***Watsonella crosbyi* from the lower Cambrian (Terreneuvian, Stage 2) Normanville Group in South Australia**

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44 19 Running title: *Watsonella crosbyi* from Cambrian Stage 2 in Australia
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48 21 **Abstract**
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50 22 Correlation of early Cambrian strata is often confounded by provincialism of key fauna.
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52 23 Hence, the widespread occurrence of the micromollusc *Watsonella crosbyi* Grabau, 1900 is an
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54 24 important biostratigraphic signpost with potential for international correlation of early
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56 25 Cambrian successions. Previous correlations of *W. crosbyi* from Australia (Normanville
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Group) suggested an Atdabanian- to Botoman-equivalent age. However, in the upper part of the Mount Terrible Formation, stratigraphic ranges of *W. crosbyi* and *Aldanella* sp. cf. *golubevi* overlap prior to the incoming of vertically burrowed ‘piperock’ which is indicative of an age no earlier than Cambrian Stage 2. The stratigraphic range of *W. crosbyi* in the Normanville Group, South Australia correlates with the ranges of the taxon in China, France, Mongolia and Siberia (though not Newfoundland). The new Australian data adds further support for considering the first occurrence of *W. crosbyi* a good potential candidate for defining the base of Cambrian Stage 2. The stratigraphic range of *W. crosbyi* through the lower Cambrian Normanville Group has been determined based on collections from measured sections. Though rare, *W. crosbyi* is part of an assemblage of micromolluscs including *Bemella* sp., *Parailsanella* sp. cf. *murenica* and a sinistral form of *Aldanella* (*A.* sp. cf. *A. golubevi*). Other fauna present include *Australohalkieria* sp., *Eremactis mawsoni*, cancelloriids and *Cupithec*a sp.

Keywords: Normanville Group, *Aldanella*, biostratigraphy, *Sunnaginia*, Stansbury Basin.

1. Introduction

The definition of the base of the early Cambrian Stage 2 of the Terreneuvian Series has become a subject of considerable controversy, especially regarding the reliability and biostratigraphic utility of the micromollusc *Watsonella crosbyi* Grabau, 1900. This taxon has a widespread distribution, and can be correlated across pre-trilobitic successions of both carbonate and siliciclastic facies in South China, Siberia, Mongolia, Avalonia, and west and east Gondwana (Table 1, Supplementary Material at <http://journals.cambridge.org/geo>, references therein). For this reason *W. crosbyi* has been suggested as a suitable index fossil for global correlation of the as yet undefined Cambrian Stage 2 (Li *et al.* 2011; Peng & Babcock,

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2011). *Watsonella crosbyi* often co-occurs with the dextrally coiled shells of the stem group mollusc, *Aldanella attleborensis* (Shaler & Foerste, 1888), which shares a similar geographical distribution and has also been suggested as a potential candidate to define the base of Cambrian Stage 2 (Parkhaev, 2014).

Comprehensive regional biostratigraphic schemes are crucial for constraining local geo- and bioevents and for developing workable global correlations (Betts *et al.* in review). However, biostratigraphic correlation and concomitant temporal subdivision can be undermined by taphonomic and taxonomic inconsistencies, and the diachronism of First Appearance Data (FAD) (see discussion by Landing *et al.* 2013). These factors are especially evident in the earliest Cambrian, where many pre-trilobitic biotas (i.e. small skeletal fossils, archaeocyaths and acritarchs) exhibit strong provincialism and facies-controlled distribution (Landing *et al.* 2013). Consequently, there has been emphasis on chemostratigraphic methods (i.e. carbon and oxygen isotopes) in combination with U/Pb zircon geochronology as an independent (or primary) means of global correlation (e.g. Maloof *et al.* 2010a; Kouchinsky *et al.* 2012; Landing *et al.* 2013; but see Parkhaev, 2014). Non-biostratigraphic methods have previously been suggested as supplementary proxies for calibration (e.g. the ZHUCE/ I' positive $\delta^{13}\text{C}$ excursion above the incoming of *Watsonella*) (Li *et al.* 2011; Landing *et al.* 2013), although Landing *et al.* (2013) emphasizes integration of biostratigraphic and chemostratigraphic data. Maloof *et al.* (2010a) applied a multiproxy approach to constrain occurrences of skeletal metazoan taxa during the Terreneuvian Series using a $\delta^{13}\text{C}_{\text{CaCO}_3}$ age model calibrated with U/Pb ID-TIMS dates of zircons from five separate ash beds in Morocco (Maloof *et al.* 2005; Maloof *et al.* 2010b) and China. By assigning time bins in 2 Ma intervals, first appearance data of *Watsonella* from sections in Siberia, Mongolia and China indicate a First Appearance Datum (FAD) no older than

~530 Ma within the Nemakit-Daldynian Stage of the Siberian regional timescale. Expanding on this work, Landing & Kouchinsky (2016) suggested that the lower occurrences of *W. crosbyi* in South China, France and Avalonia, as well as in northern Siberia are approximately coeval, within the late Fortunian.

Landing *et al.* (2013) proposed that the I'/L4/ZHUCE $\delta^{13}\text{C}$ positive excursion occurring just above the first appearance of *Watsonella crosbyi* and *Aldanella attleborensis* and the *Skiagia ornata-Fimbrioglomerella membranacea* acritarch, Zone represents the best multi-proxy approach for defining the base of Cambrian Stage 2. The use of independent time constraints as suggested by Landing *et al.* (2013) is the most workable means to more accurately define this important Cambrian Stage boundary. However, it is important that all chemostratigraphic signals (especially bulk rock) are carefully evaluated using robust protocols to ensure they are not influenced by local depositional conditions, cryptic disconformities (Parkhaev, 2014; Miall, 2014), alteration by fluid-rock interactions during subaerial exposure, as well as by diagenesis in the vadose or phreatic zones (Kaufman & Knoll, 1995; Derry, 2010; Swart, 2015).

Tracking changes in ichnodiversity and ichnodisparity during the Ediacaran-Cambrian transition has also proven an effective independent means of broadly correlating key phases of the Cambrian radiation (Seilacher, 1956; Crimes, 1987; Seilacher *et al.* 2005; Mángano & Buatois, 2014). Trace fossils reveal two distinct phases in body-plan diversification and the establishment of a Phanerozoic-style ecological structure (Mángano & Buatois, 2014). The Fortunian Stage records a rapid diversification with a global maximum of 42 ichnogenera. Extent of bioturbation was relatively low, and assemblages were dominated by horizontal traces. The transition to Cambrian Stage 2 records a dramatic increase in maximum burrowing depth and the appearance of vertical burrows, especially *Skolithos* and *Diplocraterion* 'piperock' (Mángano & Buatois, 2014). Utility of ichnofossils for global chronostratigraphic

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schemes is problematic, particularly with respect to the Cambrian period (Babcock *et al.* 2014, but see Landing *et al.* 2013). Their key limitation is a strong lithofacies dependence, which is exemplified by the almost exclusive appearance of *Skolithos* in moderate to high-energy near-shore clastic deposits (Desjardins *et al.* 2010, see table 1; Màngano & Buatois, 2014). Nevertheless, the diversity of ichnotaxa and changes in burrow morphology may prove useful as a broad indicator of age in the absence of SSFs (especially in siliciclastic-rich deposits), particularly ‘piperock’ style burrowing that first appears within Cambrian Stage 2.

Documentation of stratigraphic ranges of taxa such as *Watsonella crosbyi* or *Anabarella attleborensis* across multiple geographic regions and through various carbonate and siliciclastic successions increases their potential as candidate index fossils to define the base of Cambrian Stage 2. The final task is to integrate biostratigraphic and chemostratigraphic data to build a consistent, robust time-significant signature and to attempt to explain any differences in stratigraphic range which may limit the stratigraphic utility of these taxa.

The occurrence of *Watsonella crosbyi* in Australia has long been recognized (Daily, 1976a, b; Daily *et al.* 1976; Gravestock & Shergold, 2001; Parkhaev in Gravestock *et al.* 2001; Jenkins *et al.* 2002) but lack of formal documentation and poorly understood stratigraphic context has led to confusion about the stratigraphic range and consequently, the correlation of this taxon in Cambrian East Gondwana. Landing *et al.* (2013) and Parkhaev (2014) suggested that the stratigraphic range of *W. crosbyi* in Australia correlates with the *Abadiella huoi* trilobite Zone, in the basal part of Cambrian Series 2, Stage 3 (broadly equivalent to the Atdabanian Stage in Siberia). However, a new shelly fossil biostratigraphy for the lower Cambrian of South Australia clearly indicates the strata hosting *W. crosbyi* are considerably older (Betts *et al.*, in

review; herein). The aim of this paper is to rigorously establish stratigraphic context of *W. crosbyi* (and *Aldanella* sp. cf. *golubevi*) from measured stratigraphic sections through the lower part of the Normanville Group on Fleurieu Peninsula, eastern Stansbury Basin, South Australia. In addition, *Watsonella crosbyi* and *Aldanella* sp. cf. *golubevi* are formally described and the stratigraphic ranges of other key SSF are reassessed.

