

# 740 Ma vase-shaped microfossils from Yukon, Canada: Implications for Neoproterozoic chronology and biostratigraphy

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## ABSTRACT

Biostratigraphy underpins the Phanerozoic time scale, but its application to pre-Ediacaran strata has remained limited because Proterozoic taxa commonly have long or unknown stratigraphic ranges, poorly understood taphonomic constraints, and/or inadequate geochronological context. Here we report the discovery of abundant vase-shaped microfossils from the Callison Lake dolostone of the Coal Creek inlier (Yukon, Canada) that highlight the potential for biostratigraphic correlation of Neoproterozoic successions using species-level assemblage zones of limited duration. The fossiliferous horizon, dated here by Re-Os geochronology at  $739.9 \pm 6.1$  Ma, shares multiple species-level taxa with a well-characterized assemblage from the Chuar Group of the Grand Canyon (Arizona, USA), dated by U-Pb on zircon from an interbedded tuff at  $742 \pm 6$  Ma. The overlapping age and species assemblages from these two deposits suggest biostratigraphic utility, at least within Neoproterozoic basins of Laurentia, and perhaps globally. The new Re-Os age also confirms the timing of the Islay  $\delta^{13}\text{C}_{\text{carbonate}}$  anomaly in northwestern Canada, which predates the onset of the Sturtian glaciation by >15 m.y. Together these data provide global calibration of sedimentary, paleontological, and geochemical records on the eve of profound environmental and evolutionary change.

## INTRODUCTION

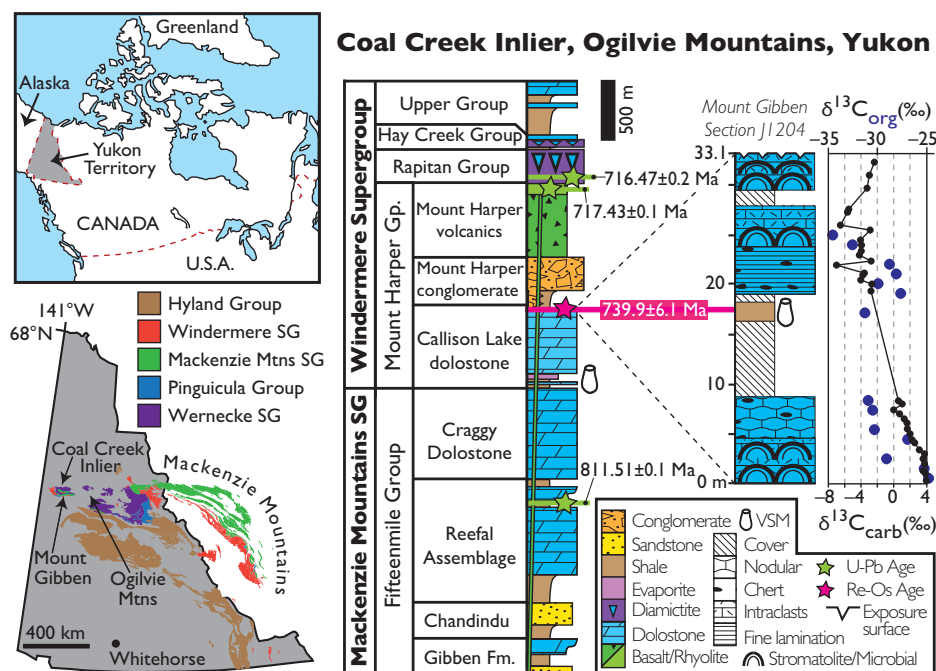
Neoproterozoic sedimentary deposits of western North America record large fluctuations in global biogeochemical cycles (e.g., Narbonne et al., 1994; Karlstrom et al., 2000; Halverson et al., 2005), the diversification of multiple eukaryotic clades (e.g., Porter and Knoll, 2000; Samuelsson and Butterfield, 2001; Cohen and Knoll, 2012), the fragmentation of Rodinia accompanied by localized mafic volcanism (e.g., Jefferson and Parrish, 1989; Prave, 1999; Macdonald et al., 2010), and multiple global glaciations (e.g., Aitken, 1991; Hoffman et al., 1998). Understanding the causal relationships among these events requires accurate stratigraphic correlation in the context of geochronologically constrained age models. However, the geographically disparate Neoproterozoic sedimentary records along the length of western North America have yet to be clearly linked in time and space due to a paucity of radiometric age constraints, non-unique chemostratigraphic ties, abundant syndimentary tectonism and associated lateral facies change, and a lack of biostratigraphically useful microfossils. Correlations have been proposed for pre-glacial Neoproterozoic strata in the southwestern United States (e.g., Dehler et al., 2001, 2010), but these schemes have not been extended to the rich sedimentary archives of northwest Canada, due primarily to a lack of age control. Here we document new vase-shaped microfossil (VSM) assemblages from Yukon, Canada, that are indistinguishable in taxonomic composition and age from those described from the Chuar Group of the Grand Canyon (Arizona, USA) and successions of similar age worldwide

