
Palaeontology, taxonomy and biostratigraphy of Cambrian assemblages from the Pertoorrta Group, Amadeus Basin, Northern Territory



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STATEMENT OF CANDIDATE

I certify that the work in this thesis entitled “*Palaeontology, taxonomy and biostratigraphy of Cambrian assemblages from the Pertaoorrta Group, Amadeus Basin, Northern Territory*” has not been submitted for a degree nor has it been submitted as part of a degree at any other university or institution other than Macquarie University. I also certify that the thesis is an original piece of research and it has been written by me. Any help or assistance that I have received in my research work, or in preparation of manuscripts, has been acknowledged.

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THESIS ABSTRACT

The Amadeus Basin is a large sedimentary province in central Australia that covers an approximate area of 170,000 square km. Despite the known occurrence of fossils from the majority of stratigraphic units within the Cambrian Pertaoorrtta Group there is a dearth of published palaeontological data, including no comprehensive biostratigraphy.

Presented as part of this thesis is a detailed investigation into three formations spanning the Cambrian Series 2–3 units of the Pertaoorrtta Group. The oldest of these, the Tempe Formation and Giles Creek Dolostone have previously been regarded as coeval. Examination of specimens from both drillcore and outcrop material from these two formations revealed a considerable diversity of new and biostratigraphically-informative fossils. The described taxa provide evidence that these two sedimentary units were deposited at different times. The Tempe Formation (in Paper 1) belongs to the Ordian, whereas the fauna from the Giles Creek Dolostone (in Papers 2–4) is distinctly younger and correlates with the overlying early Templetonian. These results suggest that the current regional stratigraphic scheme needs to be amended.

The youngest stratigraphic unit examined in this thesis is the Goyder Formation (in Paper 5). The initial age estimates for this formation were based solely on vague reports of the trilobites. Our collections demonstrate that the Goyder Formation contains a highly diverse fossil fauna with at least 20 different trilobite taxa. This assemblage indicates a late Mindyallan age (equivalent to Cambrian Series 3, Guzhangian) within the *Glyptagnostus solidotus* Zone.

Detailed logging and sampling through formations in the Pertaoorrtta Group has allowed for precise ages where little to no biostratigraphic data had previously been available. These ages have facilitated the development of a preliminary quantitative biostratigraphy of the Cambrian Series 2–3 portion of the Amadeus Basin, thus permitting more accurate intra- and interbasinal correlation.

INTRODUCTION

The Amadeus Basin, located in central Australia, contains some of the best exposed and readily accessible lower-middle Palaeozoic sedimentary rock successions in the country, providing a window into the early evolution of Australia's unique biological and geological past. The basin consists of several depositional packages of a Late Proterozoic to Carboniferous age (Lindsay & Korsch 1991). These successions range up to more than 14 km in total thickness and are dominated by carbonates, evaporites and siliciclastic rocks (Kennard & Lindsay 1991). In particular, thick sequences of fluvial and shallow marine sediments were deposited during the Ediacaran–Ordovician (as part of Pertaoorrta and Larapinta groups) at low palaeolatitudes along the eastern margin of Gondwana (Brock *et al.* 2000; Webby *et al.* 2000; Li & Powell 2001; McElhinny *et al.* 2003; Pisarevsky *et al.* 2008; Mitchell *et al.* 2010).

Palaeontological investigations of the Amadeus Basin began well over a century ago. The first fossils discovered were found by H. Y. L. Brown and F. Thornton near Tempe Downs in the 1890's (Brown 1891; Tate 1891). These fossils included trilobites, brachiopods and molluscs from the Horn Valley Siltstone, Stairway Sandstone and Stokes Siltstone of the Ordovician Larapinta Group (Brown 1891, 1892; Etheridge 1891, 1893, 1894). Subsequent work between the 1890's to 1950's added further taxa from these stratigraphic units based on the collections from the Horn Expedition of 1894 (Tate 1896; Teichert 1939; Crespin 1943; Crockford 1943; Teichert & Glenister 1952, 1954; Flower & Teichert 1957). It was also during the 1950's and 60's that Geoscience Australia (then known as the Bureau of Mineral Resources) began mapping the geology of the Amadeus Basin, generating a large collection of fossils discovered by a number of regional geologists (in particular Joklik 1955; Öpik 1956; Prichard & Quinlan 1962; Wells *et al.* 1964, 1965, 1966, 1967, 1970; Ranford *et al.* 1966; Forman 1966; Forman *et al.* 1967). These collections initiated a renewed interest in the palaeontology of the basin during the 1960's to the early 1990's, with papers describing an enormous diversity of fossils (overview in Shergold *et al.* 1991) ranging from Precambrian

stromatolites (Walter 1972) to Devonian vertebrates (Gilbert-Tomlinson 1968; Ritchie & Gilbert-Tomlinson 1977). Palaeontological research is still ongoing with a number of recent publications reporting significant new fossil discoveries (e.g. Young 2005; Young & Schultze 2005; Laurie 2006; Nicoll *et al.* 2007; Clement 2009; Jakobsen *et al.* 2014a, b; Allen *et al.* 2015).

The vast majority of this palaeontological work has focused on Late Cambrian to Early Carboniferous formations of the Larapinta and Pertnajara groups. By comparison the Ediacaran to middle Cambrian Pertaoorrtta Group has received very little attention despite the known occurrence of fossils from the majority of stratigraphic units within the group

Cambrian series	International stages	Regional stages	Amadeus Basin Stratigraphy						
Furongian	Stage 10 (undefined)	Datsonian	Pertoorrtta Group	West					East
		Payntonian							
	Jiangshanian	Iverian		'upper' Goyder Formation					
Paibian	Idamean								
Series 3	Guzhangian	Mindyallan		'lower' Goyder Formation					
		Boomerangian		Cleland Sst	Petermann Sst	Jay Creek Lst	Shannon Formation		
	Drumian	Undillan			Deception Frm				
	Floran	Templetonian			Illara Sst	Hugh River Shale	Giles Creek Dolostone		
	Stage 5 (undefined)	Ordian		Tempe Formation					
Series 2	Stage 4 (undefined)	No subdivisions		Chandler Formation					
	Stage 3 (undefined)								
Terreneuvian	Stage 2 (undefined)			Unit 4					
	Fortunian			Unit 3					
				Unit 2					
				Arumbera Sandstone					
			Namatjira Formation						

N.T.
Amadeus Basin

Figure 1. The present Australian Cambrian timescale against the previous paradigm for the temporal ranges of stratigraphic units within the Pertaoorrtta Group, Amadeus Basin, Northern Territory. Stratigraphy based on Wells *et al.* (1967); Kennard & Lindsay (1991); and Edgoose (2012). Grey shaded regions indicate a significant stratigraphic gap. The abbreviations 'Frm' = Formation, 'Lst' = Limestone and 'Sst' = Sandstone..

(Shergold *et al.* 1991). The lowest most fossiliferous unit, the Arumbera Sandstone, is one of the better documented formations. This sandstone unit contains a small Ediacaran-like biota in the basal Arumbera I and II members (Glaessner & Wade 1966; Glaessner 1969; Wade 1970; Webby 1970; Daily 1972; Glaessner & Walter 1975; McIlroy *et al.* 1997) and a diverse Early Cambrian ichnofossil assemblage with a possible hyolith taxon in the upper Arumbera IV member (Glaessner 1969; Wade 1970; Daily 1972; Glaessner & Walter 1975; Walter *et al.* 1989; Haines 1991; McIlroy & Heys 1997). The overlying transgressive Todd River Dolostone contains a diverse Atdabanian-equivalent fauna of archaeocyathids (Kruse & West 1980), linguliform brachiopods, molluscs, hyoliths, tomotiids, problematic tubes (Laurie & Shergold 1985; Laurie 1986) and trace fossils (Daily 1972). The only other fauna previously described and figured were the trilobites *Deiradonyx toddi* Öpik, 1982, '*Nepea?* sp. nov. NC', *Onaraspis somniurna* Öpik, 1968, *Onaraspis* sp., *Redlichia amadeana* Öpik, 1970a and *Xystridura gayladia* Öpik, 1975 from the Giles Creek Dolostone (Öpik 1968, 1970a, 1970b, 1975, 1982) as well as the rostroconch molluscs *Pleuropegma plicatum* Pojeta, Gilbert-Tomlinson & Shergold, 1977 and *Oepikila cambrica* (Runnegar & Pojeta, 1974) from the Goyder Formation (Pojeta *et al.* 1977). However, these taxa only make up a small proportion of the suspected faunal diversity of the Pertaoorrta Group. Tantalising reports have suggested additional faunas also occur in the Giles Creek Dolostone, Goyder Formation, Jay Creek Limestone, Hugh River Shale, Shannon Formation and Tempe Formation (Shergold 1986), yet, until the research presented herein, they have remained completely undocumented.

