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Early Paleozoic rifting and reactivation of a passive-margin rift: Insights from detrital zircon provenance signatures of the Potsdam Group, Ottawa graben: Comment

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This comment outlines fundamental problems in Lowe et al.'s synthesis (2018) of the early Paleozoic stratigraphic architecture of the eastern Ottawa-Bonnechere aulacogen that preclude an accurate analysis of the region's geological and depositional history and even an adequate stratigraphic provenance of the detrital zircons that they analyze. These problems include: inaccurate lithostratigraphic and contradictory biostratigraphic correlations that have also led to extension of the Potsdam "Group" into the Lower Ordovician; a proposed allostratigraphy that contradicts itself when tested with existing litho- and biostratigraphic data; redefinitions of earlier defined lithostratigraphic units that lead to confusion on close reading; and errors in interpreted depositional environments and lithostratigraphic contacts.

Rodinia break-up and the early Paleozoic history of NE Laurentia are recorded by structural evidence, volcanics, and siliciclastic rocks associated with an ~700-km-long graben system that extends from the Sudbury, Ontario, region into the Appalachian orogen. This down-dropped Ottawa-Bonnechere aulacogen (OBa), a major cratonic graben terminating in an orogen, is one of the oldest recognized aulocogens (Shatsky, 1946, 1955; Burke, 1977; Landing et al., 2009). It may be the failed arm of a triple junction, suggested by evidence of a mantle plume in northern Vermont (Fig. 1, Tibbet Hill volcanics), or a rift segment offset by transform faults (review in Webster and Landing, 2016). The age(s) and vertical and lateral continuity of sedimentary rocks are key to determining sediment and detrital zircon provenance and paleogeography of the OBa. Lowe et al. (2018, also 2017) combine outcrop with drill core data in an area with low relief, much Quaternary cover, and many syn- and post-depositional faults. As suggested, in part, above, problems in Lowe et al.'s (2018, also 2017) OBa synthesis include: (1) a stratigraphic nomenclature that redefines, without comment, a number of earlier defined units (e.g., their "Potsdam" and "Hannawa Falls"); (2) extension of the "Potsdam Group" up into the Ordovician; (3) correlations (e.g., their "Rivière aux Outardes Member") that subvert the allostratigraphic synthesis; (4) not relating the succession to eustatic signatures and sequence stratigraphy elsewhere in east Laurentia; (5) biostratigraphic errors in correlation; (6) misrepresentation of stratigraphic contacts and depositional facies (e.g., Altona and Theresa formations).

The older rocks in the eastern OBa are termed "Potsdam Formation" in the type area of northern New York, and have a feldspar-rich, nonfossiliferous lower interval and an upper, generally white-colored quartz arenite unit (respectively, Ausable and Keesville members; e.g., Fisher, 1968; Landing et al., 2009; Fig. 1). Clark (1966) elevated the Potsdam to group status, likely as he wanted to subdivide the sandstones members, but did not then have the ability to name formal submembers, as proposed by the North American Commission on Stratigraphic Nomenclature (NACSN, below; Brett et al., 2018). "Potsdam Group" is not a uniform concept. Clark's (1966) "Potsdam Group" included upper sandstones and dolostones now brought to the Lower Ordovician Theresa Formation, and Sanford and Arnott (2010) and Lowe et al. (2017, 2018) expanded the "Group" by including the lithologically dissimilar Altona Formation (Landing et al., 2009) as a basal member, while defining nomenclaturally different "Potsdam" subdivisions. Thus, the Ausable Formation sensu Lowe et al. (2018) is up to 400 m thicker than Sanford and Arnott's (2010) Covey Hill (Ausable) Formation and is a different stratigraphic concept as they assigned the Chippewa Bay and Edwardsville members of Sanford and Arnott (2010) to their Keeseville Formation. Another nomenclatural problem in Lowe et al. (2018, also 2017) is restriction and upgrading of Sanford and Arnott's (2010) Hannawa Falls Member (to 199 m of red fluvial siliciclastics and upper dune sand) within the Covey Hill (Ausable) Formation to 0–25 m of aeolian sandstone of a "Hannawa Falls Formation" that overlies the Ausable. NACSN (2005) recommendations on "redefinition" mean the Hannawa Falls of Sanford and Arnott (2010) should have a different name when "restricted" to the dune sandstone. Furthermore, the selection of different horizons for the Covey Hill (Ausable)–Keeseville contact leads to distinction of a "Potsdam Group" sensu Sanford and Arnott (2010), sensu Lowe et al. (2017, 2018), and sensu Clark (1966). Such awkward terms are simplified below by use of the traditional "Potsdam Formation" (Fig. 1).