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132 2. Geological setting and locality

133 The lower Cambrian Normanville Group (Fig. 1) is a sedimentary package of mixed
134 carbonates, argillites and sandstones exposed along a ~16 km NE-SW trending coastal tract in
135 the Sellick Hill-Normanville area on Fleurieu Peninsula, ~50 km south of Adelaide. Early
136 geological and stratigraphic investigations into the Cambrian rocks of this region include the
137 work of Howchin (1897) and Madigan (1925, 1927) with detailed mapping and stratigraphy
138 by Abele & McGowan (1959) and Daily (1963, 1972, 1976b).

139 [insert Figure 1 here]

140 The Normanville Group consists of an approximately 1 km thick succession of
141 predominantly marine shelf to ramp/slope limestones and shales, with minor arkosic and
142 calcareous sandstones towards the base, and significant deposits of black, pyritic shale
143 towards the top. The entire succession represents a transgressive marine event (sequence set
144 C1 of Gravestock, 1995), beginning with a shallow subtidal environment at the base, followed
145 by a shallow shelf setting with archaeocyathan-microbial bioherms, through to a deep-water
146 environment and eventually a mudstone dominated, basinal setting at the top (Alexander &
147 Gravestock, 1990; Jago *et al.* 1994; Gravestock & Gatehouse, 1995; Gravestock *et al.* 2001;
148 Jenkins *et al.* 2002).

149 In their detailed study of the lithology and stratigraphy of lower Cambrian rocks in the
150 Normanville–Sellick Hill region, Abele & McGowan (1959) recognised four distinct and

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predominantly calcareous units (in ascending order with true thickness); Wangkonda Formation (110 m), Sellick Hill Formation (210 m), Fork Tree Limestone (300 m) and Heatherdale Shale (300 m). Subsequently, Daily (1963) proposed the name Mount Terrible Formation to define a ~92 m thick package of dominantly clastic rocks resting unconformably above the Ediacaran ABC Range Quartzite (Wilpena Group) and below the Wangkonda Formation. The lower ‘*Hyolithes* sandstone’ of Abele & McGowran (1959, p. 304) originally placed within the Wangkonda Formation was recognized as the top member of the Mount Terrible Formation by Daily (1963). Together, these five lithostratigraphic units constitute the Normanville Group (Daily & Milnes, 1973, p. 4), which is overlain unconformably by the extensive greywackes and shales of the lower Cambrian Kanmantoo Group (Haines *et al.* 2009; Jago *et al.* 2003).

Almost all of the fossil material described here comes from collections originally made by the late Brian Daily (Section 1 in Fig. 1 = ‘New Sellick Hill Road’, now Main South Road). Unfortunately, Daily (1963) did not provide details on the exact location of his section through the Mount Terrible Formation. Despite changes caused by re-alignment and widening of the Main South Road since the early 1960s, it is possible to closely approximate the position of his stratigraphic section from his existing field notebooks combined with detailed geological mapping by Abele & McGowran (1959). This clearly shows where the ‘*Hyolithes* sandstone’ (= upper member, Mount Terrible Formation of Daily, 1963) intersects the Main South Road (Fig. 1). Daily’s field notebooks indicate some of his original sampling along the road section was about 0.8 km NNE along strike in Mount Terrible Gully.

In an attempt to supplement the lithostratigraphic and palaeontological details described by Daily (1963) another section (Section 2, Figs 1 and 2) was measured through the Mount Terrible Formation outcropping along Old Sellicks Hill Road,

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3 176 immediately south of Sellick Hill Quarry and approximately 2.8 km NNE of Daily's original
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5 177 section. Despite some minor differences in the thickness of the members, the lithologies are
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7 178 remarkably similar (Fig. 1). Unfortunately, despite targeted sampling in the middle and upper
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9 179 members, the section produced very little fossil material (*Eremactis mawsoni* Bengtson &
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11 180 Conway Morris in Bengtson *et al.*, 1990, indeterminate chancelloriids and phosphatic tubes).
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15 16 182 **3. Lithostratigraphy**

17 18 183 **3.a. Mount Terrible Formation**

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20 184 Daily (1963, 1972, 1976a, b) recognized three informal members of the Mount Terrible
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22 185 Formation. Whilst there is some variation in thickness of the members along strike (Fig. 1),
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24 186 the characteristic lithofacies of all members as described by Daily (1963, 1972, 1976a, b) and
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26 187 summarized by Gravestock & Cowley (1995), Gravestock *et al.* (2001, p. 25) and Gravestock
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28 188 & Shergold (2001) are readily identified in the field.

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31 189 The Mount Terrible Formation is interpreted to be part of a transgressive systems tract
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33 190 (€1.0 of Zang *et al.* 2004), equivalent to the Uratanna sequence of Mount & MacDonald
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35 191 (1992). Despite original claims of conformity (Daily 1963, p. 595), there is clearly a
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37 192 disconformable surface separating the lowest member of the Mount Terrible Formation from
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39 193 the underlying quartzites of the Neoproterozoic ABC Range Quartzite (see also Thomson &
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41 194 Horwitz, 1961). The incised nature of the contact (later noted by Daily, 1976a, p. 48) and the
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43 195 absence of late Ediacaran rocks between the ABC Range Quartzite and the lowest Cambrian
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45 196 deposits (including the fossiliferous Ediacaran member in the Rawnsley Quartzite) in the
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47 197 Flinders Ranges, indicate a considerable time gap at this stratigraphic level on the Fleurieu
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55 56 200 **3.a.1. Basal member**

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201 The lower member is a feldspathic to quartz-rich sandstone ranging from 12 m to 17 m thick,
202 characterized by thin, planar-tabular bed sets with scoured bases. The basal 3-4 m are
203 comparatively feldspathic, although each bed consists of medium to coarse-grained quartz-
204 feldspathic arenites with a pebbly, phosphatized base and a bioturbated pyritic siltstone top.
205 Low-angle cross-beds and concordant lineations indicate high-energy conditions in a
206 transgressive marine (possibly marginal marine) environment (Daily, 1963, 1976*b*;
207 Gravestock & Shergold, 2001).

208 Microfacies reveal a coarse-grained sandstone, consisting of a moderately well
209 sorted mosaic of angular to sub-rounded grains (>1 mm across), predominantly quartz
210 and rare feldspar (plagioclase represents 5-10% of the sample) (Fig. 2a-c). The grains
211 are either tightly packed with no obvious authigenic cement (Fig. 2a) or with a very
212 fine calcareous cement containing iron oxides (possibly hematite; Fig. 2b). The iron
213 oxides are concentrated in some areas to form a dark cement, red at the edges
214 (observable as framboidal clusters), or are coating the quartz grains and filling
215 intergranular spaces (Fig. 2b, c). Some beds (>30 mm thick) exhibit weakly graded
216 bedding, which coarsens upwards.

217 [insert Figure 2 here]

218 The sediments of the basal member fill small holes and fissures, presumably
219 erosional in origin, in the underlying Neoproterozoic Ediacaran ABC Range Quartzite
220 (Daily, 1976*a*). Bioturbation is evident in the pyritic siltstone at the top of the lower
221 member down to 5 m above its base (Daily, 1976*a*; Gravestock & Shergold, 2001).

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223 *3.a.2. Middle member*

224 The middle member ranges in thickness from 60 m to 67 m and comprises grey, highly
225 bioturbated and occasionally phosphatic to slightly ferruginized siltstones to very fine

226 sandstones with weathered, elliptical caverns produced by dissolution of carbonate nodules
227 towards the top of the member. Daily (1963) reported the first shelly fossils (hyoliths) at 20 m
228 above the base of the Main South Road section (Fig. 3) and imprints of indeterminate tubes at
229 25 m above the base, within bands of phosphatic shale (Callen, 1971; Daily, 1976a;
230 Gravestock & Shergold, 2001). This package is interpreted as a highstand systems tract (Daily
231 *et al.* 1976; Gravestock & Shergold, 2001).

232 Microfacies of the middle member show the transition to intense sediment mixing, with
233 the original fabric often impacted or destroyed by pervasive, mainly horizontal, bioturbation.
234 In some horizons the fine-grained mottled fabric is represented by uniform, sub-angular
235 quartz grains ($>125\ \mu\text{m}$) within a frequently hematite stained calc-silt matrix (Fig. 2d, e).
236 Fabrics unaffected by intensive bioturbation have repeated interlaminae (1-3 mm thick) which
237 are very fine-grained and quartz-rich, and fine upwards into homogenous silts and micrites
238 (Fig. 2g). Elongate to ovoid clasts within these laminae, often of different lithology to the
239 surrounding matrix, may be compressed infilled horizontal burrows (Fig. 2f).