Most of the previous palaeontological studies on the Pertaoorrta Group are largely taxonomic in nature, with limited biostratigraphic information. This has lead to there being no currently recognised and comprehensive Cambrian biostratigraphy for the Amadeus Basin. The only unit which has been treated biostratigraphically is the Todd River Dolostone (Laurie & Shergold 1985). Over the past 30 years, some advances have been made with regard to

establishing a biostratigraphic zonation of the younger Ordovician Larapinta Group and the intra- and interbasinal correlation of this succession (e.g., Cooper 1981; Shergold *et al.* 1991; Shergold 1991; Laurie 2006; Jakobsen *et al.* 2014a, b). By comparison much of the fossil data for the Pertaoorrtta Group is known only from spot localities with little or no stratigraphic control. Hence intra- and interbasinal correlations to the Pertaoorrtta Group have remained relatively poorly resolved.

THESIS OBJECTIVES & FORMATTING

The objectives of this thesis have been: **(1)** to taxonomically document the poorly known fossil assemblages from the most prospective and underexplored sedimentary package within the Pertaoorrtta Group; and **(2)** to develop a high resolution Cambrian biostratigraphy for the Pertaoorrtta Group, as well as improving correlations between this sequence and contemporaneous rocks on a national and global scale.

These twin aims are jointly addressed in Papers 1–5, each representing a stand-alone manuscript, which documents either the entire fauna of a formation or a select component (e.g. trilobites). As such, each paper is formatted according to the guidelines for a specific target journal, having either been published, or currently in the submission process. This explains slight differences in text formatting, referencing style and figures which follow the requirements of the selected journals. Pagination throughout the thesis is has been made consistent by the addition of page numbers (centred at the bottom of the page) to provide easy reference. Original pagination for published manuscripts has also been retained, so as to keep the documents unaltered. Abstracts from two presentations (an oral and poster respectively) delivered at separate international conferences during my period of candidature are also included in an appendix at the end of the thesis.

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ESTIMATED PROPORTION OF CONTRIBUTION TO ARTICLES

Co-authored and submitted papers	Extent of intellectual input by the candidate (%)				
	Study concept and design	Acquisition of data ^{1*}	Analysis and interpretation of data	Drafting of manuscript ^{2*}	Critical revision
Paper 1. Fauna and biostratigraphy of the Cambrian (Series 2, Stage 4; Ordian) Tempe Formation (Pertaoorrt Group), Amadeus Basin, Northern Territory	100%	90%	90%	95%	85%
Paper 2. New bradoriid arthropods from the Giles Creek Dolostone (Cambrian Series 3, Stage 5; Templetonian), Amadeus Basin, central Australia	100% ^{3*}	50%	90%	95%	85%
Paper 3. Trilobites from the Giles Creek Dolostone (Cambrian Series 3, Stage 5; Templetonian) Amadeus Basin, central Australia.	100%	60%	90%	95%	85%
Paper 4. Linguliformean brachiopods from the early Templetonian (Cambrian Series 3, Stage 5) Giles Creek Dolostone, Amadeus Basin, Northern Territory	100% ^{3*}	50%	90%	95%	85%
Paper 5. Trilobites and agnostoid arthropods from the Goyder Formation (Cambrian Series 3, Guzhangian; Mindyallan), Amadeus Basin, central Australia	100%	90%	90%	95%	85%

^{1*} Fieldwork and acid processing of the RRG section for Papers 2, 3, 4 was partly completed in 2010 by a team acknowledged in the corresponding papers. However I recollected from this locality in 2014 and photographed all the material.

^{2*} Regional geological maps and stratigraphic columns were originally drafted by Dean Oliver from Dean Oliver Graphics Pty Ltd and have been acknowledged throughout. All adjustments, corrections and amalgamations of Dean Oliver's figures were my responsibility.

^{3*} A small number of SEM images used in Papers 3 & 4 were modified from my previous Bachelor of Science (Honours) thesis.

PAPER 1

Fauna and biostratigraphy of the Cambrian (Series 2, Stage 4; Ordian) Tempe Formation (Pertaoorrta Group), Amadeus Basin, Northern Territory.

Fauna and biostratigraphy of the Cambrian (Series 2, Stage 4; Ordian) Tempe Formation (Pertaoorrta Group), Amadeus Basin, Northern Territory

PATRICK M. SMITH, GLENN A. BROCK and JOHN R. PATERSON

SMITH, P.M., BROCK, G.A. & PATERSON, J.R., 2015. Fauna and biostratigraphy of the Cambrian (Series 2, Stage 4; Ordian) Tempe Formation (Pertaoorrta Group), Amadeus Basin, Northern Territory. *Alcheringa* 39, 40–70. ISSN 0311-5518

A new faunal assemblage is reported from the Tempe Formation (Cambrian Series 2, Stage 4; Ordian) retrieved from the Hermannsburg 41 drill-core, Amadeus Basin, central Australia. Two trilobite taxa, including one new species *Gunnia fava* sp. nov., four brachiopod taxa, including the age-diagnostic *Karathele napuru* (Kruse), *Kostjubella djagoran* (Kruse) and *Micromitra nerranubawu* Kruse, together with a bradoriid, helcionellids, hyoliths, echinoderms, cancelloriids, sponges and problematic tubes are described. The fauna has close links to those of the neighbouring Daly, Georgina and Wiso basins and suggests that the Tempe Formation correlates with the Australian Ordian stage (either the *Redlichia forresti* or *Xystridura negrina* assemblage zones). The Giles Creek Dolostone in the eastern Amadeus Basin, previously regarded as coeval with the Tempe Formation, has recently been reported to be of early Templetonian age in its type section. The described taxa from the Tempe Formation confirm that these two sedimentary units are not contemporaneous and that regional stratigraphic schemes should be amended.

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Key words: trilobites, brachiopods, shelly fossils, East Gondwana, Australia.

CAMBRIAN fossils from the Amadeus Basin (Fig. 1) were first reported by Madigan (1932) over 80 years ago, but no formal systematic descriptions were published until the late 1960s (Öpik 1968). Scientific descriptions of Cambrian shelly fossils have largely focused on faunas preserved in the Todd River Dolostone (Kruse & West 1980, Kennard 1983, Laurie & Shergold 1985, Laurie 1986), Giles Creek Dolostone (Öpik 1968, 1970a, b, 1975, 1982, Smith *et al.* 2014) and the Goyder Formation (Öpik 1967, Pojeta *et al.* 1977), with almost nothing published on other Cambrian units from the basin (see Shergold 1986, Shergold *et al.* 1991 for an overview). Although the clastic-dominated central part of the basin (Deception Formation, and Cleland, Illara and Petermann sandstones) is unfossiliferous, the marine deposits of the Tempe Formation have largely been overlooked. Based on the preliminary reports of Wells *et al.* (1970) and Shergold (1986), the Tempe Formation and the Giles Creek Dolostone (particularly prevalent in the east of the basin), have largely been assumed to be contemporaneous based on their fossil content (Shergold 1986). The main aim of this investigation is to systematically sample shelly fossils from the Hermannsburg 41 drillcore from the central

Amadeus Basin in order to complete the first taxonomic descriptions of the fauna from the Tempe Formation, compile biostratigraphic range data for all fossil taxa and compare the assemblages with those from the Giles Creek Dolostone (Smith 2012, Smith *et al.* 2014) in order to test the proposed stratigraphic correlation of these units.

Geological setting and locality

The Amadeus Basin is a large intracratonic depocentre of Neoproterozoic to Carboniferous sedimentary rocks located in central Australia (Fig. 1). The eastern and western boundaries of the basin are buried under younger sedimentary deposits, and the northern and southern limits are structural and/or erosional rather than depositional (Edgoose 2012). The Hermannsburg 41 corehole was drilled by the Bureau of Mineral Resources (now Geoscience Australia) in 1985 with the purpose of investigating the stratigraphy of the Pertaoorrta Group within the Carmichael Sub-basin, in particular around the area of the Gardiner Range, about 200 km west of Alice Springs (Fig. 1). The Pertaoorrta Group within the Carmichael Sub-basin reaches a maximum thickness of 2800 m, although the average thickness is closer to 2100 m (Lindsay & Korsch 1989, 1991). Similar