The generally unfossiliferous, lowest siliciclastics in the eastern OBa (SE Ontario–northern New York–SW Quebec) are regarded in many reports to record Ediacaran subsidence (e.g., Sanford and Arnott, 2010, their fig. 5; review in Landing et al., 2009). However, the oldest sedimentary rocks of the eastern OBa are surprisingly young and show abrupt late Early Cambrian marine onlap with subsidence of the "mouth" of the OBa south and SSW of Montreal, with coeval faulting and down-drop of the northern Vermont shelf ~80 km ESE to form the anoxic Franklin Basin (Landing, 2007, 2012; Landing et al., 2007, 2009; Fig. 1). This rejuvenation of a passive margin (eastern OBa and on-strike Franklin Basin) persisted into the middle Cambrian with deposition of higher

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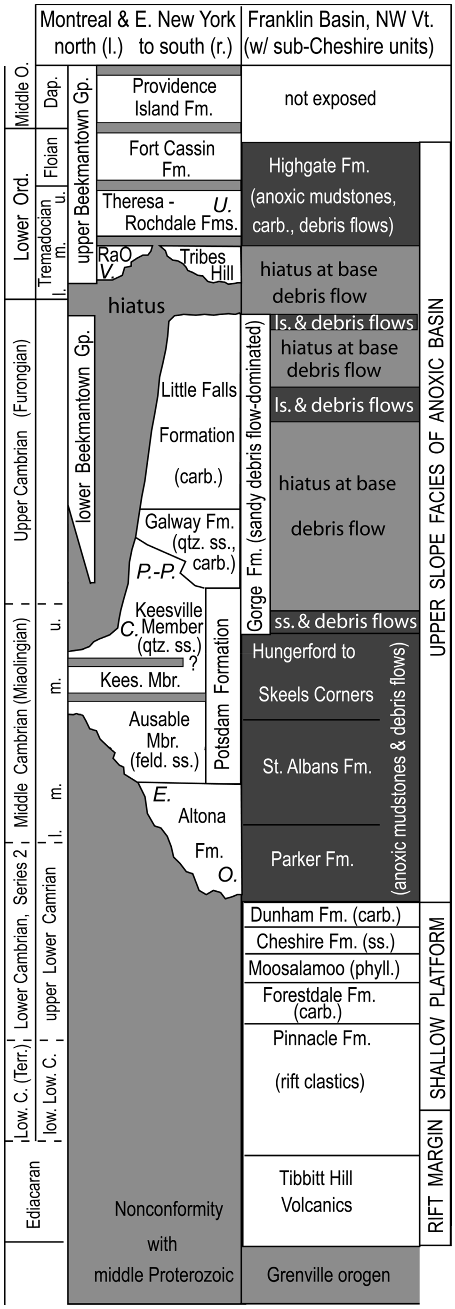

Figure 1. Composite eastern OBa and Franklin Basin successions (modified from Landing et al., 2009, fig. 9). Covey Hill (Ausable) of Sanford and Arnott (2010) to 400 m thicker than Ausable of Lowe et al. (2018); intra-Keeseville unconformity (Lowe et al., 2018) not reported in equivalent Cairnside-Keeseville-Nepean Formation (Sanford and Arnott, 2010). RaO is purported Rivière aux Outardes Member of Keeseville Formation of Lowe et al. (2017, 2018), but is a siliciclastic-dolostone interval correlated herein with Tribes Hill Formation and identical Saint-Clotilde Member. Figure divides Cambrian into three global subseries (e.g., Landing et al., 2018, fig. 1 caption and references therein): Lower—Terreneuvian Series + Series 2; Middle—Mialoingian Series; Upper—Paibaian Series. Abbreviations: C.—Cambrian; carb.—carbonate; Dap.—Dapingian; *E.—Ehmaniella*; Fm.—Formation; Gp.—Group; Kees.—Keeseville; l./low./Low.—lower/lower/Lower; ls.—limestone; m—middle; Mbr.—Member; *O.—Olenellus*; *P.-P.—Prosaukia-Ptychaspis*; phyll.—phyllite; RaO—"Rivière aux Outardes"; ss.—sandstone; u.—upper; *U.—Ulrichodina quadraplicatus*, *V.—Variabiloconus bassleri*.