240 [insert Figure 3 here]

242 3.a.3. Top member

243 In Daily's (1963) section on Main South Road, the top member consists of a 20-30 m package
244 of strongly cavernous, fine-grained calcareous sandstones with pyritic and argillaceous
245 siltstone interbeds. The same lithostratigraphic package in Section 2 (Fig. 3) only exposes the
246 basal beds followed by a ~ 20 m covered interval obscuring the contact with the overlying
247 Wangkonda Formation, suggesting the upper member could be slightly thicker than originally
248 measured by Daily (1963). The sandstone is bioturbated, with shelly fossils occurring as
249 phosphatic steinkerns located within a 6 m interval in Section 1 in a weathered band of muddy
250 calcareous siltstone (Daily, 1963, 1969; Gravestock & Shergold, 2001) (Fig. 3). Microfacies

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display a predominantly homogeneous fabric of very fine sand- to silt-sized, moderately rounded quartz grains (Fig. 2h, i). Hematite staining is pervasive but forms mainly as irregular wavy solution seams and laminae throughout the unit (Fig. 2h, i).

4. Biostratigraphy

4.a. Regional correlation

4.a.1. Previous work

There has been considerable confusion regarding the age and correlation of the Normanville Group in recent literature. Most contention is traced back to poorly constrained biostratigraphy in the Sellick Hill Formation and the conformably overlying Fork Tree Limestone. Alexander & Gravestock (1990) conducted a thorough sedimentological study of the Sellick Hill Formation and described five Facies Associations (A to E; oldest to youngest) from coastal exposures along the Fleurieu Peninsula. Although Alexander & Gravestock (1990) reported the presence of trilobites in Facies Association D of the Sellick Hill Formation, subsequent attempts to locate trilobites in this unit have been unsuccessful. As far as is known there are no substantiated records of trilobites from either the Sellick Hill Formation or the Fork Tree Limestone. Archaeocyaths from the upper Sellick Hill Formation (Facies Association D to E) and lower Fork Tree Limestone have previously been correlated with the Atdabanian to Botoman Stages of Siberia (Debrenne & Gravestock, 1990). However, based on the shelly fossil data presented by Betts *et al.* (2015; in review) and the data presented herein this correlation requires close investigation. Gravestock (1984) and Kruse & Shi (in Brock *et al.* 2000, p.14) indicate the oldest archaeocyaths in the Arrowie Basin are equivalent to Daily's (1956) Faunal Assemblages 1-2 which they suggest are late Atdabanian equivalent in age. However, difficulties including

strong endemism (Kruse & Shi in Brock *et al.* 2000) and identification of archaeocyaths (Gravestock *et al.* 2001) remain a primary concern regarding their utility for regional correlation (Jenkins *et al.* 2002; Peng *et al.* 2012).

Adding to the confusion surrounding the age of the Normaville Group succession are the assemblage ‘zones’ (especially molluscan zones) erected by Gravestock *et al.* (2001) based on drill cores and stratigraphic sections measured in the Stansbury Basin. Gravestock *et al.* (2001) correlated the upper Wangkonda Formation and lower Sellick Hill Formation (Facies Association A of Alexander & Gravestock, 1990) with their *Bemella communis* zone and the remainder of the Sellick Hill Formation (uppermost Facies Association A to C) to the *Stenotheca drepanoida* zone. These molluscan zones were suggested to have an Atdabanian age and to correlate with the *Abadiella huoi* (for discussion of genus see Paterson & Brock, 2007, p. 127; Landing *et al.* 2013, p. 159) and *Pararaia tatei* trilobite zones of the Arrowie Basin despite the fact that trilobites are completely unknown from the Wangkonda and Sellick Hill formations. This correlation was reported in subsequent publications (e.g. Gubanov, 2002; Parkhaev *et al.* 2012; Landing *et al.* 2013). However, the molluscan biozones of Gravestock *et al.* (2001) have very poorly defined boundaries and are based on poorly preserved, long-ranging taxa. Close inspection of the data given by Gravestock *et al.* (2001) reveals clear temporal discrepancies between the sections on the Yorke and Fleurieu peninsulas (Betts *et al.* in review). For instance, Gravestock *et al.* (2001, p. 38) state that ‘the lower boundary of the *Bemella communis* ‘zone’ is established by the appearance of *Bemella communis*... and *Aroonia seposita*’ in the Aquitaine SYC-101 well, while in the SADME Minlaton 1 drillhole, they state that the base of the *B. communis* zone is equivalent to the first appearance of the index species only (p. 44). In fact, no species recorded in the *B. communis* zone, not even the eponym, is common to all records of that zone. Indeed, the only species representative of the *B. communis* zone in the Yalkalpo-2 drill core is *Pelagiella subangulata*

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(Tate, 1892), which is the eponym of the zone below the *B. communis* zone. The holotype of *B. communis* (PIN 4664/1331) is a poorly preserved phosphatic steinkern (Gravestock *et al.* 2001, pl. XXIX, fig 2a-c) from sample SH22 in Facies Association A of the Sellick Hill Formation at a level taken to correspond to the boundary between the *B. communis* and *S. drepanoida* zones.

4.a.2. Current study

Shelly fossils were recovered from two stratigraphic levels within the Mount Terrible Formation: from the topmost silty-sandstone layer within the middle member, about 63 m above the base of the section; and an approximately 4 m interval (at 79-83 m above the base of the section) within the top member (=Section 1, Fig. 3). The fauna is composed mainly of molluscs (*W. crosbyi*, *Aldanella* sp. cf. *golubevi*, *Bemella* sp., *Parailsanella* sp. cf. *murenica* Zhegallo in Esakova & Zhegallo, 1996), as well as *Eremactis mawsoni* Bengtson & Conway Morris in Bengtson *et al.*, 1990, *Australohalkieria* sp., *Hyolithellus micans* Billings, 1871 and *Cupitheca* sp. This assemblage represents the oldest known shelly fossil assemblage from Australia. Micromolluscs *W. crosbyi* and *A. sp. cf. A. golubevi* are described in detail below (5. Systematic palaeontology). Other faunal elements are illustrated for completeness, but poor preservation precludes assignment to species for most taxa (Fig. 4).

[insert Figure 4 here]

The univalved molluscs *Bemella* sp. and *W. crosbyi* range from the middle member of the Mount Terrible Formation (Fig. 3) into Facies Association C of the Sellick Hill Formation (see Gravestock *et al.* 2001, fig. 17). Jenkins *et al.* (2002) reported (but did not figure) *Watsonella sibirica* (Missarzhevsky, 1974) from the middle member of the Mount Terrible Formation in a restudy of material collected by Brian Daily. *Watsonella sibirica* is now considered a synonym of *Watsonella crosbyi*

(Landing, 1989; Kouchinsky, 1999; Li *et al.* 2011; Devaere *et al.* 2013). The halkieriid *Australohalkieria* sp. originally described (as *Halkieria* sp. A) by Bengtson *et al.* (1990, p. 77) is now known to range from the middle member of the Mount Terrible Formation up into the Wangkonda Formation (Fig. 3; Bengtson *et al.* 1990, fig. 49A-I). The coeloscleritophoran *Eremactis mawsoni* ranges from the middle member of the Mount Terrible Formation to Facies Association D of the Sellick Hill Formation in the Normanville Group.

Regional correlation of the Mount Terrible Formation and lithostratigraphic equivalents, including the Winulta Formation (Daily, 1990) in the western Stansbury Basin (Yorke Peninsula) and at least, partially, the Uratanna Formation (Daily, 1973), in the Arrowie Basin has been hampered by lack of fossils (Daily, 1972). Faunal ties between the lowermost Cambrian units on Yorke and Fleurieu Peninsulas are limited to indeterminate, long ranging hyoliths and chancelloriids. The enigmatic sabelliditids (organic-walled tubes) were reported by Daily (1976a) from the Mount Terrible Formation (lower part of the top member) and from the Uratanna Formation (lower 100–150 m) by Mount & MacDonald (1992), but these are taxonomically intractable and consequently difficult to utilize for correlation.

The coarse-grained and intensely bioturbated facies of approximately the lowermost 60 m of the Mount Terrible Formation was not conducive to preservation of shelly fossils. The predominance of siliciclastics in the eastern Stansbury and the Arrowie basins explains the absence of *W. crosbyi* and associated shelly taxa from these regions. Hence, the local first occurrence and range of *W. crosbyi* in the Mt. Terrible Formation track lithofacies changes into calcareous sandstone, so are clearly lithofacies-specific (see Jacquet *et al.* in prep). Hence whilst the occurrence of *W. crosbyi* in the Mt. Terrible Formation is clearly within Stage 2, this cannot be construed as necessarily correlating with the first appearance of the taxon on a global scale.