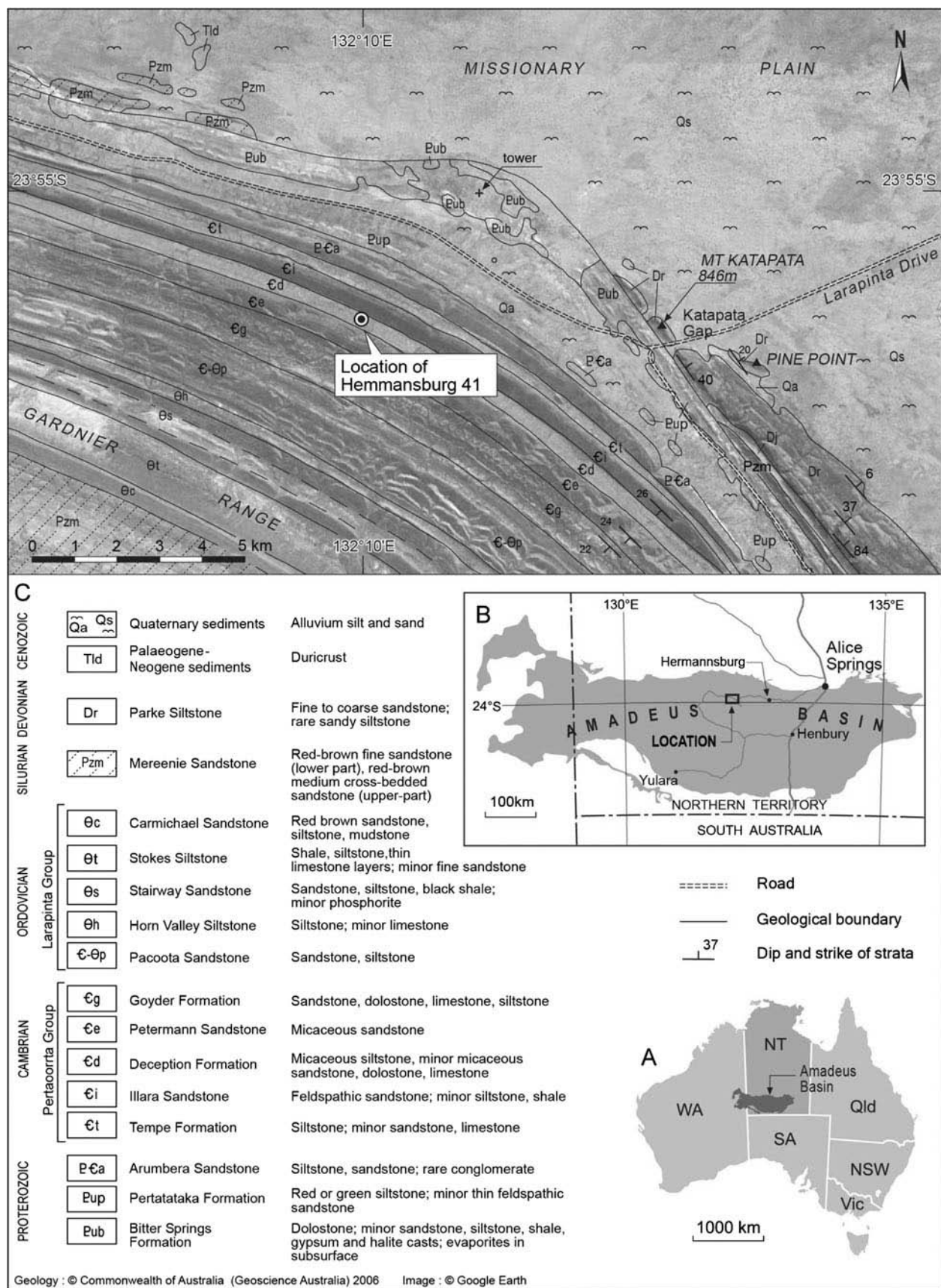


Fig. 1. A, map of Australia showing the location of the Amadeus Basin. B, map of the Amadeus Basin showing the position of corehole Hermannsburg 41 at 23°56'03"S, 132°05'36"E. C, detailed geological map of the Hermannsburg 41 corehole study area.

thicknesses were deposited in the Ooraminna Sub-basin to the east (Lindsay & Korsch 1989).

In the western regions of the Amadeus Basin, the Pertaoorrt Group was divided into five stratigraphic sequences (C1–C5) by Kennard & Lindsay (1991). The oldest sequence (C1) is represented by units 1 and 2 of the Arumbera Sandstone, which is largely Ediacaran in age. Sequence C2 is represented by lower Cambrian units 3 and 4 of the Arumbera Sandstone and possibly the mixed carbonate and siliciclastic Namatjira Formation. Disconformably above is sequence C3 represented by the lower Cambrian Tempe Formation. The final two sequences, C4–5 are represented by middle to upper Cambrian clastic and carbonate units, the Illara Sandstone, Deception Formation, Petermann Sandstone and Goyder Formation (Kennard & Lindsay 1991).

The Tempe Formation was originally described by Wells *et al.* (1965) as a member of the 'Pertaoorrt Formation', and later redefined by Ranford *et al.* (1966) as a separate formation after the redescription of the Pertaoorrt Group. For the most part, exposures of the Tempe Formation are restricted to the central-western regions of the Amadeus Basin, and no surface exposures are known east of approximately 131°30'E, 24°30'S (Bradshaw 1991a). Many exposures of the Tempe Formation are heavily eroded with poor outcrop in strike valleys and typically covered by rubble from the overlying and topographically resistant Illara Sandstone. The western limit of the formation is unknown, but it is interpreted to occur in the Cleland Hills west of the Gardiner Range (Bradshaw 1991a) and is cited as being present in the Mt Winter 1 drillcore (Bradshaw 1991a, Zang & Walter 1992). The Tempe Formation disconformably overlies the Chandler Formation and possibly the Arumbera Sandstone, with the surface being marked by red siltstone and weathered breccia layers (Bradshaw 1991a, b). Disconformably overlying the Tempe Formation is the Illara Sandstone, defined by a sharp lithological break and distinct depofacies change from marine to fluvial depositional cycles.

The Hermannsburg 41 core was drilled in the Gardiner Range (Fig. 1) about 6 km west of Katapata Gap at coordinates 23°56'03"S, 132°05'36"E (Owen 1986). It represents one of the few complete stratigraphic cores intersecting the Tempe Formation, and was originally spudded on the Deception Formation and then completely drilled from the ground surface (top of the drillcore) through the Illara Sandstone, Tempe Formation and Chandler Limestone before finishing in the upper parts of the Arumbera Sandstone, with a total depth of 444.5 m (Owen 1986, Zang & Walter 1992). The Tempe Formation was intersected between 241.04 m (top) and 384.64 m (base) from the surface and is thus 143.60 m thick (Fig. 2). Owen (1986) and Bradshaw (1991a) provided detailed lithological and sedimentological descriptions of the Tempe Formation within the core, so only a summary is provided here.

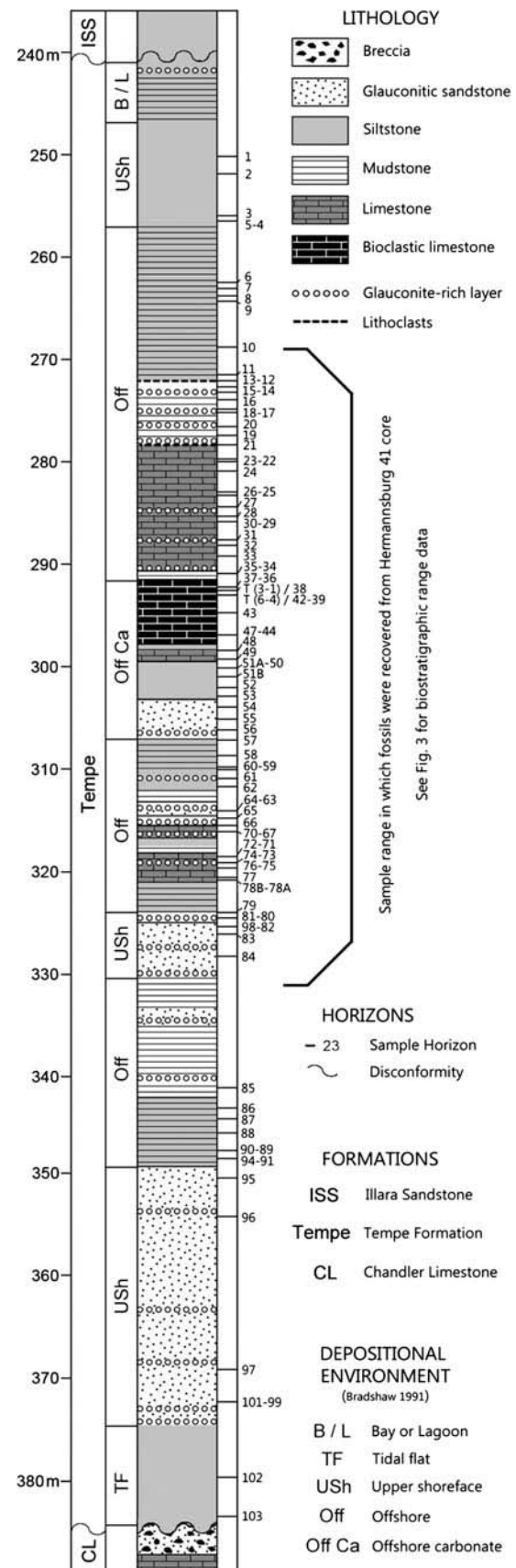


Fig. 2. Lithostratigraphic column of the Tempe Formation (between 384.64 m and 241.04 m) within the Hermannsburg 41 corehole. All sampled horizons are indicated. Measurements are in metres (true thickness) from the top of the drillcore. For biostratigraphic ranges, see Fig. 3.

