977. Evolution of the Appalachian–Ouachita salients and recesses from reentrants and promontories in the continental margin. *American Journal of Science* **277**, 1233–78.
Vogdes, A. W. 1893. A classification and annotated bibliography of the Paleozoic Crustacea, 1698–1892, to which is added a catalogue of North American species. *Proceedings of the California Academy of Sciences* **1907**, 412 pp.
Walcott, C. D. 1890. The fauna of the lower Cambrian or *Olenellus* Zone. *U.S. Geological Survey Tenth Annual Report 1888–1889*, pp. 509–763.
Walcott, C. D. 1891. Correlation papers, Cambrian. *U.S. Geological Survey Bulletin* **81**, 477 pp.
Walcott, C. D. 1912. New York Potsdam–Hoyt fauna. *Smithsonian Miscellaneous Collections* **57**, 251–304.
Walcott, C. D. 1924. Cambrian geology and paleontology, V, No. 2, Cambrian and lower Ozarkian trilobites. *Smithsonian Miscellaneous Collections* **75**, 51–60.
Wiesnet, D. R. 1961. Composition, grain size, roundness, and sphericity of the Potsdam Sandstone (Cambrian) in northeastern New York. *Journal of Sedimentary Petrology* **31**, 5–14.
Wiesnet, D. R. & Clark, T. H. 1966. The bedrock structure of Covey Hill and vicinity, northern New York and southern Quebec. *U.S. Geological Survey Professional Paper* **550-D**, D35–D38.
Wilmarth, M. G. 1938. Lexicon of geologic names of the United States (including Alaska). *U.S. Geological Survey Bulletin* **896**, 2396 pp.
Wilson, A. E. 1946. Geology of the Ottawa–St. Lawrence Lowland, Ontario and Quebec. *Canada Geological Survey Memoir* **241**, 65 pp.
Wolf, R. R. & Dalrymple, R. W. 1984. Sedimentology of the Cambro-Ordovician sandstones of eastern Ontario. *Ontario Geological Survey Miscellaneous Paper* **121**, 240–52.
Young, G. A. & Ludvigsen, R. 1989. Mid-Cambrian trilobites from the lowest part of the Cow Head Group, western Newfoundland. *Geological Survey of Canada Bulletin* **392**, 49 pp.

Appendix 1. Stratigraphic nomenclature of Potsdam Formation

Clark (1966, 1972) proposed the Covey Hill and Cairnside formations, respectively, for intervals that comprise the lower and upper part of the Potsdam in southwest Quebec, but

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which are lithologically comparable to the earlier proposed Ausable and Keeseville members of New York (Alling, 1919 and Emmons, 1841, respectively). Without explanation, Clark (1966) also elevated the Potsdam to a group-level unit, a change in status that may have been prompted by the fact that the Beekmantown Group overlies the Potsdam, and, perhaps, Clark (1966) felt that the Beekmantown should be underlain by a group-level unit. In reviewing the nomenclature of the Potsdam, Clark (1966) did not completely discuss the existing stratigraphic divisions of the Potsdam to the south in northern New York. As noted by Wilmarth (1938, pp. 93, 1078–9), Emmons' (1841) 'Keeseville sandstone' had come to be understood as the upper 'white Potsdam sandstone' by the early 20th century (e.g. Chadwick, 1915, 1920; Alling, 1919), while the Ausable is the lower, reddish and feldspathic Potsdam under the 'white Potsdam sandstone'. Clark (1966, table p. 6) tentatively regarded the Keeseville as the 'lithic correlative' of his Cairnside interval (originally proposed as a member), and never referred to the underlying Ausable sandstones in adjacent New York as a potential senior synonym/'lithic correlative' to his Covey Hill Formation.