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351 Siliciclastic depositional settings are often conducive to the preservation of trace
352 fossils. In the absence of diverse early Cambrian skeletal fauna, the potential for using
353 trace fossils for intra- and inter-basin correlation in South Australian successions has
354 long been recognized (Daily, 1972; Gravestock & Shergold, 2001). The predominantly
355 shallow marine to sub-tidal siliciclastic strata of the basal Cambrian successions in
356 Australia record a transition from an assemblage dominated by shallow burrowing,
357 architecturally complex traces to one which is monospecific or of low-diversity and
358 characterized by significantly increased burrowing depth (>1 m) (Mangano & Buatois,
359 2014). Mangano & Buatois (2014) have demonstrated that a clear change in behavior
360 and benthic community structure, with the emergence of vertical U-shaped burrows
361 (with spreite) such as *Diplocraterion*, is widespread during the Cambrian Radiation.

362 Whilst bioturbation is pervasive in the middle member of the Mount Terrible
363 Formation, no ichnotaxa can be clearly identified. In contrast, trace fossils present in
364 the contemporaneous Uratanna Formation in the Arrowie Basin are well documented
365 and include important ichnogenera and species such as *Trichophycus pedum* (used to
366 define the Ediacaran-Cambrian boundary) and *Rusophycus* spp. in the uppermost part
367 (Daily, 1972, 1976a; Mount, 1989; Gravestock & Cowley, 1995). These ichnotaxa also
368 extend into the lower Parachilna Formation (Jensen *et al.* 1998; Gravestock &
369 Shergold, 2001). Trace fossils have also been reported from outcrop in the Winulta
370 Formation (*Trichophycus pedum*, *Plagiogmus arcuatus* and *Diplocraterion* sp.)
371 (Gravestock & Shergold, 2001), the Arumbera Sandstone in the Amadeus Basin
372 (*Rusophycus* sp., *T. pedum*, *Diplichnites* sp. and *Plagiogmus* sp.) and the Mount
373 Baldwin Formation in the Georgina Basin (*Bergaueria* sp., *Helminthopsis* sp.,
374 *Treptichnus* sp. and *Diplocraterion parallelum*) (Glaessner, 1969; Daily, 1972;
375 Gravestock & Shergold, 2001). *Diplocraterion* burrows first appear in the sandy

interbeds of the Wangkonda Formation on the Fleurieu Peninsula (Daily, 1976a), and traces identified as *D. paralellum* are extremely abundant in beds in the lower part of the Parachilna Formation in the Arrowie Basin (Gravestock & Cowley, 1995; Mangano & Buatois, 2014).

The global shift to an advection-dominated system resulting from deep-tiering benthic communities forming straight and U-shaped burrow systems is characteristic of the Terreneuvian, Stage 2 (Mangano & Buatois, 2014, fig. 1). This provides some measure of biostratigraphic control for the Mount Terrible Formation, with the first appearance of *Watsonella crosbyi* below that of *Diplocraterion* piperock in the overlying Wangkonda Formation thus indicating an interval broadly equivalent with Cambrian Stage 2.

Watsonella crosbyi was reported from two horizons in Facies Association A and C respectively of the Sellick Hill Formation, which overlies the Wangkonda Formation (Parkhaev in Gravestock *et al.* 2001, pl. XLII, figs 15-16). Revaluation of the taxa occurring within the upper range of *Watsonella crosbyi* in the Sellick Hill Formation illustrated by Gravestock *et al.* (2001) include *Bemella communis* Parkhaev in Gravestock *et al.* 2001, *B. incomparabilis* Parkhaev in Gravestock *et al.*, 2001, *Obtusoconus brevis* Zhegallo in Esakova & Zhegallo, 1996, *Anuliconus truncatus* Parkhaev in Gravestock *et al.*, 2001, and *Australohalkieria parva* (Conway Morris in Bengtson *et al.*, 1990); most are represented by incomplete steinkerns. These co-occurring taxa are either restricted to the Sellick Hill Formation or they have very long stratigraphic ranges. The last occurrence of *W. crosbyi* low in Facies Association C of the Sellick Hill Formation is approximately ~50 m below the first occurrence of the widespread tommotiid *Sunnaginia imbricata* Missarzhevsky in Rozanov *et al.*, 1969 which occurs through Facies Association C to E of the SHL section (Fig. 5).

[insert Figure 5 here]

New stratigraphic sections (SHL and FTL, Fig. 1) measured through upper Facies Association C of the Sellick Hill Formation through the entire Fork Tree Limestone reveal

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shelly assemblages including *Kulparina rostrata*, *Dailyatia ajax*, *D. macroptera* and a probable new species of the paterinid brachiopod, *Askepasma*. This assemblage represents the *Kulparina rostrata* Zone, recently defined in the Arrowie Basin by Betts *et al.* (in review), and entirely predates the incoming of trilobites. This strongly supports a pre-trilobitic, Terreneuvian, Stage 2 age for all units of the Normanville Group below the Heatherdale Shale.

The 300 m thick succession of deep-water, fine-grained siliciclastics of the Heatherdale Shale overlies the Fork Tree Limestone. This unit is generally poorly fossiliferous, although the presence of trilobites (Jago *et al.* 1984; Jenkins & Hasenohr, 1989) and bivalved arthropods (*Isoxys*) (Jago *et al.* 2006; Paterson *et al.* 2010) suggests a *P. janeae* Zone age for the upper part of the Heatherdale Shale.

4.b. Global Correlation

Daily (1972, 1976a) first suggested the Mount Terrible Formation could be correlated with the Tommotian Stage of Siberia based on shelly faunas (including *Watsonella*) and sabellitids. This view was later supported by Jenkins *et al.* (2002) who proposed that the occurrence of *W. sibirica* (= *W. crosbyi*) in the middle member of the Mount Terrible Formation was evidence of an early to middle Tommotian-equivalent age. Our correlation is mainly based on the occurrence of *Watsonella crosbyi* and *Aldanella* sp. cf. *golubevi* as well as the shelly fauna and trace fossils in overlying strata. *Watsonella crosbyi* is widely distributed in upper Terreneuvian strata (discussed further below), and *A. golubevi* is known only from transitional Fortunian-Stage 2 strata of Siberia. However, other species of *Aldanella* have longer stratigraphic ranges in the Terreneuvian (Parkhaev & Karlova, 2011; Parkhaev, 2014). Other taxa recovered from the Mount Terrible Formation are long-ranging and are therefore less useful for global correlation. However, the stratigraphic range of *S. imbricata* has previously

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2
3 426 been used to define a biozone in the pre-trilobite Bonavista Group in Newfoundland which
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5 427 succeeds the *Watsonella crosbyi* Zone of the underlying Chapel Island Formation (Fig. 6)
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7 428 (Landing, 1988; Landing *et al.* 1989; Palacios *et al.* 2011). Similarly, the interval with
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9 429 *Sunnaginia imbricata* in Facies Association C though to E of the Sellick Hill Formation (~ 50
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11 430 m above the last local appearance of *W. crosbyi* in the lower part of Facies Association C)
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13 431 provides strong evidence that the Mount Terrible Formation represents the early part of
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15 432 Cambrian Stage 2 (Fig. 6).

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18 433 [insert Figure 6 here]
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21 434 In connection with recent efforts to define the chronostratigraphic divisions of the
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23 435 Cambrian period, the stratigraphic range of *Watsonella crosbyi* has been extensively studied.
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25 436 *Watsonella crosbyi* is one of the most widely distributed shelly fossils in the early part of the
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27 437 Cambrian period (Terreneuvian) with a near global distribution (Table 1, online
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29 438 Supplementary Material) and has been suggested as a suitable index fossil to define the lower
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31 439 boundary of the Cambrian Stage 2 (Terreneuvian Series) (Li *et al.* 2011; Peng & Babcock,
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33 440 2011). However, the utility of *W. crosbyi* for global correlation has also been questioned
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35 441 because of the supposed long stratigraphic range of the taxon (Parkhaev *et al.* 2012; Landing
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37 442 *et al.* 2013). Restudy of the stratigraphic range of *W. crosbyi* in France (Devaere *et al.* 2013),
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39 443 Siberia (Landing & Kouchinsky, 2016), Mongolia (Brasier *et al.* 1996) and Australia (herein)
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41 444 suggests that it is restricted to early-middle Stage 2 (Fig. 6). However, in Avalonia, *W.*
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43 445 *crosbyi* has been reported to range from Member 3 of the Chapel Island Formation (*W.*
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45 446 *crosbyi* Zone) into the Fosters Point Formation (*Camenella baltica* Zone), in horizons
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47 447 suggested to correlate with the first appearance of trilobites in Siberia (Landing, 1989;
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49 448 Landing *et al.* 2013).
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54 449 In Siberia, the first appearance of *W. crosbyi* has usually been suggested to coincide
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56 450 with the base of the Tommotian Stage (*Nochoroicyathus sunnaginicus* Zone; Rozanov *et al.*
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2008). However, it has recently been shown that *W. crosbyi* occurs substantially below the base of the Tommotian Stage in northern Siberia (Fig. 6) (Nagovitsyn *et al.* 2015; Landing & Kouchinsky, 2016). As a complication, the base of the Tommotian remains poorly defined and is ultimately based on the simultaneous incoming of numerous taxa coinciding with a hiatus at the base of the Pestrotsvet Formation in the stratotype Dvortsy section in southern Siberia (Landing *et al.* 2013; Landing & Kouchinsky, 2016).