The Tempe Formation in Hermannsburg 41 is dominated by dark grey-green mudstone with interbedded limestone and cross-bedded glauconitic sandstone, the latter being more common at the base and decreasing towards the top of the unit. Limestone, glauconitic in places, forms approximately 20% of the formation and is more common towards the upper half of the unit. Stylolitic fabrics are present in more massive beds, and these strata tend to host more crushed and fragmented fossil remains. Thin laminations of siltstone and fine sandstone, both rich in glauconite, are commonly interbedded with dark mudstones. Two beds of intraclast brecciation occur in the upper parts of the formation at 269.94 and 276.74 m (Fig. 2).

Bradshaw (1991a) provided a comprehensive sedimentological analysis of the Tempe Formation in the Hermannsburg 41 core. This work, supplemented by descriptions of lithology and sedimentary structures by McCubbin (1982), Enos (1983) and Shinn (1983) led Bradshaw (1991a) to propose a detailed depositional environment for the unit. Overall, the Tempe Formation represents a high-energy, nearshore to shallow shelf environment containing offshore, shoreface, tidal flat and lagoon sedimentary depofacies. Bradshaw (1991a) suggested that the Tempe Formation was deposited during a marine transgression, which covered the exposed and eroded Chandler Limestone. Sea level apparently reached its maximum during deposition of the carbonate intervals then receded, shallowing until eventual subaerial emergence. This was followed by initial onlap and deposition of the Illara Sandstone. The relatively high incidence of fragmentation and abrasion (including rounded skeletal remains in the fossil material) support Bradshaw's (1991a) interpretation of a high-energy environment during the deposition of the Tempe Formation.

Age and biostratigraphy

The age of the Tempe Formation was originally given as 'early Middle Cambrian' by Joyce G. Tomlinson based on brachiopod, trilobite, hyolith and gastropod faunas (Wells *et al.* 1970). Subsequent work by John R. Laurie (in Shergold 1986) also reported the presence of *Chancelloria* sp., *Pelagiella* sp., *Stenothecoides* sp., ? *Eothele* sp., *Paterina* sp. and *Zepaera* sp. along with two unnamed genera of hyoliths from phosphatic residues. However, none of these taxa (and those listed by Joyce G. Tomlinson) has ever been figured or systematically described. These preliminary identifications led Shergold (1986) to suggest that the formation was part of either the Ordian or early Templetonian stages using the Australian stage time scale, with his opinion being that the unit was more likely Ordian based on the sedimentary history of the eastern Amadeus Basin (i.e., equivalent to the Giles Creek Dolostone). Owen (1982) and Zang & Walter (1992) later published the acritarchs from both the Hermannsburg 41 and Mt. Winter 1 drill-

core with the assemblages being broadly similar to the 'Middle Cambrian' of the Eastern European Platform, though Zang & Walter (1992) acknowledged that at least five species are indicative of an 'Early Cambrian' age. Their conclusion was that the Tempe Formation is likely 'early Middle Cambrian' (Ordian-early Templetonian of Öpik 1968) based on their data.

Northern Territory correlations

The fauna from the Tempe Formation in the Hermannsburg 41 core shows greatest similarity to that of the Tindall Limestone in the Daly Basin in which *Gunnia lutea* Gatehouse, 1968 (a closely allied species to *Gunnia fava* sp. nov.), *Karathele napuru* (Kruse, 1990), *Kostjubella djaoran* (Kruse, 1990), *Micromitra nerranubawu* Kruse, 1990 and possibly *Xingrenaspis* sp. cf. *X. tongshanensis* (= *Tongshania* sp. cf. *T. tongshanensis*) (Qiu & Lin in Qiu *et al.*, 1983) all co-occur. This fauna was grouped together as an 'upper fauna' in the Tindall Limestone, which also contained common ptychoparioids and an unnamed species of *Xystridura* Öpik, 1975. The 'upper fauna' was originally interpreted to be of early Templetonian age based on the presence of *Tongshania* sp. cf. *T. tongshanensis* Qiu & Lin in Qiu *et al.*, 1983 and *Gunnia* sp. cf. *G. concava* (Deiss, 1939), which Kruse (1990) correlated with the Maochuangian Stage of China and the *Bathyriscus*–*Elrathina* Zone of North America. However, Kruse's (1990) age estimates were based on the now superseded Ordian-early Templetonian Stage (see discussion in Shergold 1989, 1995), thus predating Laurie's (2006) revised definition of the Templetonian Stage (followed herein). Recently, the reassignment of both *Tongshania* sp. cf. *T. tongshanensis* and *Gunnia* sp. cf. *G. concava* as separate species within *Xingrenaspis* Yuan & Zhou in Zhang *et al.*, 1980 by Peng *et al.* (2009) broadens the age estimate of Kruse (1990) to encompass both the Ordian and early Templetonian as defined by Laurie (2006), although this does not affect the international correlations of Kruse (1990), which may be evaluated in relation to subsequent correlations. The possible presence of *Redlichia guizhouensis* Zhou in Lu *et al.*, 1974 recorded as *Redlichia* sp. by Kruse (1990) and commented on by Paterson & Brock (2007) suggests an Ordian age for the Tindall Limestone (see below).

The neighbouring Georgina Basin is also known to host *K. napuru*, *Kostjubella djaoran* and possibly *M. nerranubawu* in the Gum Ridge Formation (Kruse 1998) and *Kostjubella djaoran* with other species of *Karathele* and *Micromitra* in the Thornton Limestone (= Hay River Formation, Smith *et al.* 2013) (Percival & Kruse 2014). Both these formations host the age-diagnostic trilobite *Redlichia gumridgensis* Laurie in Kruse *et al.*, 2004 (Kruse 1998, Laurie 2012), known from the *Xystridura negrina* Assemblage Zone of Ordian age in the Panton Formation of the Ord Basin

(Kruse *et al.* 2004), further supporting an Ordian age for the Tempe Formation in the Hermannsburg 41 core. The Top Springs Limestone of the Georgina Basin also contains a fauna with *K. napuru*, *Kostjubella djagoran* and possibly *M. nerranubawu* (Kruse 1991). This same formation also contains the trilobite *Redlichia forresti* (Etheridge in Foord, 1890) from the eponymous Ordian zone immediately below the *Xystridura negrina* Assemblage Zone. Only two drillcores (neither containing *R. forresti*) have been sampled through the Top Springs Limestone; hence it is uncertain if the ranges of these brachiopods overlap with *R. forresti*. Given that both *K. napuru* and *Kostjubella djagoran* range low in the Tindall Limestone (see Kruse 1990, fig. 2) it is possible that they range into the *R. forresti* Assemblage Zone, but this is uncertain. Other occurrences of *K. napuru* and *Kostjubella djagoran* in the Northern Territory include the Montejinni Limestone of the Wiso Basin, which has previously been assigned an Ordian age after being linked with the Gum Ridge Formation (Kruse 1998) based on the presence of the aforementioned brachiopods and a form akin to *Redlichia foraminifera* Sun & Chang in Chang 1937.

National and international correlations

Outside the Northern Territory, the most similar faunas to those of the Tempe Formation appear to be in South Australia, with the trilobites and associated brachiopods being the most age-diagnostic taxa in this region. *Karathele napuru* and *Kostjubella djagoran* are known to occur in the Wirrealpa Limestone within the Arrowie Basin (Brock & Cooper 1993) and *Kostjubella djagoran* in the Ramsay and Coobowie limestones within the Stansbury Basin (Holmer & Ushatinskaya in Gravestock *et al.* 2001). Jago *et al.* (2006) used these occurrences in a preliminary brachiopod biostratigraphy for South Australia, creating the *Vandalotreta djagoran* (= *Kostjubella djagoran*) Assemblage Zone, which they correlated with the Ordian stage. Interestingly, the trilobite *Redlichia guizhouensis* (Jell in Bengtson *et al.* 1990, Paterson & Brock 2007) occurs in association with *K. napuru* and *Kostjubella djagoran* in the Wirrealpa Limestone. This trilobite defines the *R. guizhouensis* Zone of northern Guizhou, Yangtze Platform, South China (Zhou & Yuan 1980, Zhou *et al.* 1980, Zhou & Zhen 2008), which is equivalent to, and possibly synonymous with, the *R. nobilis* Zone of the mid-Lungwangmiaoan Stage (Zhang 1985, 2003, Jell in Bengtson *et al.* 1990, Paterson & Brock 2007, Yuan & Ng 2014). This supports the results of other authors who have correlated Ordian faunas with the Lungwangmiaoan Stage of China (Shergold 1997, Chang 1998, Geyer & Shergold 2000, Peng 2003, Shergold & Geyer 2003, Peng *et al.* 2012) and the Toyonian Stage of the Siberian Platform (Brock & Cooper 1993, Zhuravlev 1995, Holmer *et al.* 1996). In a recent review of developments

in Australian Cambrian biostratigraphy, Kruse *et al.* (2009) considered the Ordian to be at least partly (if not entirely) equivalent to Series 2, Stage 4. This suggestion is based primarily on the upper range limit for *Redlichia* Cossmann, 1902, in Australia with additional considerations given to the occurrence of oryctocephalid trilobites (Shergold 1969) and the widespread Chinese zonal trilobite species *Bathynotus kueichouensis* Lu in Wang, 1964 (Öpik 1975, Shergold & Whittington 2000, Webster 2009, Peng *et al.* 2014) in the basal Arthur Creek Formation, which overlies the Gum Ridge Formation and Thornton Limestone (= Hay River Formation) in the Georgina Basin (Laurie 2004, 2012).