marine deposits of the Altona Formation and their upward replacement by Ausable Formation fluviatile arkoses (Landing et al., 2009).

Sanford and Arnott (2010, p. 26) substituted "Jericho Member" for Landing et al.'s (2009) Altona Formation and noted the latter "were presumably unaware of the term "Jericho Member" previously proposed for the same strata" in a 2004 technical report for the New York State Energy Research and Development Authority. However, stratigraphic units cannot be proposed in unpublished reports (NACSN, 2005). In any case, the Altona became the lowest member of the Covey Hill (Ausable) in Sanford and Arnott (2010) and Ausable of Lowe et al. (2017, 2018) formations.

Lowe et al. (2018, p. 1380, their fig. 3) state that the Altona "intertongues with fluviatile arkose of the Ausable Formation" and incorrectly cited Landing et al. (2009) as holding this opinion. Lowe et al. (2018, fig. 3, lower) incorrectly show the Altona above fluviatile arkose of an undifferentiated Ausable Formation in its type area. However, a borehole in its type area shows the Altona resting on middle Proterozoic basement without intervening arkose (Landing et al., 2007, 2009; Fig. 1). In the Quonto-International St. Vincent de Paul No. 1 core near Montreal ~60 km NNE of the type locality, Lowe et al. (2018, fig. 3, upper) also show the Altona separated from middle Proterozoic basement by several meters of undifferentiated Ausable fluvial arkose. This is contradicted by Sanford and Arnott (2010, p. 26) who assign the lowest part of this core to the Altona ("Jericho Member"). Furthermore, the top of the purported "Ausable Formation" under the Altona in the core (Lowe et al., 2017, their fig. 7A and table 3 caption) differs from the fluviatile, "red to grey coarse-grained arkose" of the Ausable and is most similar to the trough cross-bedded, whitish, feldspathic quartz arenite of member 1 of the Altona in its type area (Landing et al., 2009, their fig. 4). Almost all "Altona" localities that yielded Proterozoic detrital zircons (Lowe et al., 2018, their table 1, samples AS-2–5) are "braided fluvial." This is not an Altona facies (Landing et al., 2009) and is better referred to as an "undifferentiated Ausable Formation." Reevaluation of Lowe et al.'s (2018) "Altona" outcrops in Quebec and Ontario may be needed.

The Altona Formation is an important unit in the OBa. It is relatively thick in its type area (84 m) and the only Cambrian OBa unit that is bracketed biostratigraphically. Upper lower and middle Middle Cambrian trilobites from the Altona (Landing et al., 2009) indicate it brackets an ~7 m.y. interval (i.e., late Early and middle Middle Cambrian dates in Landing et al., 1998, 2015) that may exceed any other OBa Cambrian unit in duration.

The Altona is not a "tidal flat" facies (i.e., Lowe et al., 2018, fig. 3; also 2017). Trough cross-bedded sandstone likely deposited under trade wind control dominates in lower member 1, and hummocky cross-stratified (HCS) sandstone occurs in upper member 2 (Landing et al., 2009; Lowe et al., 2017, their fig. 8A). As HCS has depths of formation of 13–50 m (e.g., Dumas and Arnott, 2006), assignment of the Altona to a tidal flat facies is incorrect. Thick dolostones with large burrows in the upper Altona do not reflect intertidal, evaporitic facies (Lowe et al., 2017, p. 7) but record the hydrothermal dolomitization with minor sulphide mineralization common in eastern New York (Landing et al., 2007, 2009). Thinner dolostones with planar laminae (e.g., Lowe et al., 2017, their figs. 8B and 8C) likely show downslope(?) transport of carbonate and quartz silt, and the dolomite–organic-rich laminae figured by Lowe et al. (2017, figs. 8B, 8C) are not intertidal "microbial mats" but horizontal stylolites. Similarly, normally graded feldspathic quartz arenites high in the Altona (Landing et al., 2009, their fig. 4; Lowe et al., 2017, p. 10, their fig. 8D caption) do not record "sheetfloods near the mouth of a nearby braided river" but are likely subtidal shelf tempestites.