The *W. crosbyi* Assemblage Zone in South China (Steiner *et al.* 2007; Li *et al.* 2011) is usually correlated with the basal Tommotian Stage of Siberia, although Landing & Kouchinsky (2016) suggest that it is better correlated with pre-Tommotian strata in northern Siberia (the Ary-Mas-Yuryakh and Kotujkan River sections). The stratigraphic range of *W. crosbyi* in Mongolia has also been controversial with some authors correlating strata in the upper Bayan-Gol Formation containing *W. crosbyi* with either the Adtabanian (Brasier *et al.* 1996; Landing *et al.* 2013) or Tommotian (Esakova & Zhegallo, 1996) stages of Siberia. These views have recently been challenged by Smith *et al.* (2015) who argue that this interval is pre-Tommotian based largely on new carbon chemostratigraphic isotope data. Similarly, in the Montagne Noire of France, strata containing *W. crosbyi* have been correlated with the Botoman (Kerber, 1988), Tommotian (Devaere *et al.* 2013) and pre-Tommotian stages of Siberia (Landing & Kouchinsky, 2016).

The global first appearance of *W. crosbyi* is now demonstrated to occur in strata that predate the base of the Tommotian Stage of Siberia (as defined by the FAD of *N. sunnaginicus*) based on carbon isotope stratigraphy from Mongolia, South China, Siberia and Avalonia (Fig. 6) (Smith *et al.* 2015; Landing & Kouchinsky 2016). In all these regions, the FAD of *W. crosbyi* occur below significant positive $\delta^{13}\text{C}$ excursions

(L4 in China, Li *et al.* 2009; I' in Bol'shaya Kounamka and the Ary Mas Yuryakh section of northern and eastern Siberia, Knoll *et al.* 1995, Kouchinsky *et al.* 2001, Landing & Kouchinsky, 2016; F in Mongolia, Brasier *et al.* 1996) which correlate with the 6p excursion in Morocco following Maloof *et al.* (2010a).

Caution is advised when correlating carbon isotope curves between continents, especially in the absence of comprehensive biostratigraphic data. Carbon isotope data are lacking for strata containing *W. crosbyi* in the Montagne Noire of France, but the associated fauna closely corresponds with that from the *W. crosbyi* Zone of South China (Devaere *et al.* 2013) and thus is likely pre-Tommotian equivalent.

In Australia, the Mount Terrible Formation consists predominantly of siliciclastics and hence is unsuitable for $\delta^{13}\text{C}$ chemostratigraphic analyses. Betts *et al.* (2015, in prep) presented preliminary carbon-isotope chemostratigraphy measured through the upper 62 m of the Sellick Hill Formation, (Facies Association C to E) at the SHL section, Myponga (Fig. 1). The isotopic curve has values from -2 to -4 per mil, presenting a distinctly negative trend similar to the global Shiyantou carbon isotope excursion (SHICE) (Zhu *et al.* 2006). More comprehensive sampling and isotopic analyses of carbonates from the Wangkonda and Sellick Hill Formations above the Mount Terrible Formation on Fleurieu Peninsula will be presented elsewhere.

The apparently disjunct occurrences of *W. crosbyi* in France (Kerber, 1988), Mongolia (Brasier *et al.* 1996) and South Australia (Gravestock *et al.* 2001) have been used as arguments for the supposed diachroneity of the FAD of *W. crosbyi* (Rozanov *et al.* 2008; Parkhaev *et al.* 2012; Landing *et al.* 2013). However, revision of anomalous occurrences has shown that the range of *W. crosbyi* correlates most closely with the late Nemakit-Daldynian and early Tommotian Stage of Siberia (Devaere *et al.* 2013; Smith *et al.* 2015; herein). In fact, the only area where *W. crosbyi* has a range that includes strata above the early Tommotian are

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in Avalonian Newfoundland. There, *W. crosbyi* is reported to have a 650 m thick composite stratigraphic interval (Chapel Island to Fosters Point Formation; Landing, 1989; Landing *et al.* 2013). However, this range includes the unfossiliferous strata of the Random Formation (Fig. 6). Based on the changes in the perceived stratigraphic ranges and correlations of *W. crosbyi* in Mongolia, France, Siberia and Australia (see above), the long stratigraphic range of the species in Avalonia seems to invite reinvestigation, especially since the record of this taxon is largely based on relatively poorly preserved specimens on bedding surfaces (Bengtson & Fletcher, 1983).

5. Systematic Palaeontology

All specimens are housed in the palaeontological collections of the South Australian Museum (Prefix SAM P).

Phylum MOLLUSCA Linnaeus, 1758
Class, Order and Family Unknown
Genus WATSONELLA Grabau, 1900
Type species. *Watsonella crosbyi* Grabau, 1900

Remarks. The orientation used here for descriptive purposes is that suggested by Devaere *et al.* (2013, fig. 13.). *Watsonella* was described by Pojeta & Runnegar (1976) as ‘pseudobivalved’ where presence of a dorsal ridge or groove (Fig. 6f, g, i, k, n) may represent a variably preserved separation between the two ‘pseudovalves’, similar to more derived rostroconchs.

Designation of *Wastonella* as the ‘oldest known rostroconch’ (Landing *et al.* 1988, p. 691) deserves reconsideration following new insights into shell

microstructures preserved on phosphatic steinkerns. Similarities between shell microstructure textures and their respective spatial distribution on the steinkerns of *Anabarella* and *Watsonella* indicate a closer phylogenetic affiliation with bivalves (Kouchinsky, 1999; Carter, 2001). Only a few specimens described herein preserve the characteristic ‘spiny’ microstructure (see Vendrasco *et al.* 2011a, pl. 6, figs. 1-2, pl. 7, fig. 2) near the dorsum and step-like textures (see Vendrasco *et al.* 2011a, pl. 6, figs. 3, 4, pl. 7, fig. 1) on the valves, although polygonal textures are not preserved (Fig. 6h). Comprehensive investigation of the horizontally oriented blades imprinted on the shell surface of *Anabarella* and *Watsonella* demonstrate an evolutionary progression towards the laminar structures present in the earliest confirmed bivalves (*Pojetaia* and *Fordilla*) (Vendrasco *et al.* 2011a, b). Stratigraphically, there is also a clear discrepancy in timing between the appearance of *Watsonella* and the earliest undoubted rostroconchs (Vendrasco *et al.* 2011b). In addition, documentation of a bivalved larval shell in a juvenile *Watsonella* specimen from Tommotian deposits in Yakutia, Siberia (Dzik, 1994, fig. 12g) supports the hypothesis of a closer relationship with bivalves and would serve to separate the genus from the rostroconchs. However, this feature is rarely preserved and undivided or incompletely divided larval shells have also been reported in *Watsonella* (Vendrasco *et al.* 2011b). Nevertheless, there is now mounting morphological, microstructural and stratigraphic evidence to suggest that that *Watsonella* represents a stem bivalve rather than an early rostroconch.

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546 ***Watsonella crosbyi* Grabau, 1900**

547 Fig. 7a-n

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549 1900 Grabau, *Watsonella crosbyi*; p. 632, pl. 1, figs. 9a-g.