(Porter and Knoll, 2000; Porter et al., 2003). Given their abundance, diversity, preservation, and time-calibrated record, VSMs could represent the first temporally well-resolved biostratigraphic assemblage zone for pre-Ediacaran strata, opening a new window for regional and

global stratigraphic correlation that goes beyond previous broad morphoclass-based biostratigraphic comparisons.

## STRATIGRAPHY

The Coal Creek inlier in the Ogilvie Mountains (Yukon, Canada) hosts an ~3-km-thick sequence of ca. 780–540 Ma Windermere Supergroup strata (Fig. 1; Mustard and Roots, 1997). The Mount Harper Group consists of three informal units; in stratigraphically ascending order, these are (1) the Callison Lake dolostone, an ~400-m-thick mixed siliciclastic and carbonate deposit; (2) the Mount Harper conglomerate, an ~1100-m-thick rift-related clastic succession; and (3) the Mount Harper volcanics, an ~1200-m-thick intermediate to mafic volcanic complex (Mustard and Roots, 1997; Macdonald et al., 2010). Age constraints on the Mount Harper Group are provided by U-Pb chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) ages on zircon of  $811.51 \pm 0.25$  Ma from a tuff in the underlying Fifteenmile Group, a



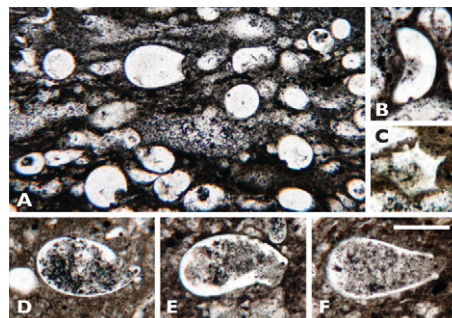
**Figure 1.** Simplified map locations and schematic lithostratigraphy of the Coal Creek inlier, Yukon, Canada. Vase-shaped microfossils (VSMs) described herein are from Callison Lake dolostone. Measured section J1204 highlights location of fossil and Re-Os age horizon, as well as bounding  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{13}\text{C}_{\text{org}}$  (blue data points) data from the Islay anomaly. Geologic map of Yukon is adapted from Wheeler and McFeely (1991). Abbreviations: SG—Supergroup; Gp.—Group; Fm.—Formation; Mtns—mountains.

717.43 ± 0.14 Ma from rhyolite in the upper member of the Mount Harper volcanics, and 716.47 ± 0.24 Ma from a tuff interbedded with diamictite correlated with the glacially influenced Rapitan Group in the Mackenzie Mountains (Fig. 1; Macdonald et al., 2010).