The Altona Formation reflects long-term (7 m.y.) marine deposition at the mouth of the OBa and represents a facies belt across which little sand was transported into the Franklin Basin during Parker Formation deposition (Fig. 1). Lowe et al. (2018) speculate that the open shelf (not intertidal) Altona intertongues with fluviatile sandstone of the undifferentiated Ausable Formation. However, Altona deposition may have largely preceded possible middle Middle Cambrian intensification of OBa faulting, increased production of "Ausable arkoses," and abrupt upward replacement of the Altona shelf by Ausable fluviatile sands (Fig. 1).

Sanford and Arnott (2010) provide no reason to downgrade the Altona Formation (their "Jericho Member") to a member and include it as the base of their Covey Hill (Ausable) Formation. Lowe et al.'s (2017, p. 6) argument using NACSN (2005) Article 25b to make the Altona a member of their Ausable Formation is moot: no evidence indicates that the geochronologically long-ranged Altona is intercalated with, rather than largely older than, Ausable Formation fluvial arkoses (Landing et al., 2009; Fig. 1). Even if part of the Altona is intercalated with the undifferentiated Ausable Formation of Lowe et al. (2018), the lithic differences (marine shelf feldspathic quartz arenite, red mudstone, and dolostone versus fluviatile, subaerial red and gray arkose) and the relatively tabular form of the Altona comport with assignment to a formation—a lithostratigraphic grade that reflects a recommendation that formations should correspond whenever possible to genetic units (NACSN, 2005, Articles 23e, 24 introduction, 24c).

Stratigraphic continuity of the Potsdam Formation is broken by several regionally extensive hiatuses (Fig. 1). The durations of these breaks are difficult to bracket because of the absence of fossils in the Ausable Formation sensu Lowe et al. (2018) (but without the Altona Formation as a basal "member") and their rarity in the quartz arenite-dominated Keeseville Formation sensu Lowe et al. (2017, 2018, fig. 3). As discussed below, available fossils restrict the Potsdam Formation to the Cambrian and preclude its description as "Cambrian–Ordovician" (e.g., Sanford and Arnott, 2010; Lowe et al., 2017, 2018).

The oldest fossils known in the Keeseville Member (Fig. 1) are Laurentian *Crepicephalus* Zone trilobites found near the Quebec–New York border (Fisher, 1968) and farther south near Fort Ann, New York (Landing et al., 2007, stop 1.4). Not noted by Lowe et al. (2018, fig. 3, lower), these upper middle Cambrian trilobites suggest the upper Altona Formation–lower Keeseville interval was ~3 m.y. long (i.e., ca. 503 Ma date on the upper Altona, noted above, and ca. 500 Ma date in the *Crepicephalus* Zone fide Peng and Babcock, 2008). Thus, the Ausable Formation (without the Altona), the Ausable–Keeseville hiatus, and the lower Keeseville (Lowe et al., 2018, fig. 3, lower) bracket less time than the Altona. Lowe et al. (2018, fig. 3, lower) show a long hiatus below the Keeseville with almost none of the member extending into the upper middle Cambrian. However, the widespread occurrence of *Crepicephalus* Zone trilobites in eastern New York suggests that much more of the Keeseville in the SE OBa is upper middle Cambrian.

The youngest fossils that can be confidently related to the Keeseville Member are the trilobites *Ptychaspis* and *Prosaukia* (Fisher, 1968). These taxa must not be figured at the Cambrian–Ordovician boundary (Lowe et al., 2018, fig. 3 lower, assemblage b), but occur about in the middle upper Cambrian in sandstone-rich facies of the Upper Mississippi Valley. A ca. 500 Ma estimate on lower Keeseville trilobites and a ca. 494 date (hazarded herein) on the Upper Mississippi Valley *Ptychaspis-Prosaukia* Zone correlated into the *Ellipsocephaloides-Idahoia* Zone of south Laurentian carbonate facies (see chronology Peng and Babcock, 2008) mean the oldest and youngest trilobites known from the Keeseville suggest a duration roughly comparable to or even less than the Altona Formation.