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3 550 2013 Devaere, Clausen, Steiner, Álvaro & Vachard; *Watsonella crosbyi* Grabau; p. 37 figs
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5 551 14.1-33, 15.1-14. (Includes full synonymy).
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9 553 *Figured Material.* Four internal moulds (SAM P53331-53335), with an additional 33
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11 554 unfigured specimens.
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15 556 *Diagnosis.* See Devaere *et al.* (2013, p. 40).
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19 558 *Description.* Univalved (pseudobivalved), bilaterally symmetrical and laterally compressed
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21 559 phosphatic steinkerns; subelliptical in lateral view. Steinkerns range from 0.9-2.7 mm in
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23 560 length, 0.54-1.67 mm in height and 0.29-0.57 mm in width. Lateral surfaces nearly flat, but
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25 561 more strongly convex near dorsum and posterior margin where these surfaces are conjoined.
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27 562 In lateral view, dorsum variably convex, tending to be most strongly convex towards
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29 563 posterior. Anterior extremity angular (Fig. 7a), broadly acute; posterior extremity with
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31 564 strongly convex apex overhanging strongly concave subapical field; apertural margin tends to
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33 565 be fairly evenly curved. In dorsal view, steinkerns elongate subelliptical to subrectangular,
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35 566 with maximum width tending to be towards posterior (Fig. 7f, k, l, n). Dorsum with narrow
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37 567 median furrow (Fig. 7f, i, n) or very weak ridge (Fig. 7l) along dorsum midline, extending
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39 568 from anterior extremity of shell to just near apex where it sometimes bifurcates (Fig. 7f, g, k).
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41 569 Subapical field very short and poorly preserved in all specimens. Aperture long, slit-like,
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43 570 width similar along entire length (Fig. 7b). In some specimens, what appear to be internal
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45 571 imprints of concentric growth lines are present (Fig. 7a, e). There is also what appears to be
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47 572 an impression of a lamellar texture on the lateral surface of one of the steinkerns (Fig. 7h).
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3 575 *Remarks.* *Watsonella crosbyi* has received thorough taxonomic revision (Parkhaev in
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5 576 Gravestock *et al.* 2001; Li *et al.* 2011; Devaere *et al.* 2013). The material examined herein
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7 577 closely resembles specimens described by Parkhaev (in Gravestock *et al.* 2001, Pl. XLII, figs
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9 578 15-16) from the Sellick Hill Formation. Parkhaev (in Gravestock *et al.* 2001, p. 188)
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11 579 distinguished the Sellick Hill Formation specimens from the Siberian species, *Watsonella*
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13 580 *sibirica* (= *Heraultia sibirica* Missarzhevsky, 1974), based on its comparatively narrow
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15 581 anterior aperture, flattened valves and ‘less risen anterior margin of the aperture’. Jenkins *et*
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17 582 *al.* (2002) reexamined material collected by Brian Daily from the Mount Terrible Formation
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19 583 (most likely that documented in this paper), and referred the specimens to *W. sibirica*.
20
21 584 However, *W. sibirica* is now rightly regarded as a junior synonym of *W. crosbyi* (Li *et al.*
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23 585 2011; Devaere *et al.* 2013) and the features used to delineate the species by Parkhaev (in
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25 586 Gravestock *et al.* 2001) are considered to be within the range of intraspecific variation.
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27 587 Similarly, Yu (2014) described and illustrated specimens of *Watsonella yunnanensis* (He and
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29 588 Yang, 1982) from the Dahai Member of the Yuhucun Formation, East Yunnan, China, which
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31 589 are also now considered to be synonymous with *W. crosbyi* (Li *et al.* 2011; Devaere *et al.*
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33 590 2013). Yu (2014) distinguished the Chinese material from the type species based on its
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35 591 smaller size, blunt rounded beak, longer and wider ventral, anterior and posterior gapes,
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37 592 where the latter extends beyond the sub-apical shield and partially along the dorsum (Yu,
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39 593 2014, fig. 5). However, these characteristics vary within the concept of the species (Li *et al.*
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41 594 2011), including the extended posterior gape, which is most likely a feature caused by
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43 595 secondary phosphatization (see Fig. 7d).
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52 597 *Stratigraphic Range in South Australia.* Middle and top members of the Mount Terrible
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54 598 Formation and Facies Association A to C of the Sellick Hill Formation, Normanville Group,
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56 599 Fleurieu Peninsula, eastern Stansbury Basin. Terreneuvian, Stage 2.
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5 601 Order HELCIONELLIDA Geyer, 1994
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7 602 Family ALDANELLIDAE Linsley & Kier, 1984
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9 603 Genus ALDANELLA Vostokova, 1962
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11 604 Type species. *Aldanella attleborensis* (Shaler & Foerste, 1888).
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16 606 *Aldanella* sp. cf. *golubevi* Parkhaev, 2007
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18 607 Fig. 7o-x
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21 608
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23 609 *Figured Material.* 7 figured steinkerns (SAM P53336-53341), with an additional 7 unfigured
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25 610 specimens.
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29 612 *Description.* Asymmetrical, sinistrally coiled low turbate shell (Fig. 7o-v); up to 1.64 mm in
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31 613 diameter (average 1.42 mm), shell composed of 1.5-1.7 whorls expanding strongly, with last
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33 614 whorl occupying 58% of the maximum shell diameter. Shell height 32% of maximum shell
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35 615 diameter; spire flattened, projecting only slightly; apex rounded (Fig. 7w-x). Aperture ovate,
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37 616 approximately 2.5 times as wide as high; upper margin flattened, lower margin slightly
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39 617 convex (Fig. 7o-q, t), distal margin strongly curved. Umbilicus broadly concave. Faint,
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41 618 shallow furrows, convex towards aperture are present on the upper surface of some specimens
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43 619 (Fig. 7r).
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46 620
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49 621 *Remarks.* Steinkerns of *Aldanella* from South Australia all exhibit sinistral coiling (Fig. 7r-s,
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51 622 u-v), unlike the dextral coiling that normally characterizes the genus. Whether the shell is a
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53 623 true mirror-image of the typical dextral form, or whether it is dextrally hyperstrophic is
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55 624 unknown due to the poor preservation of diagnostic shell features, especially muscle scars. A
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‘pathological’ sinistrally coiled *Aldanella* was originally described by Golubev (1976, pl. 3, fig. 13), and subsequently, an assemblage of sinistrally coiled *Aldanella* was reported by Parkhaev (2007) from the western Anabar Region of the Siberian Platform. The identification of this particular sinistral assemblage as stratigraphically isolated from other dextral species of *Aldanella* in conjunction with it having a unique pointed apex, led Parkhaev (2007) to refer the shells to a new species, *A. golubevi*. This taxon is known to co-occur with both *A. attleborensis* and *A. crassa* in Fortunian – Stage 2 transitional beds of the eastern and western Anabar Region (Golubev, 1976; Parkhaev & Karlova, 2011).

The broad similarities between the South Australian material and Siberian sinistrally coiled *A. golubevi* are limited to the tight coiling of the whorls, their strong expansion and the low to almost flattened spire. These characteristics further distinguish this taxon from other sinistral taxa attributed to the genera *Barskovia* Golubev, 1976 and *Nomgoliella* Missarzhevsky, 1980, which otherwise possess more oval or rounded apertural cross-sections respectively. Unfortunately, the diagnostic pointed apex of *A. golubevi* (Parkhaev, 2007, pl. 2, figs 7, 10b) is not present in our collection (Fig. 7w-x), which consists exclusively of steinkerns. Consequently, the South Australian material is cautiously compared with *A. golubevi*.

Stratigraphic Range in South Australia. Top member, Mount Terrible Formation, Normanville Group, Fleurieu Peninsula. Eastern Stansbury Basin; Terreneuvian, Stage 2.

6. Conclusion

Paucity of cosmopolitan, biostratigraphically significant shelly taxa hinders early Cambrian global correlation. However, the micromollusc *W. crosbyi* is now known from China, France, Siberia, Mongolia, Avalonia and Australia and provides a crucial biostratigraphic link

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between pre-trilobitic strata in disparate palaeocontinents. The revised interpretation of the stratigraphic range of *W. crosbyi* in South Australia strongly suggests that it is restricted to early Cambrian Stage 2 (Peng *et al.* 2012).

In the Mount Terrible Formation, the stratigraphic range of *Watsonella crosbyi* (including overlap with *Aldanella* sp. cf. *golubevi*) predates the incoming of *Diplocraterion* piperock in the Wangkonda Formation. Furthermore, occurrence of *W. crosbyi* in South Australia predates the local appearance of *Sunnaginia imbricata* in the upper part of the overlying Sellick Hill Formation, which is succeeded by a fauna indicative of the pre-trilobitic *Kulparina rostrata* Zone (Betts *et al.* in review). The stratigraphic range of *W. crosbyi* in the Normanville Group is estimated as ~244 m (true thickness; per data in Alexander & Gravestock, 1990; Gravestock *et al.* 2001; herein). Carbon isotope values through the Facies Association C to E of the Sellick Hill Formation are suggestive of the negative SHICE event, further supporting an early Stage 2 age for *W. crosbyi* (though additional chemostratigraphic data through the Mount Terrible and Wangkonda Formations is required). The new Australian data strengthens the correlative value of *W. crosbyi* as an index fossil to define the base of Cambrian Stage 2.

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- Table 1. Global occurrences of *Watsonella crosbyi* Grabau, 1900.
- Fig. 1. Regional geological map of the Normanville Group between Sellick Hill-Normanville along the Fleurieu Peninsula, South Australia. Measured stratigraphic sections indicated.
- Fig. 2. Microfacies from Section 1 (base coordinates: 35°20'30.3"S: 138°28'39.0"E) of the three members of the Mount Terrible Formation. (a-c) Basal member, feldspathic to quartz-rich sandstone; a. 1.4 m above the base of the section (cross polarized light). b-c. 8.2 m above the base of the section, arrows indicate framboidal clusters. (d-g) Middle member, bioturbated siltstones to very fine sandstones, occasionally phosphatic to slightly ferruginised; d-e. 16.6 m

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993 above base of the section. f-g. 57.6 m above the base of the section, f. burrow, g. repeated
994 interlaminae. (h-i) Top member, fine-grained calcareous sandstones siltstone interbeds: h. 83
995 m above the base of the section (35°20'28.7"S: 138°28'36.4"E). i. 100.4 m above base of the
996 section (35°20'28.4"S: 138°28'35.8"E).