The lower Mount Harper Group records mixed marine and terrestrial deposition intimately associated with an east-west-trending, syndepositional north-side-down fault scarp that outlines the remnants of a Proterozoic half-graben (Mustard and Roots, 1997). Basal deposits of the Callison Lake dolostone unconformably overlie brecciated and silicified strata of the Fifteenmile Group, and consist of an ~4–30-m-thick interval of sandstone, siltstone, and discontinuous beds of quartz and chert pebble conglomerate that transition into ~5–30 m of black to varicolored and mud-cracked shale interbedded with laterally discontinuous stromatolitic bioherms that host poorly preserved VSMs. Basal Callison Lake siliclastic deposits are sharply overlain by an ~15–100-m-thick medium gray dolostone characterized by pisolitic grainstone, microbial laminae, morphologically diverse stromatolites, evaporite pseudomorphs, intraclast conglomerate, and mechanically bedded dolomicrite and/or dolosiltite, which also contains intercalated black shale composed predominantly of authigenic talc [ $Mg_3Si_4O_{10}(OH)_2$ ] (Tosca et al., 2011). These strata are overlain by 200–300 m of dolostone characterized by abundant microbial lamination, domal stromatolitic bioherms, and cross-bedded oolitic grainstone, with abundant early diagenetic chert. The Callison Lake dolostone culminates with another recessive ~10–40-m-thick unit of fossiliferous black shale, locally silicified and interbedded with stromatolitic and microbial dolostone, that is gradationally to abruptly overlain by sandstone and conglomerate of the Mount Harper conglomerate (Fig. 1). Callison Lake strata record peritidal to shallow subtidal deposition in an episodically restricted marginal marine basin, the subsidence of which was largely driven by regional extension.

## PALEONTOLOGY

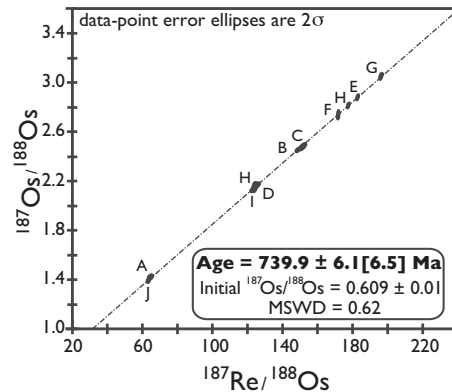
A diverse VSM assemblage (Fig. 2) occurs in the uppermost organic-rich silicified shale of the Callison Lake dolostone (Fig. 1; section J1204, 16.8–18.2 m). Because of pervasive silicification, the fossils cannot readily be freed from their matrix and so must be evaluated in petrographic thin section. Individual thin sections contain many hundreds of essentially random cross sections through VSMs (Fig. 2A). As in the Chuar Group assemblage (Porter et al., 2003), nearly all preserved fossils are tear-shaped tests characterized by (1) circular outline in transverse section; (2) radially or bilaterally symmetrical form with a rounded aboral



**Figure 2.** Neoproterozoic vase-shaped microfossils (VSMs) from Callison Lake dolostone, Yukon, Canada. (Slide number and England Finder Coordinates are given for each image.) A: Low-magnification image showing abundance of VSM tests, with centrally located specimen of *Melanocyrrillium hexodiadema* (J1204.16.8; K23/0). Scale = 100  $\mu$ m. B: *Palaeoarcella athanata* (J1204.16.8; H31/1). Scale = 50  $\mu$ m. C: Cross section of *Melanocyrrillium hexodiadema* aperture (F930.15.5; O33/4). Scale = 50  $\mu$ m. D: *Bombycion micron* (J1204.18.1; H32/2). Scale = 40  $\mu$ m. E: *Bonniea dacruchares* (J1204.18.1; W31/1). Scale = 50  $\mu$ m. F: *Cyclio-cyrrillium torquata* (J1204.18.1; L43/1). Scale = 50  $\mu$ m.

pole opposite a tapered oral end with aperture; (3) broad size ranges, from ~20 to 200  $\mu$ m in length and ~15 to 120  $\mu$ m in width; (4) morphologically diverse apertures ~10–40  $\mu$ m wide; and (5) ~1–3- $\mu$ m-thick test walls. Most sections through Callison Lake specimens do not yield systematically diagnostic characters; however, because the fossils are so abundant, each thin section includes many dozens of individuals that permit species-level comparison to Chuar Group populations (Porter et al., 2003). Thus, we can identify *Melanocyrrillium hexodiadema* (Figs. 2A and 2C), *Palaeoarcella athanata* (Fig. 2B), *Bombycion micron* (Fig. 2D), *Bonniea dacruchares* (Fig. 2E), and *Cyclio-cyrrillium torquata* (Fig. 2F), as well as *Bonniea pytinaia*, *C. simplex*, *Hemisphaeriella ornata*, and other long-necked unnamed forms (not illustrated).