Other faunal elements of the Tempe Formation in the Hermannsburg 41 core are more difficult to utilize for biostratigraphy, as they are left under open nomenclature or are long-ranging. At least five taxa are similar to species known from the 'first discovery limestone' of the Coonigan Formation on the Gnalta Shelf in far western New South Wales. These include: *M. nerranubawu*, *Xingrenaspis* sp., *Dorispira* sp. cf. *D. terraaustralis*, *Protowenella* sp. and *Linguloidea* gen. et sp. indet. The 'first discovery limestone' of the Coonigan Formation has been considered by several authors to be Ordian in age (Roberts & Jell 1990), however, lack of biostratigraphic data impedes a more precise age determination. Similarly, taxa such as *Conotheca* sp. cf. *C. australiensis* Bengtson in Bengtson *et al.*, 1990 and *M. nerranubawu* from the Hermannsburg 41 core have also been recorded in the Pincally and Wydjah formations of the Gnalta Group, western New South Wales (Brock & Percival 2006), and *Conotheca* sp. cf. *C. australiensis*, *K. napuru* and *Kostjubella djagoran* are known to occur in the glacial erratic boulders on King George Island, Antarctica (Holmer *et al.* 1996). Unfortunately, both of these faunas lack strong biostratigraphic control, thus introducing a level of uncertainty regarding direct correlation.

Regional stratigraphic implications

The Tempe Formation and Giles Creek Dolostone crop out in the central and eastern parts of the Amadeus Basin, respectively, and have previously been regarded as essentially equivalent in age (e.g., Shergold 1986, fig. 1; Kennard & Lindsay 1991, fig. 4; Gravestock & Shergold 2001, fig. 6.5). This correlation has subsequently become entrenched in recent stratigraphic syntheses (Marshall 2005, Marshall *et al.* 2007, Haines *et al.* 2010, Edgoose 2012). However, recent description of the bradoriids and trilobites (Smith *et al.* 2014) from the Giles Creek Dolostone in the type area at Ross River Gorge reveals an abundant, but relatively low diversity biomineralized arthropod fauna. The trilobites include age-diagnostic taxa such as *Xystridura filifera* Öpik, 1975 and *Pagetia silicunda* Jell, 1975. These taxa are associated with the agnostids *Itagnostus oepiki*

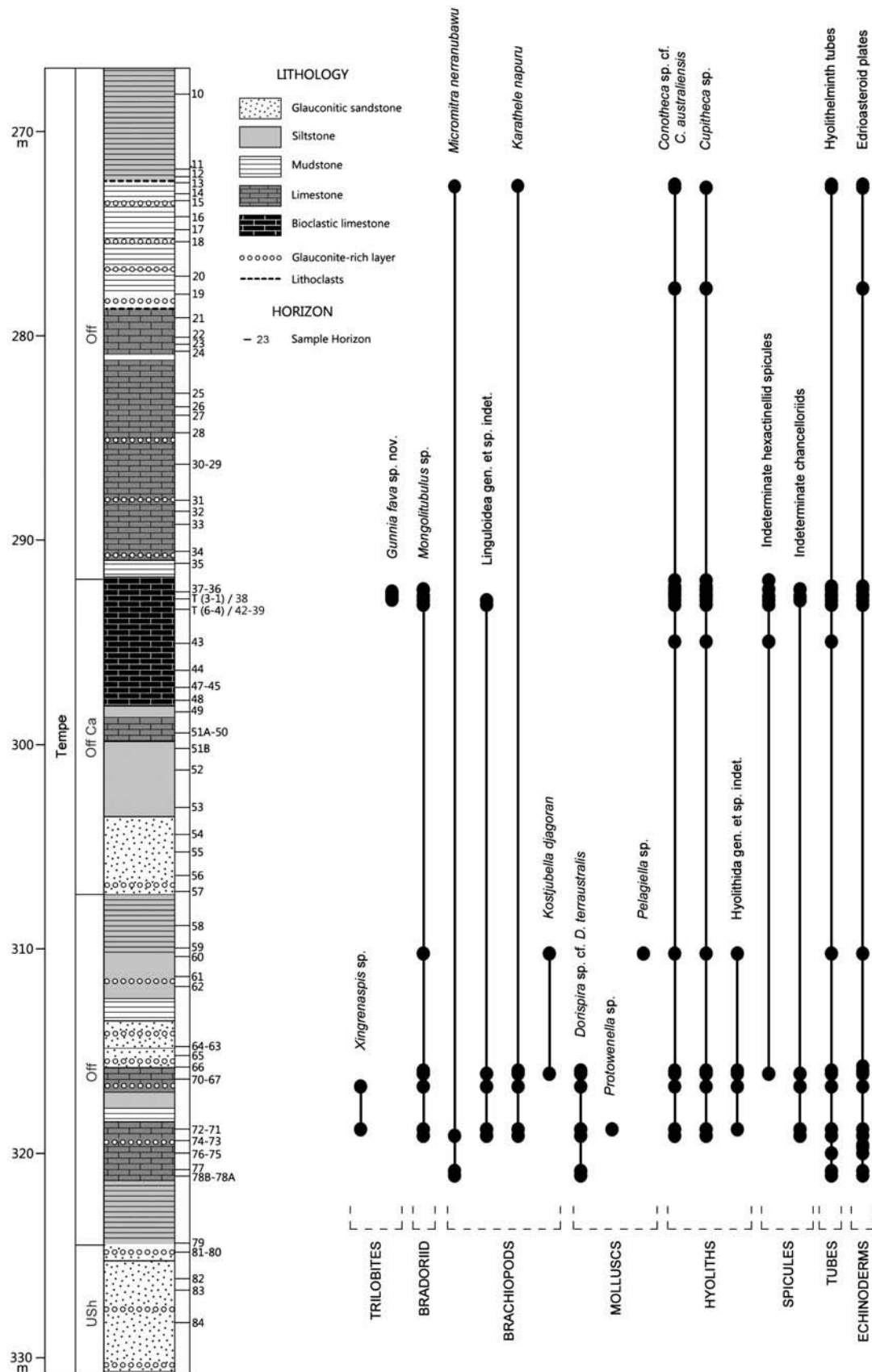


Fig. 3. Lithostratigraphic column of the fossiliferous interval of the Tempe Formation in the Hermannsburg 41 drillcore. All sampled horizons are indicated. Stratigraphic occurrences of all taxa in the core are plotted next to the column. Measurements in metres (true thickness) from the top of the drillcore (ground surface).

Laurie, 2004 and *Pentagnostus praecurrens* (Westergård, 1936), respectively, in the Georgina Basin and Gnalta Shelf (Öpik 1979, Roberts & Jell 1990). The stratigraphic ranges of these agnostids have been thoroughly documented through the Arthur Creek Formation in the Georgina Basin and indicate an age within the *Pentagnostus anabarensis* Zone and/or *Pentagnostus praecurrens* Zone of the early Templetonian (Laurie 2004, 2006, 2012). This would place the Giles Creek Dolostone within Cambrian Series 3, Stage 5, traditionally equivalent to the early Middle Cambrian in Australia.

The documentation of the fauna from the Tempe Formation suggests an age discrepancy between the two units. Interestingly, Shergold (1995, chart 5) also noted a lack of correlation between these units (without explanation) in the Cambrian correlation charts for the Amadeus Basin. Previous attempts at correlation have highlighted the presence of *Redlichia amadeana* Öpik, 1970b, *Onaraspis somniurna* Öpik, 1968 and *Onaraspis* sp. of Öpik (1968) as indicative of an Ordian age for the Giles Creek Dolostone. However, the precise stratigraphic (and geographic) locations of *Redlichia amadeana* and *Onaraspis somniurna* remain uncertain. Similarly, the specimen referred to *Onaraspis* sp. from Gaylad Dam (Loc. #AS33) by Öpik (1968) is known only from a possible cranidium fragment and an incomplete pygidium, making generic assignment to *Onaraspis* Öpik, 1968 questionable. Despite extensive systematic collecting of trilobites (and other fauna) by the authors through the Giles Creek Dolostone at Ross River Gorge, none of these taxa was recovered. It seems very likely that the specimens described by Öpik (1968) from spot localities are not derived from the Giles Creek Dolostone as previously asserted. As such, all current faunal data provide no evidence to suggest that the Tempe Formation and Giles Creek Dolostone are contemporaneous.