998 Fig. 3. Lithostratigraphic column and biostratigraphy of faunas from the Mount Terrible
999 Formation for Section 1 (after Gravestock & Shergold, 2001, fig. 6.3) and Section 2.

1001 Fig. 4. (a-b) Indeterminate chancelloriid sclerites. (a) SAM P53318, plan view. (b) SAM
1002 P53319, basal view. (c-f) *Eremactis mawsoni* Bengtson & Conway Morris in Bengtson *et al.*,
1003 1990. (c-d) SAM P53320. c. lateral view; d. oblique lateral view. (e-f) SAM P53321. e. lower
1004 surface; f. oblique view of foramen. (g-m) *Australohalkieria* sp. (g-h) SAM P53322, palmate
1005 sclerite. g. lateral view; h. lower surface. (i) SAM P53323, palmate sclerite, lower surface. (j-
1006 k) SAM P53324, cultrate sclerite. j. lower surface; k. upper surface. (l-m) SAM P53325, top
1007 member of the Mount Terrible Formation; cultrate sclerite. l. upper surface; m. lateral view.
1008 (n-r) *Bemella* sp. (n-o) SAM P53326. n. lateral view; o. apical view. (p-r) SAM P53327. p.
1009 supra-apical view; q. lateral view; r. apical view. (s-u) *Parailsanella* sp. cf. *murenica*
1010 Zhegallo in Esakova & Zhegallo, 1996, SAM P53328. s. apical view; t. lateral view; u. supra-
1011 apical view. (v-w) *Cupithec*a sp. (v) SAM P53329. (w) SAM P53330.

1013 Fig. 5. *Sunnaginia imbricata* Missarzhevsky in Rozanov *et al.*, 1969 from the Sellick Hill
1014 Formation (SHL section base coordinates: 35°22'36.30"S; 138°22'5.30"E); scale bars=200
1015 µm. (a, b) Dextral sclerites from SHL/82.5, 56.3 m true thickness, Facies Association E; a.
1016 apical view, SAM P53342; b. apical view, SAM P53343. (c-f) Dextral sclerites from

1017 SHL/50.9, 34.7 m true thickness, Facies Association D; c. apical view, SAM P53344; d.
 1018 adapical view, SAM P53345; e. apical view, SAM P53346; f. adapical view, SAM P53347.
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1020 Fig. 6. Global chronostratigraphic correlation chart of Terreneuvian Series, Fortunian and
 1021 Stage 2. Biostratigraphic and biozone data from Steiner *et al.* 2007, Kouchinsky *et al.* 2012,
 1022 Devaere *et al.* 2013, Landing *et al.* 2013, Yang, 2014 (references therein) and Landing &
 1023 Kouchinsky, 2015. Isotopic data from Maloof *et al.* 2010a; and geochronological data from
 1024 Maloof *et al.* 2010a and Compston *et al.* 2008. Error bars have been included for SHRIMP
 1025 dates.

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 1027 Fig. 7. (a-n) *Watsonella crosbyi* Gabau, 1900, all specimens collected by Brian Daily from the
 1028 middle member (3) of the Mount Terrible Formation, McGowran Locality, off Old Sellick
 1029 Hill Road, Sellick Hill, Fleurieu Peninsula. (a-d) SAM P53331. a. lateral view; b. ventral
 1030 view; c. magnification of apical area; d. posterior view. (e-i) SAM P 53332. e. lateral view,
 1031 square shows location of h; f. dorsal view, squares show location of g and i; g. magnification
 1032 of diverging dorsal median furrow; h. magnification of lamella-fibrillar micro-ornamnet. (j-l)
 1033 SAM P53333. j. lateral view; k. posterior view; l. dorsal view. (m) SAM P53334, posterior
 1034 view. (n) SAM P53335, dorsal view. (o-x) *Aldanella* sp. cf. *golubevi*, from the upper member
 1035 of the Mount Terrible Formation. (o) SAM P53336, apertural view. (p) SAM P53337,
 1036 apertural view. (q-r) SAM P53338. q. apertural view; r. spire view. (s-t, x) SAM P53339. s.
 1037 spire view; t. apertural view; x. magnification of apex. (u) SAM P53340, spire view. (v-w)
 1038 SAM P53341. v. spire view; w. magnification of apex.

Fig. 1. Regional geological map of the Normanville Group between Sellick Hill-Normanville along the Fleurieu Peninsula, South Australia. Measured stratigraphic sections indicated.
170x124mm (300 x 300 DPI)

Fig. 2. Microfacies from Section 1 (base coordinates: 35°20'30.3"S: 138°28'39.0"E) of the three members of the Mount Terrible Formation. (a-c) Basal member, feldspathic to quartz-rich sandstone; a. 1.4 m above the base of the section (cross polarized light). b-c. 8.2 m above the base of the section, arrows indicate framboidal clusters. (d-g) Middle member, bioturbated siltstones to very fine sandstones, occasionally phosphatic to slightly ferruginised; d-e. 16.6 m above base of the section. f-g. 57.6 m above the base of the section, f. burrow, g. repeated interlaminae. (h-i) Top member, fine-grained calcareous sandstones siltstone interbeds: h. 83 m above the base of the section (35°20'28.7"S: 138°28'36.4"E). i. 100.4 m above base of the section (35°20'28.4"S: 138°28'35.8"E).

176x391mm (300 x 300 DPI)

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176x391mm (600 x 600 DPI)

Fig. 3. Lithostratigraphic column and biostratigraphy of faunas from the Mount Terrible Formation for Section 1 (after Gravestock & Shergold, 2001, fig. 6.3) and Section 2. 183x207mm (300 x 300 DPI)

Fig. 4. (a-b) Indeterminate cancelloriid sclerites. (a) SAM P53318, plan view. (b) SAM P53319, basal view. (c-f) *Eremactis mawsoni* Bengtson & Conway Morris in Bengtson et al., 1990. (c-d) SAM P53320. c. lateral view; d. oblique lateral view. (e-f) SAM P53321. e. lower surface; f. oblique view of foramen. (g-m) *Australohalkieria* sp. (g-h) SAM P53322, palmate sclerite. g. lateral view; h. lower surface. (i) SAM P53323, palmate sclerite, lower surface. (j-k) SAM P53324, cultrate sclerite. j. lower surface; k. upper surface. (l-m) SAM P53325, top member of the Mount Terrible Formation; cultrate sclerite. l. upper surface; m. lateral view. (n-r) *Bemella* sp. (n-o) SAM P53326. n. lateral view; o. apical view. (p-r) SAM P53327. p. supra-apical view; q. lateral view; r. apical view. (s-u) *Parailsanella* sp. cf. *murenica* Zhegallo in Esakova & Zhegallo, 1996, SAM P53328. s. apical view; t. lateral view; u. supra-apical view. (v-w) *Cupithecra* sp. (v) SAM P53329. (w) SAM P53330. 147x129mm (600 x 600 DPI)

Fig. 5. *Sunnaginia imbricata* Missarzhevsky in Rozanov et al., 1969 from the Sellick Hill Formation (SHL section base coordinates: 35°22'36.30"S; 138°22'5.30"E); scale bars=200 μm. (a, b) Dextral sclerites from SHL/82.5, 56.3 m true thickness, Facies Association E; a. apical view, SAM P53342; b. apical view, SAM P53343. (c-f) Dextral sclerites from SHL/50.9, 34.7 m true thickness, Facies Association D; c. apical view, SAM P53344; d. adapical view, SAM P53345; e. apical view, SAM P53346; f. adapical view, SAM P53347.

Fig. 6. Global chronostratigraphic correlation chart of Terreneuvian Series, Fortunian and Stage 2. Biostratigraphic and biozone data from Steiner *et al.* 2007, Kouchinsky *et al.* 2012, Devaere *et al.* 2013, Landing *et al.* 2013, Yang, 2014 (references therein) and Landing & Kouchinsky, 2015. Isotopic data from Maloof *et al.* 2010a; and geochronological data from Maloof *et al.* 2010a and Compston *et al.* 2008. Error bars have been included for SHRIMP dates.

Fig. 6. Global chronostratigraphic correlation chart of Terreneuvian Series, Fortunian and Stage 2. Biostratigraphic and biozone data from Steiner *et al.* 2007, Kouchinsky *et al.* 2012, Devaere *et al.* 2013, Landing *et al.* 2013, Yang, 2014 (references therein) and Landing & Kouchinsky, 2015. Isotopic data from Maloof *et al.* 2010a; and geochronological data from Maloof *et al.* 2010a and Compston *et al.* 2008. Error bars have been included for SHRIMP dates.