All observed VSMs reflect a taphonomic history similar to that of Chuar Group populations; they are siliceous or calcareous internal molds commonly coated with thin layers of pyrite, iron oxide, or organic matter (Fig. 2; Porter and Knoll, 2000). Porter and Knoll (2000) outlined the taphonomic processes that preserved such microfossils and summarized previous interpretations of their biological affinities, making a strong case for viewing Chuar Group VSMs as testate amoebae placed phylogenetically within the Amoebozoa and Rhizaria. As such, these fossils provide our earliest direct evidence of protistan predation, including the evolutionarily important innovation of eukaryovory, the capture and ingestion of other eukaryotic cells (Porter, 2011; Knoll, 2014).



**Figure 3.** Re-Os isochron for upper Callison Lake dolostone (Yukon, Canada) with an age uncertainty of 6.5 m.y. (in brackets) when uncertainty of  $^{187}\text{Re}$  decay constant is included. MSWD—mean square of weighted deviates. Isotope composition and abundance data are presented in the Data Repository (see footnote 1).

## GEOCHRONOLOGY

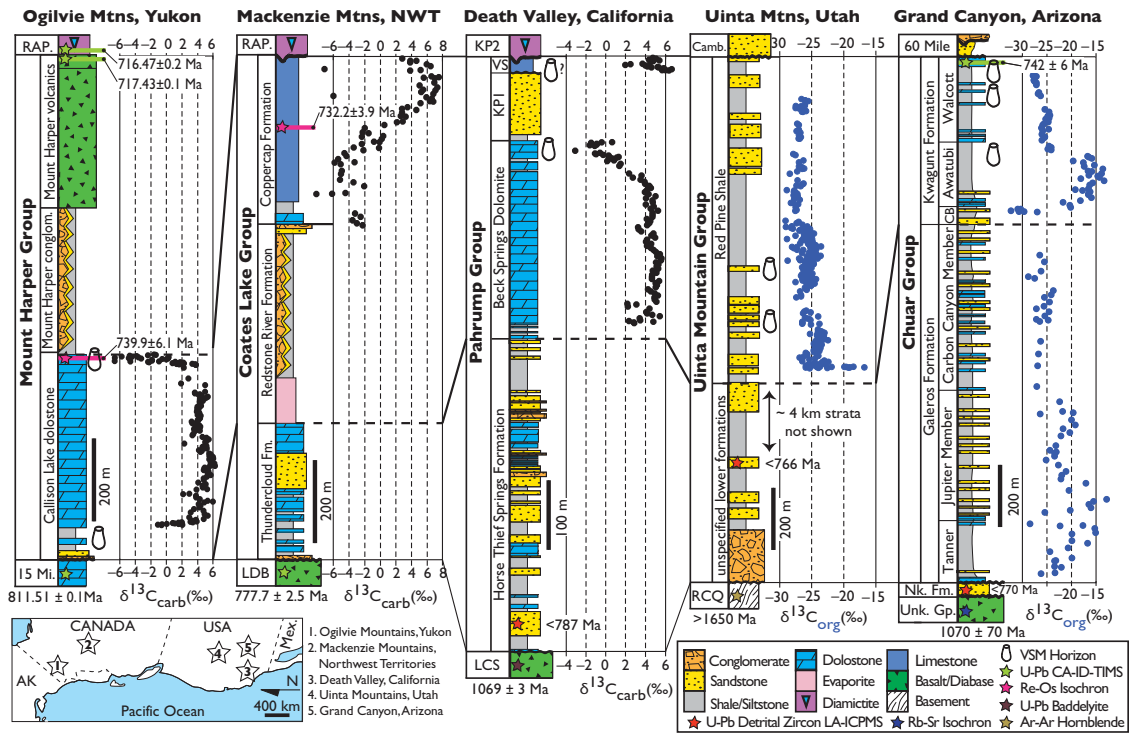
Silicified black shale of the Callison Lake dolostone was collected from a VSM-bearing outcrop near Mount Gibben in the Coal Creek inlier (Fig. 1; section J1204, 16.8–18.2 m). This 2.4-m-thick exposure was sampled at high resolution for Re-Os geochronology, and bounding stromatolitic dolostone was collected at ~1 m resolution for  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{13}\text{C}_{\text{org}}$  chemostratigraphy (Fig. 1; details of the sampling procedure and analytical methods are provided in the GSA Data Repository<sup>1</sup>). A Re-Os age of 739.9 ± 6.1 Ma ( $\pm 6.5$  m.y. if including  $^{187}\text{Re}$  decay constant uncertainty;  $n = 10$ , mean square of weighted deviates, MSWD = 0.62,  $2\sigma$ , initial  $^{187}\text{Os}/^{188}\text{Os} = 0.609 \pm 0.01$ ) was obtained from this horizon (Fig. 3). This Re-Os age is within error of the U-Pb zircon age of 742 ± 6 Ma from a reworked tuff interbedded with VSM-bearing black shale of the upper Chuar Group (Fig. 4), providing a distinct geochronological tie for our paleontological comparisons.