Two formation-level terms that must be regarded as invalid are 'Allens Falls' (Krynine, 1948) and 'Nicholville' (Postel, Nelson & Wiesnet, 1959). These terms have been used for the lowest Potsdam or as sub-Potsdam formations that rest on the Grenville orogen in northwest New York (e.g. Fisher, 1968, 1977). These 'units' were never formally defined in the literature; 'Allen Falls' appeared as a name in an abstract and 'Nicholville' appeared as an undefined map unit. The 'Allen Falls' and 'Nicholville' were named from isolated conglomerate and sandstone outcrops from the thin Potsdam successions on the southwest margin of the Ottawa–Bonnechere aulocogen. Both 'units' are considered herein as local, lower, coarser-grained and, possibly, terrestrial facies of the upper Potsdam (that is, Keeseville Member), and are lithologically comparable to the lower 'Nepean Sandstone' further north in Ontario (see Wolf & Dalrymple, 1984; E. Landing, unpub. field data).

Our evaluation of the nomenclature of the Potsdam is that a simplified, uniform lithostratigraphic nomenclature should be applied in New York, Ontario and Quebec. We agree with Lewis (1971, p. 855) that 'studies of the sandstones . . . may show that Cairnside should be replaced by . . .. Keeseville (see Wilmarth, 1938; Fisher, 1956)', and also see 'Covey Hill' as a junior synonym of Ausable. Indeed, 'Covey Hill' is a synonym of itself, and cannot be maintained as a lithostratigraphic term, because Clark (1966) proposed 'Covey Hill' as a formation and as a member-level unit of that formation (Fig. 2, 'Covey Hill (restricted)'; see North American Commission on Stratigraphic Nomenclature, 1983, Article 19). Another local term for Potsdam sandstones is Wilson's (1946) 'Nepean Sandstone', which includes lower, reportedly fluvial, and higher shallow-marine quartz arenites in the western Ottawa–Bonnechere aulocogen in Ontario (Wolf & Dalrymple, 1984; Dix, Salad Hersi & Nowlan, 2004). Indeed, Clark (1966, p. 33) noted that 'Nepean' includes sandstones traditionally termed 'Potsdam'. Both the dominant lithologies and their stratigraphic positions lead us to propose that the 'Nepean' and 'Cairnside' formations are best regarded as junior synonyms of the Keeseville Member. Finally, as the Keeseville and Ausable sandstones can be distinguished as lithologically distinct, member-level divisions of the Potsdam (Fisher, 1956, 1968, 1977), the Potsdam is best regarded as a formation-level lithostratigraphic unit in its type region of northern New York. The 'Potsdam Group' in adjacent Quebec (e.g. Clark, 1966, 1972) is also best termed the 'Potsdam Formation'.

Appendix 2. Altona Formation (new)

The Altona Formation (new) is a lithologically distinctive, heterolithic unit that includes feldspathic and quartzose quartz arenites, local quartz and feldspathic granule–pebble conglomerates, siliciclastic mudstones, and bedded carbonates (now hydrothermal dolostones). The Altona nonconformably overlies middle Proterozoic (*c.* 1 Ga) gneisses and associated intrusives, and is overlain by the Ausable Member of the Potsdam Formation. The thickness of the Altona Formation is ∼ 84 m in borehole 1-02 in the type area of the formation in Clinton County, New York. Borehole 1-02 is in the southeastern part of the Altona Flat Rock, from which the name 'Altona Formation' is derived. 'Altona' is not in use for any stratigraphic unit in North America, but has been used provisionally ('Altona Formation' within quotation marks) for this identical stratigraphic interval in a recent regional geological synthesis and field trip guide (Landing, 2007; Landing *et al.* 2007). Representative sections in the Altona Formation include a succession low in the formation along the road-cut and drainage ditch along Rte 190 and a relatively continuous succession high in the formation along the Little Chazy River on Atwood Farm. These two representative sections, with the Atwood Farm succession selected as the type section of the formation, suggest that the Altona Formation can be divided into two informal units. These include an informal lower 'member 1' dominated by interbedded feldspathic sandstones and purple, red and brownish mudstones, and a upper 'member 2' with comparable mudstones, thin- to medium-bedded dolostones, and subordinate feldspathic and quartzose sandstones (Fig. 4). Trace and body fossils and sedimentary structures of the Altona Formation are all consistent with deposition under marine-dominated conditions. Trilobites from the lower and upper parts of the Altona indicate a terminal early Cambrian–middle middle Cambrian correlation of the formation.