Systematic palaeontology

Terminology used to describe bradoriids follows, for the most part, Siveter & Williams (1997) and Williams & Siveter (1998). Use of the term valve ('bivalved head shield' or just 'head-shield' of Siveter *et al.* 2003, p. 13) is used in a strictly descriptive sense and has no phylogenetic connotation. For hyoliths, the terminology follows that of Sysoyev (1976). All other groups use the terminology found in their respective treatises (Whittington & Kelly 1997, Williams 2000).

Taxa that have previously been formally and adequately documented from the Northern Territory are discussed, but not redescribed. All measurements are in millimetres unless otherwise stated. All illustrated and described specimens are provided with CPC numbers and are held in the Commonwealth Palaeontological Collection (prefix CPC) maintained by Geoscience

Australia, Canberra. Stratigraphic ranges for all taxa are given in terms of depth in metres from the top of the Hermannsburg 41 core. Distribution is provided only for taxa where a specific epithet could be assigned (Fig. 3).

Phylum PORIFERA Grant, 1836

Class HEXACTINELLIDA Schmidt, 1870

Indeterminate hexactinellid spicules (Fig. 4A–H)

Remarks. Spicules are rare in the Hermannsburg 41 core, occurring either as moulds (Fig. 4A, E, G, H) or as original siliceous material (Fig. 4C, D, F). At least three forms are represented; pentacts (five-rayed spicules; Fig. 4A, C, E–H), hexacts (six-rayed spicules; Fig. 4B) and octacts (eight-rayed spicules; Fig. 4D). Sizes of the three forms vary slightly, with the hexacts and octacts reaching up to 500 µm in length and the pentacts reaching 1 mm.

Hexactinellid spicules are common elements in Cambrian rocks from Australia (e.g., Bengtson *et al.* 1990, Kruse 1990, Kruse 1998, Mehl 1998, Paterson *et al.* 2007, Topper *et al.* 2009). Many spicules in the Hermannsburg 41 drillcore resemble described and illustrated hexactinellid spicules from the Ordian and Templetonian rocks of the Georgina Basin (Kruse 1990, Mehl 1998), in particular the polytacts (Kruse 1990, pl. 24, fig. C; Mehl 1998, pl. 3, figs 13–16). A few specimens also resemble material from the Toyonian-equivalent Wirrealpa and Ramsay limestones in South Australia (Brock & Cooper 1993, fig. 6.1–4) and erratic boulders from King George Island, Antarctica (Wrona 2004, fig. 5D, E, G).

Material. Over 100 specimens. Specimens range from 316.30 m to 292.20 m (Fig. 3) below the top of the drillcore.

Phylum UNCERTAIN

Order CHANCELLORIIDA Walcott, 1920

Family CHANCELLORIIDAE Walcott, 1920

Indeterminate cancelloriids (Fig. 4I–M)

Remarks. Material from the Hermannsburg 41 core primarily consists of phosphatic internal moulds and coatings of several cancelloriid sclerites commonly occurring as single or clumped rays (Fig. 4I–M). Owing to the poor preservation, all cancelloriid sclerites from the Hermannsburg 41 core are treated as indeterminate species.

Preserved spicules include 8 + 1 and 6 + 1 sclerites with a flat base, small to medium central basal disc and small circular basal pores. The more numerous radial rays diverge from the central ray at 50–60° (Fig. 4I). This morphology is similar to sclerites described from the Ordian Pincally Formation of New South Wales (Brock & Percival 2006). Another species with comparable morphology is *Chancelloria racemifundis* Bengtson in Bengtson *et al.*, 1990 from the Templetonian of the

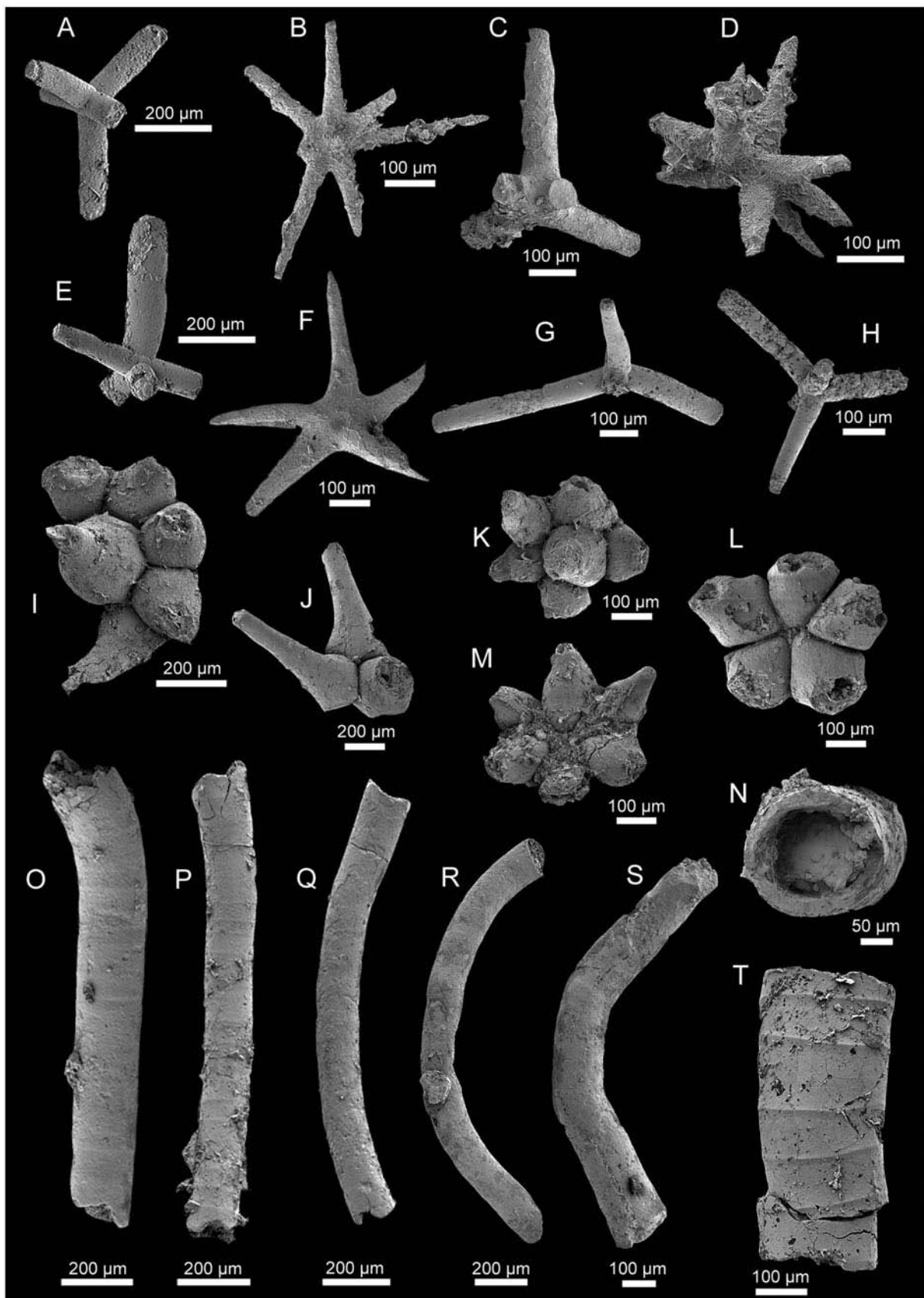


Fig. 4. Indeterminate spicules from the Ordian Tempe Formation in the Hermannsburg 41 drillcore (all measurements denote depth from top of the drillcore). A–H, indeterminate hexactinellid spicules. A, CPC41800, sample 68, 316.30 m, phosphatic mould of pentact spicule. B, CPC41801, sample 68, 316.30 m, phosphatic mould of hexact spicule. C, CPC41802, sample 70, 316.43 m, pentact spicule. D, CPC41803, sample 70, 316.43 m, octact spicule. E, CPC41804, sample 70, 316.43 m, pentact spicule. F, CPC41805, sample 70, 316.43 m, pentact spicule. G, CPC41806, sample 128, 292.98 m, broken pentact spicule. H, CPC41807, sample 128, 292.98 m, pentact spicule. I–M, indeterminate cancelloriid spicules. I,

Northern Territory (Mehl 1998), Cambrian Series 2, Stage 3 and 4 of South Australia (Bengtson in Bengtson *et al.* 1990) and Toyonian-equivalent of Antarctica (Wrona 2004). However, *Chancelloria racemifundis* can be distinguished by the presence of raised spherulitic structures around the basal foramina and a circular ridge around the basal facet; these features are absent in the Tempe Formation specimens.

Material. Thirteen specimens. Specimens range from 319.34 m to 292.98 m (Fig. 3) below the top of the drillcore.