## DISCUSSION

Early fragmentation of Rodinia ca. 780–720 Ma generated local tectonism, mafic volcanism, and regional basin subsidence in western North America (e.g., Jefferson and Parrish, 1989; Prave, 1999; Karlstrom et al., 2000). In northwestern Canada, the Mount Harper Group and Coates Lake Group were deposited in a series of narrow, fault-bounded basins between ca.

<sup>1</sup>GSA Data Repository item 2014244, a summary of sampling techniques, detailed analytical methods, data tables containing all isotopic and geochronological data, and a compilation of global vase-shaped microfossil occurrences, is available online at [www.geosociety.org/pubs/ft2014.htm](http://www.geosociety.org/pubs/ft2014.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

**Figure 4.** Schematic lithostratigraphy, geochronology, and carbon isotope chemostratigraphy of basal Windermere Super-group strata from western North America. All  $\delta^{13}\text{C}_{\text{org}}$  data are shown with blue data points. Data are summarized from (1) this paper and Macdonald et al. (2010); (2) Jefferson and Parrish (1989) and Rooney et al. (2014); (3) Macdonald et al. (2013) and Mahon et al. (2014); (4) Dehler et al. (2010) and Nelson et al. (2011); (5) Karlstrom et al. (2000) and Dehler et al. (2010). Numbers correlate to inset map. Abbreviations: AK—Alaska; Mex.—Mexico; carb—carbonate; org—organic; VSM—vase-shaped microfossil; Mtns—Mountains; conglom.—conglomerate; 15 Mi.—Fifteenmile Group; LDB—Little Dal basalt; RAP.—Rapitan Group; KP—Kingston Peak Formation; VS—Virgin Spring limestone; LCS—Lower Crystal Spring Formation; RCQ—Red Creek Quartzite; Camb.—Cambrian; CB—Carbon Butte Member; NK. Fm.—Nankoweap Formation; Unk. Gp.—Unkar Group; LA-ICP-MS—laser ablation–inductively coupled plasma–mass spectrometry; CA-TIMS—chemical abrasion–thermal ionization mass spectrometry.



777 and 720 Ma (Jefferson and Parrish, 1989; Mustard and Roots, 1997). Farther south, the Chuar, Pahrup, and Uinta Mountain groups were also deposited in extensional basins between ca. 780 Ma and 740 Ma (Fig. 4; Timmons et al., 2001; Dehler et al., 2001, 2010). Based on a compilation of previously published carbon isotope chemostratigraphy, the new Re-Os age constraints discussed herein, and the first appearance of VSMs in different basins along the length of the Cordillera, we can begin to correlate these pre-Sturtian basins with confidence throughout western North America (Fig. 4).

Interestingly, all of these ca. 780–720 Ma basins in western North America host VSM assemblages and/or pronounced carbon isotopic fluctuations below Sturtian glacial deposits (Fig. 4), hinting at complex links between tectonics, biogeochemical cycling, and climate (Karlstrom et al., 2000). In conjunction with the U-Pb CA-TIMS zircon ages from the Mount Harper and Rapitan Groups of the Coal Creek inlier and the Re-Os age of 732.2 ± 3.9 Ma within a large negative  $\delta^{13}\text{C}_{\text{carb}}$  anomaly in the Coates Lake Group of the Mackenzie Mountains (Rooney et al., 2014), the Re-Os geochronology and chemostratigraphy presented herein suggest a clear correlation between the Mount Harper Group and Coates Lake Group (Fig. 4). Furthermore, this  $\delta^{13}\text{C}_{\text{carb}}$  isotopic pattern is indistinguishable from that of the Beck Spring Dolomite in Death Valley, which also hosts VSMs in association with a large negative carbon isotope anomaly