The belief that northerly and westerly diachronous onlap of the Potsdam continued into the Early Ordovician (e.g., Fisher, 1968) is not supported by any evidence. This conclusion has been "justified" with the reassignment, without discussion by Sanford and Arnott (2010), of lithologically problematical sandstones with upper Tremadocian conodonts from the Theresa Formation (Dix et al., 2004) to the Nepean Formation and correlation of these sandstones with the purportedly coeval Keeseville. However, an unbroken Cambrian–Ordovician succession in the OBa is unlikely. With exception of the Great Basin and Southern Oklahoma aulacogen, continuous boundary interval sequences are unknown on the Laurentian shelf, where an unconformity separates upper Cambrian and lower, not lowermost, Tremadocian rocks (e.g., Landing, 1988).

The best evidence that the upper Potsdam Formation is not Lower Ordovician and that the stratigraphic architecture of the OBa preserves a eustatic signature and is more complex than portrayed is presented by Lowe et al. (2018, fig. 3, upper, assemblage e). They figure a "Cambrian–Ordovician boundary" fauna from the top of allounit 2 and top of their "Rivière aux Outardes Member" (RaO) of the "middle Keeseville." This report is very problematical. The RaO was named (Clark, 1966) from SW Quebec based on sandstones that are finer-grained than the overlying uppermost Potsdam and have swale-like structures. He never reported the RaO as "a locally calcareous marine unit" fide Lowe et al. (2017, p. 16), although Salad Hersi and Lavoie (2000b) found a dolomitic sandstone-rich interval of the RaO north of Montreal.

Lowe et al. (2018, fig. 3, upper) show their "RaO" extending from Quebec along the northern OBa outcrop belt into Ontario. Their assignment of their "RaO" to the lower part of the quartz arenite-dominated Keeseville is unwarranted as the RaO is feldspathic in its type area and best referred to the Ausable (e.g., Salad Hersi and Lavoie, 2000a). It is unclear how Lowe et al. (2017, p. 16) recognize the "RaO" (their allounit 2) as they only note that Salad Hersi and Lavoie (2000b) "did not recognize the cryptic unconformity between the Ausable and Keeseville." Actually, a "paleokarst" caps the RaO in its type area (Salad Hersi and Lavoie, 2000b, fig. 5), which alternatively, might fit well as the unconformity at the top of the Covey Hill (Ausable) of Sanford and Arnott (2010) and within the same strata later, confusingly, termed "Keeseville Formation" by Lowe et al. (2018). Unfortunately, there is a second unconformity above the type RaO and in the quartz arenites of the "Cairnside Formation" (=Keeseville) in Quebec (Salad Hersi and Lavoie, 2000a). This second unconformity is not accounted for in Lowe et al.'s (2018, fig. 3) allostratigraphy and lithostratigraphic synthesis and leads to a questioning of their stratigraphic architecture of the Potsdam Formation.

The correlation and best name for Lowe et al.'s (2018, fig. 3, upper) "RaO" and its significance as a key unit of their "allounit 2" are problematical. Sanford and Arnott (2010) termed this interval the Edwardsville and Chippewa Falls members of the Covey Hill (Ausable) Formation, and G.S. Nowlan (*in* Lowe et al., 2017, their appendix 1) recovered conodont elements from the "Chippewa Falls Member" at the Rockland outcrop in Ontario. The lithostratigraphic assignment of these conodont-bearing strata is, frankly, obscure, as the Rockland locality has three formational assignments in the earlier literature. The "Chippewa Falls Member" strata of G.S. Nowlan's report (i.e., Covey Hill [Ausable] Formation of Sanford and Arnott, 2010) are also termed the RaO Member of the Keeseville "Formation" in the same report (Lowe et al., 2017). In addition, Sanford and Arnott (2010, p. 37) described the Rockland rocks as Nepean (i.e., Keeseville) Formation. However, the dolostone (unknown elsewhere in the Nepean)-quartz sandstone association at Rockland is comparable to facies traditionally referred to the Lower Ordovician Theresa Formation (e.g., Salad Hersi et al., 2002).