131x103mm (300 x 300 DPI)

Fig. 7. (a-n) *Watsonella crosbyi* Gabau, 1900, all specimens collected by Brian Daily from the middle member (3) of the Mount Terrible Formation, McGowran Locality, off Old Sellick Hill Road, Sellick Hill, Fleurieu Peninsula. (a-d) SAM P53331. a. lateral view; b. ventral view; c. magnification of apical area; d. posterior view. (e-i) SAM P 53332. e. lateral view, square shows location of h; f. dorsal view, squares show location of g and i; g. magnification of diverging dorsal median furrow; h. magnification of lamella-fibrillar micro-ornament. (j-l) SAM P53333. j. lateral view; k. posterior view; l. dorsal view. (m) SAM P53334, posterior view. (n) SAM P53335, dorsal view. (o-x) *Aldanella* sp. cf. *golubevi*, from the upper member of the Mount Terrible Formation. (o) SAM P53336, apertural view. (p) SAM P53337, apertural view. (q-r) SAM P53338. q. apertural view; r. spire view. (s-t, x) SAM P53339. s. spire view; t. apertural view; x. magnification of apex. (u) SAM P53340, spire view. (v-w) SAM P53341. v. spire view; w. magnification of apex.

210x263mm (600 x 600 DPI)

Proof For Review

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Geological Magazine

Watsonella crosbyi from the lower Cambrian (Terreneuvian, Stage 2) Mount Terrible Formation in South Australia

Sarah M. Jacquet, Thomas Brougham, Christian B. Skovsted, James B. Jago, John R. Laurie, Marissa J. Betts, Timothy P. Topper and Glenn A. Brock

Supplementary Material

Table 1. Global occurrences of Watsonella crosbyi Grabau, 1900.

Palaeo-continents	Country	Geology and Stratigraphy	Time interval	Biozone(s)	Source
South China	China	Maidiping Formation, Maidiping and Gaoqiao, Emei County, Sichuan Province	Meishucunian	Watsonella crosbyi Assemblage Zone (Zone III)	Xing et al. 1984; Yu, 1987; Steiner et al. 2007; Yang, 2014
		Maidiping Formation, Hongzhai and Bangou, Ganlu County, Sichuan Province	Meishucunian	Watsonella crosbyi Assemblage Zone	Yu, 1987
		Dahai Member, Zhujiaping Formation, Dahai, Zhujiaping and Jiashewan, Huize County, Yunnan Province	Meishucunian	Watsonella crosbyi Assemblage Zone	Luo et al. 1982, 1984; Yu, 1987; Qian, 1989; Qian et al. 1996; Li et al. 2011
		Dahai Member, Zhujiaping Formation, Xiaotan, Yongshan County, Yunnan Province	Meishucunian	Watsonella crosbyi Assemblage Zone (Zone III)	Qian, 1989; Li & Xiao, 2004; Steiner et al. 2007; Li et al. 2011; Yang, 2014
		Dahai Member, Zhujiaping Formation, Xianfeng and Baizai, Xundian County, Yunnan Province	Meishucunian	Watsonella crosbyi Assemblage Zone	Yu, 1987; Yang, 2014
		Dahai Member, Zhujiaping Formation, Laolin and Lishuping, Huize County, Yunnan Province	Meishucunian	Watsonella crosbyi Assemblage Zone (Zone III)	Yang, 2014
		Dahai Member, Zhujiaping Formation, Yulu, Huize County, Yunnan Province	Meishucunian	Watsonella crosbyi Assemblage Zone	Feng & Sun, 2003
		Meishucun Formation, Meishucun, Jinning County, Yunnan Province	Meishucunian	Watsonella crosbyi Assemblage Zone	He & Yang, 1982

		Upper Maidiping Formation, Yangjiadun, Eastern part of the Yangtze Gorge, Yichang County, Hubei Province	Meishucunian	<i>Watsonella crosbyi</i> Assemblage Zone	Qian <i>et al.</i> 1979
		Huangshandong Member, Tongying Formation, Huangshandong, Yichang County, Hubei Province	Meishucunian	<i>Watsonella crosbyi</i> Assemblage Zone	Yu, 1987; Qian, 1989; Li <i>et al.</i> 2011; Yu, 2014
		Huangshandong Member, Tongying Formation, Tianzhushan, Yichang County, Hubei Province	Meishucunian	<i>Watsonella crosbyi</i> Assemblage Zone	Yu, 1987, 2014
Avalonia	USA	Red limestone boulders, Weymouth Formation, Sandy Cove and Pleasant Beach, Cohasset, Massachusetts	Begadean	<i>Sunnaginia imbricata</i> - <i>Camenella baltica</i> Zone	Shaler & Foerste, 1888; Grabau, 1900; Pojeta & Runnegar, 1976; Landing, 1989
		Lower Member, Weymouth Formation, Hoppin Reservoir, North Attleboro area, Massachusetts	Begadean	<i>Watsonella crosbyi</i> Zone	Landing, 1988
	New- foundland	Chapel Island Formation to ?Fosters Point Formation, Southeastern Newfoundland	Upper Placentian	<i>Watsonella crosbyi</i> Zone- <i>Camenella baltica</i> Zone	Bengtson & Fletcher, 1982; Landing <i>et al.</i> 1989, Landing <i>et al.</i> 2013
	UK	Home Farm Member (<i>Hyolithes</i> Limestone), Hartshill Formation, Nuneaton, English Midlands	Comley	<i>Camenella baltica</i> Zone	Brasier, 1984
West Gondwana	France	Heraultia Limestone, Marcou Formation, Montagne Noire	No Stage Subdivisions [Tommotian equivalent]	<i>Watsonella-Oelandiella</i> Zone	Cobbold, 1935; Runnegar & Jell, 1976; Pojeta & Runnegar, 1976; Runnegar & Pojeta, 1985; Kerber, 1988; Devaere <i>et al.</i> 2013
Siberian Platform	Siberia	Lower reaches of Lena River (no Formation specified), northern flanks of the Anabar Uplift	Tommotian	No Biozone specified	Ushatinskaya & Parkhaev, 2005
		Member IIIb, Kessyusia Formation, Olenek Uplift sections	Tommotian	<i>Nochoroicyathus sunnaginicus</i> Zone	Khomentovsky & Karlova, 1993; Kouchinsky, 1999

		Pestrotsvet Formation , Malyi Chaydakh River	Tommotian	<i>Nochoroicyathus sunnaginicus</i> Zone	Khomentovsky and Karlova, 1993
		Pestrotsvet Formation, Selinde River	Tommotian	<i>Nochoroicyathus sunnaginicus</i> - <i>Dokidocyathus regularis</i> Zones	Rozanov <i>et al.</i> 1969; Matthews and Missarzhevsky, 1975; Khomentovsky & Karlova, 1993; Kruse <i>et al.</i> 1995
		Sunagin Member, Pestrotsvet Formation, Nemnekey section between the Gonam and Nemnekey rivers	Tommotian	<i>Nochoroicyathus sunnaginicus</i> Zone	Khomentovsky & Karlova, 1993
		Pestrotsvet Formation, Lena River	Tommotian	<i>Dokidocyathus regularis</i> Zone / <i>Lapworthella tortuosa</i> Zone	Rozanov <i>et al.</i> 1969; Matthews & Missarzhevsky, 1975; Kruse <i>et al.</i> 1995; Varmalov <i>et al.</i> 2008
		Pestrotsvet Formation, Aldan River	Tommotian	<i>Nochoroicyathus sunnaginicus</i> - <i>Dokidocyathus regularis</i> Zones	Rozanov <i>et al.</i> 1969; Varmalov <i>et al.</i> 2008
		Krasnoporog Formation, Sukharikha River	Tommotian	<i>Ladatheca annae</i> Zone	Rowland <i>et al.</i> 1998
		Unit 4, Medvezh'ya Formation, Kotui River	Tommotian	<i>Nochoroicyathus sunnaginicus</i> Zone	Rozanov <i>et al.</i> 1969; Missarzhevsky, 1989; Kouchinsky, 1999
		Upper Kessyusa Formation, Olenek and Khorbusuonka rivers	Tommotian	<i>Watsonella- Lapworthella</i> Zone	Knoll <i>et al.</i> 1995
		Upper member of the Mattaia Formation, Olenek Valley near mouth of Boroulakh Creek	Nemakit- Daldynian (?) - Tommotian	<i>Nochoroicyathus sunnaginicus</i> Zone	Nagovitsin <i>et al.</i> 2015
Zavkhan terrane	Mongolia	Bayan-Gol Formation, Zhavkhan Province	Tommotian	<i>Watsonella crosbyi</i> Zone	Voronin <i>et al.</i> 1982; Esakova & Zhegallo, 1996; Braiser <i>et al.</i> 1996
East Gondwana	Australia	Mount Terrible Formation, Fleurieu Peninsula	No Stage Subdivisions [Terreneuvian Series, Stage 2]	<i>Watsonella crosbyi</i> Zone	Daily, 1976; Herein

		Facies Association A to C, Sellick Hill Formation, Myoponga Beach, Fleurieu Peninsula	No Stage Subdivisions [Terreneuvian Series, Stage 2]	<i>Watsonella</i> <i>croosbyi</i> Zone	Parkhaev in Gravestock <i>et al.</i> 2001; Jenkins <i>et</i> <i>al.</i> 2002; Herein
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