(Fig. 4; Macdonald et al., 2013). We correlate these  $\delta^{13}\text{C}_{\text{carb}}$  anomalies with the pre-Sturtian Islay anomaly because of their stratigraphic position below glacial deposits and their broad covariance with  $\delta^{13}\text{C}_{\text{org}}$  and lack of covariance with  $\delta^{18}\text{O}_{\text{carb}}$  (Fig. 1; Table DR1 in the Data Repository; Rooney et al. 2014). This  $\delta^{13}\text{C}_{\text{carb}}$  excursion is commonly associated with a distinct recovery to enriched  $\delta^{13}\text{C}_{\text{carb}}$  values prior to the onset of glacial sedimentation (e.g., Prave et al., 2009; Hoffman et al., 2012), clearly seen in the Coates Lake Group but masked by siliciclastic deposits in the Mount Harper Group (Fig. 4). Tziperman et al. (2011) suggested that accelerating eukaryotic diversification led to increased export production, triggering dynamic effects in the carbon cycle due to anaerobic respiration, consumption of  $\text{CO}_2$ , and the initiation of glaciation. Our data are consistent with this model insofar as it relates the Islay  $\delta^{13}\text{C}_{\text{carb}}$  anomaly to the abundant preservation of diverse VSMs; however, the apparent ~15 m.y. age disparity before the onset of the Sturtian glaciation suggests that any evolutionary influence on the Neoproterozoic Earth system must be interpreted broadly and not specifically in terms of the Islay event. Our new geochronological data sever the proposed link between the Islay anomaly and the onset of global glaciation (Tziperman et al., 2011; Hoffman et al., 2012), unless there are multiple Islay-like  $\delta^{13}\text{C}_{\text{carb}}$  anomalies recorded in ca. 745–716 Ma preglacial strata or an earlier episode of glaciation.

Globally, strata above the Bitter Springs  $\delta^{13}\text{C}_{\text{carb}}$  anomaly (younger than 811 Ma; Macdonald et al., 2010) but below Sturtian glaciogenic rocks are characterized by an increased diversity of eukaryotes that includes morphologically complex acritarchs, diverse VSM populations (see Table DR3 for a summary of global VSM occurrences), complex protistan scales, and a number of simple multicellular and coenocytic taxa (Knoll et al., 2006; Cohen and Knoll, 2012). Of these, VSMs are particularly well suited for biostratigraphic correlation, given their distinctive forms, relative ease of preservation, wide facies distribution, and limited stratigraphic range; they meet the requirements of biostratigraphic index fossils. Previous workers have noted the potential utility of VSMs for Neoproterozoic biostratigraphy (e.g., Knoll and Vidal, 1980; Porter and Knoll, 2000; Dehler et al., 2001); however, these suggestions were based on broad morphoclass comparisons without tight radiometric age constraints. In contrast, we suggest that VSMs in the Callison Lake and Chuar strata constitute a species-level assemblage zone comparable to those used to delimit time in Phanerozoic successions. Traditionally, Proterozoic taxa were held to have long stratigraphic ranges, far different from most Phanerozoic species (Knoll, 1994), but the advent of eukaryote-ingesting predators would be predicted to increase protistan turnover rates, much as carnivory did among Cambrian animals (Knoll, 2014), and this may underpin



the limited stratigraphic longevity inferred for Chuar Group–Callison Lake dolostone VSMs. At most, the Chuar–Callison Lake assemblage zone characterizes an interval comparable in length to a Phanerozoic epoch or period, and our radiometric dates suggest that its duration could have been considerably shorter, more akin to Phanerozoic ages. Lower Callison Lake fossils occur about one-third of the way between the well-characterized upper fossiliferous horizon and a subjacent ca. 811 Ma tuff in the Fifteenmile Group. Consistent with data from other basins (Fig. 4), this suggests that VSMs in general occur through an interval tens of millions of years in duration; but, because of poor preservation, the lower fossils do not provide information on the stratigraphic ranges of individual species. Thus, the new results promise a transition from established Proterozoic biostratigraphic links, where morphoclass correlations are coarse and many of the taxa used to correlate among basins have long ranges, to species-level assemblage zone correlation constrained by radiometric age constraints.

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