Phylum and Class UNCERTAIN

Order HYOLITHELMINTHIDA Fischer, 1962

Family HYOLITHELLIDAE Walcott, 1886

Hyalolithelminthid tubes (Fig. 4N–T)

Description. Fragmentary phosphatic, straight, curved to sinuous tubes with a near-circular cross-section, 100–248 µm in diameter. Low angle of taper (<5°); maximum length 1.3 mm. External ornament varies between individuals, most with weak concentric growth lines, remainder have a smooth surface. All known tubes are broken at apertural and apical ends.

Remarks. Hyolithelminth tubes are commonly reported from Cambrian deposits around the world (Skovsted & Peel 2011), but they are also one of the most poorly studied and enigmatic groups of shelly fossils. Previous attempts to classify hyolithelminthids have often differentiated groups based on cross-sectional tube outline, degree of taper, and the transverse ornamentation (e.g., Bengtson in Bengtson *et al.* 1990). However, there is an extensive degree of character variation within samples and a high incidence of fragmentation has prompted some (e.g., Paterson *et al.* 2007, Topper *et al.* 2009) to suggest a more conservative approach to hyolithelminthid taxonomy.

Specimens from the Hermannsburg 41 core are small, abraded fragments (Fig. 4N–T). These specimens display a wide range of morphology, resembling specimens previously referred to *Hyolithellus* Billings, 1871, *Torellella* Holm, 1893 and *Sphenothallus* Hall, 1847. Generic placement of these fragments is difficult given the extent of fragmentation and abrasion. A few well-preserved tubes have a circular cross-section (Fig. 4N) and are either straight (Fig. 4O, P) or curved (Fig. 4Q–S) with simple weak annular growth lines (Fig. 4T) that are reminiscent of both *Hyolithellus micans* Billings, 1871 and *Hyolithellus filiformis* Bengtson in Bengtson *et al.*, 1990, respectively. Tubes from the Hermannsburg 41

core resemble *H. micans* from the Ordian Pincally Formation, New South Wales (Brock & Percival 2006, fig. 5B–D); *H. micans* and *H. filiformis* from Toyonian-equivalent erratics on King George Island, Antarctica (Wrona 2004, figs. 25A–E); *Hyolithellus* sp. from the Cambrian Series 2, Stage 4 Forteau Formation (Skovsted & Peel 2007, fig. 6E, F) and *Hyolithellus* sp. from the Cambrian Series 2, Stage 4 Kinzers Formation (Skovsted & Peel 2010, fig. 3.10, 3.11). Given the lack of taxonomically useful characters for classifying hyolithelminth tubes, the Tempe Formation specimens are left under open nomenclature.

Material. Over 100 specimens. Specimens range from 321.28 m to 272.85 m (Fig. 3) below the top of the drillcore.

Phylum ?MOLLUSCA Cuvier, 1797

Class HYOLITHA Marek, 1963

Order ORTHOTHECIDA Marek, 1966

Family CIRCOTHECIDAE Missarzhevskiy in Rozanov *et al.*, 1969

Conotheca Missarzhevskiy in Rozanov *et al.*, 1969

Type species. *Conotheca mammilata* Missarzhevskiy in Rozanov *et al.*, 1969.

?**Conotheca** sp. cf. **C. australiensis** Bengtson in Bengtson *et al.*, 1990 (Fig. 5A–D, G)

?2001 *Conotheca* cf. *australiensis* Bengtson in Bengtson *et al.* 1990; Qian *et al.*, p. 33, pl. 1, figs 6–10.

?2003 *Conotheca* cf. *C. australiensis* Bengtson in Bengtson *et al.* 1990; Wrona, p. 191, fig. 5A–E.

?2006 *Conotheca* cf. *C. australiensis* Bengtson in Bengtson *et al.* 1990; Brock & Percival, p. 86, fig. 6F–H.

?2007 Orthothecid conchs indet.; Skovsted & Peel, p. 738, fig. 5F, G.

?2010 *Conotheca* cf. *australiensis* Bengtson in Bengtson *et al.* 1990; Skovsted & Peel, fig. 2.12–2.14.

Description. Conch maximum length 7 mm, angle of divergence (AD) 10–14°, straight, slightly tapering towards the posterior, apex typically missing. Conch diameter 1.2 mm. Cross-section circular in outline. Internal sculpture smooth. A few internal moulds preserve an impression of the gently concave internal surface replicating the shape of the operculum. Impressions show operculum had wide cardinal processes and narrow, divergent clavicles.

← CPC41808, sample 40, 293.40 m, plan view of phosphatic internal mould from an incomplete 8+1 ray. **J**, CPC41809, sample 71, 319.02 m, oblique lateral view of phosphatic internal mould from an incomplete ray. **K**, CPC41810, sample 42, 293.64 m, plan view of phosphatic internal mould from an incomplete 6+1 ray. **L**, CPC41811, sample 68, 316.30 m, plan view of phosphatic internal mould from an incomplete 5+0 ray. **M**, CPC41812, sample 67, 316.15 m, plan view of phosphatic internal mould from an incomplete 6+0 ray. **N–T**, hyolithelminth tubes. **N**, CPC41813, sample 70, 316.43 m, detail of circular apertural end. **O**, CPC41814, sample 67, 316.15 m, straight tube with slight bend. **P**, CPC41815, sample 70, 316.43 m, straight tube with slight curve. **Q**, CPC 41816, sample 71, 319.02 m, slightly curved tube. **R**, CPC41817, sample 71, 319.02 m, curved tube. **S**, CPC41904, sample 71, 319.02 m, curved tube. **T**, CPC41818, sample 70, 316.43 m, detail of tube surface showing concentric ring ornamentation on some individuals.