Nomenclatural problems aside, the age-diagnostic conodont *Variabiloconus bassleri* was found in "RaO" samples at Rockland; this supplies a fourth stratigraphic interpretation that is preferred herein and mandates reevaluation of the OBa stratigraphic architecture of Lowe et al. (2018, fig. 3). This fossil occurrence is placed at the Cambrian–Ordovician boundary and top of allounit 2 by Lowe et al. (2018, fig. 3, upper, assemblage e). However, *V. bassleri* is a diagnostic upper lower Tremadocian form and suggests an age of ca. 483 ± 1 Ma (Landing et al., 1997), which is ~5 m.y. younger than the top of the Cambrian and ~9 m.y. younger than the "guesstimate" on the youngest confidently known Keeseville trilobites. More importantly, *V. bassleri* is characteristic of the lowest Ordovician depositional sequence that occurs across Laurentia (Fig. 1, "RaO").

Coeval, but carbonate-dominated, upper lower Tremadocian rocks occur in the southern OBa in New York (Fisher's, 1968, "Spellman Formation," and Tribes Hill Formation of Landing et al., 2012) and SW Quebec (identical Saint-Clotilde Member in Clark, 1966). However, these Lower, not lowermost, Ordovician Tribes Hill–Saint–Clotilde carbonates are not figured nor are their relationships shown to lower Paleozoic allounits in the OBa by Lowe et al. (2018, fig. 3, lower). These carbonates correlate with the "RaO" locality with *V. bassleri*. Thus, this "RaO" locality is much younger than allounit 2/allounit 3 of the Potsdam Formation in the OBa, and cannot be fundamental to defining allounit 2. The conodont-bearing "RaO" locality seems to record a siliciclastic-rich equivalent of the Tribes Hill depositional sequence, the lowest part of which has siliciclastic mudstone and thin sand in New York (Fig. 1; e.g., Landing et al., 2012).

As detailed by Landing (2012), the Potsdam is succeeded by two formations of the Beekmantown Group composed of carbonates (limestone/hydrothermal dolostone) with minor quartz arenites in eastern New York. Both of these similar formations have been mistakenly referred to the "Theresa Formation" of the eastern OBa in a number of reports. The Theresa in its type region of southern Ontario and into SW Quebec is a Lower Ordovician unit. It has conodonts (e.g., *Ulrichodina quadraplicata*; *Calaptoconus quadraplicatus* in Lowe et al., 2017) no older than late Tremadocian, is thus younger than the Tribes Hill depositional sequence, and unconformably locally overlies quartz arenites of the Potsdam "Group" (Salad Hersi et al., 2002; Dix et al., 2004). The Theresa is regarded as a siliciclastic-rich equivalent of an upper Tremadocian depositional sequence known as the carbonate-dominated Rochdale (="Fort Ann") Formation in eastern New York (e.g., Landing et al., 2012; Fig. 1).

A similar dolostone and quartz arenite unit is the late Cambrian Galway Formation, which conformably overlies and is laterally equivalent to the upper Potsdam in eastern New York (e.g., Landing, 2012), The Galway has been mapped as "Theresa" on the OBa's south flank (e.g., Fisher, 1968). Lowe et al.'s (2018, fig. 3, lower) illustration of a sandstone-dolostone interval conformable with the Potsdam is likely correct, but this overlying interval is upper Cambrian Galway and not Lower Ordovician Theresa Formation. The "Theresa" is not a diachronous, westerly younging "Cambrian–Ordovician" unit (Lowe et al., 2018, fig. 3, lower). Indeed, almost all "Theresa" reports in the southeasternmost OBa have grouped the upper Cambrian Galway and a Lower Ordovician Theresa with a cryptic unconformity between them into a "Theresa" (e.g., Lowe et al., 2018, fig. 3, upper). The Theresa *s.s.* is a second Ordovician depositional sequence above the lowest Ordovician Tribes Hill/"RaO" unit in Lowe et al. (2017, 2018) that records eustatic, likely not epeirogenic, control in OBa deposition.

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