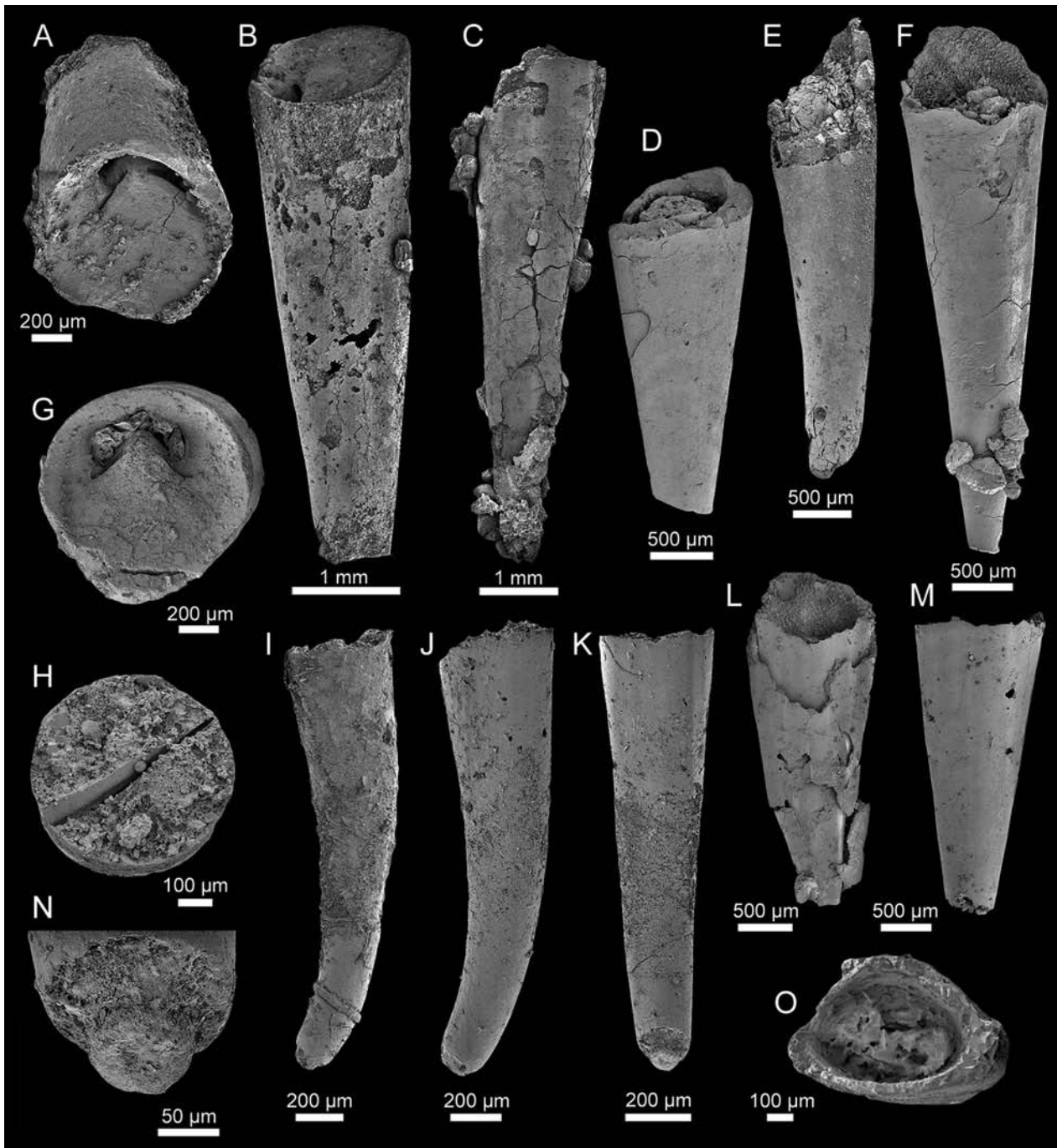


Fig. 5. Hyoliths from the Ordian Tempe Formation in the Hermannsburg 41 drillcore (all measurements denote depth from top of the drillcore). **A–D, G**, *Conothecha* sp. cf. *C. australiensis* Bengtson in Bengtson *et al.*, 1990. **A**, CPC41819, sample 70, 316.43 m, apertural view of phosphatic internal mould showing impression of concave internal surface of the operculum with cardinal processes. **B**, CPC41820, sample 71, 319.02 m, lateral view of phosphatic internal mould. **C**, CPC41821, sample 71, 319.02 m, lateral view of phosphatic internal mould. **D**, CPC41822, sample 71, 319.02 m, lateral view of smaller phosphatic internal mould. **G**, CPC41823, sample 71, 319.02 m, apertural view of phosphatic internal mould showing impression of concave internal surface of the operculum with cardinal processes. **E, F, L, M, O**, Hyolithida gen. et sp. indet.. **E**, CPC41828, sample 67, 316.15 m, lateral view of phosphatic internal mould. **F**, CPC41829, sample 67, 316.15 m, dorsum of phosphatic internal mould. **L**, CPC41830, sample 70, 316.43 m, dorsum of fragmented phosphatic internal mould. **M**, CPC41831, sample 70, 316.43 m, venter of phosphatic internal mould. **O**, CPC41832, sample 71, 319.02 m, apertural view of phosphatic internal mould showing rounded-triangular cross-section. **H–K, N**, *Cupithec*a sp.. **H**, CPC41824, sample 70, 316.43 m, apertural view of phosphatic internal mould showing circular cross-section. **I**, CPC41825, sample 42, 293.64 m, lateral view of phosphatic internal mould showing possible septa at base. **J**, CPC41826, sample 40, 293.40 m, lateral view of phosphatic internal mould. **K, N**, CPC41827, sample 42, 293.64 m. **K**, rotated lateral view of phosphatic internal mould. **N**, enlargement of *Cupithec*a-like termination of conch.

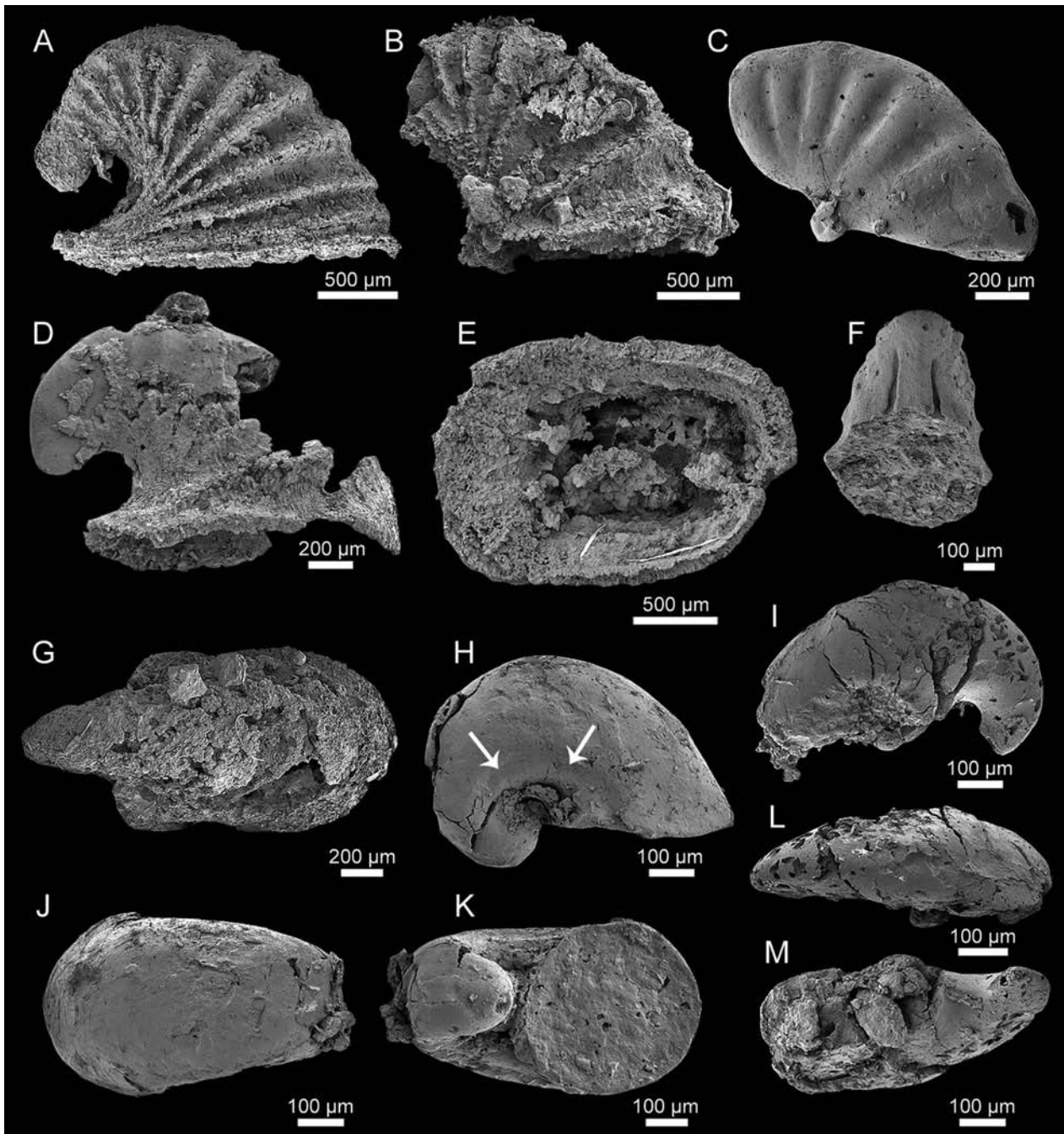


Fig. 6. Micromolluscs from the Ordian Tempe Formation in the Hermannsburg 41 drillcore (all measurements denote depth from top of the drillcore). A–G, *Dorispira* sp. cf. *D. terraustralis* (Runnegar & Jell, 1976). A, E, CPC41833, sample 71, 319.02 m. A, lateral view of silicified specimen. E, apertural view of silicified specimen. B, CPC41834, sample 71, 319.02 m, lateral view of silicified partial specimen. C, CPC41835, sample 72, 319.34 m, lateral view of phosphatic internal mould. D, CPC41836, sample 71, 319.02 m, lateral view of silicified partial specimen. F, CPC41837, sample 71, 319.02 m, anterior(?) view of phosphatic internal mould showing pair of radial ridges on internal surface. G, CPC41838, sample 71, 319.02 m, apical view of silicified specimen. H, J, K, *Protowenella* sp.. H, J, K, CPC41839, sample 71, 319.02 m. H, lateral view of phosphatic internal mould showing lateral umbilical channel (indicated with two white arrows). J, apical view of phosphatic internal mould. K, apertural view of phosphatic internal mould. I, L, M, *Pelagiella* sp.. I, L, M, CPC41840, sample 60, 310.43 m. I, lateral view of phosphatic internal mould. L, apical view of phosphatic internal mould. M, apertural view phosphatic internal mould.

Remarks. The Tempe Formation specimens consist largely of steinkerns (Fig. 5A–D, G) and resemble *Conotheca australiensis* Bengtson in Bengtson *et al.*, 1990 from Cambrian Series 2, Stage 3–4 of South Australia in both size and overall shape (see Bengtson *et al.* 1990, fig. 144). A few unfigured specimens from the Tempe Formation are more strongly curved dorsally

and in this respect they are almost identical to specimens described as *Conotheca* cf. *C. australiensis* from the Ordian Pincally and Wydjah formations of New South Wales (Brock & Percival 2006), Toyonian-equivalent glacial erratic boulders on King George Island, Antarctica (Wrona 2003), and the Orthothecid indet. conchs from the Cambrian Series 2, Stage 4

Forteau Formation, Newfoundland (Skovsted & Peel 2007). All steinkerns possess a circular cross-section (Fig. 5G) and have a slight apical taper (Fig. 5B, C) and two very deeply incised cardinal process impressions (Fig. 5A, G). Other specimens described under *Conotheca* cf. *australiensis*, by Qian *et al.* (2001, pl. 1, figs 6–10) from the lower Cambrian of the southern Shaanxi province, China, are similar in many respects, although they appear to have the opercula preserved. As the identification of *Conotheca* is largely based on opercula, the absence of such material from the Tempe Formation prevents definitive identification.

Distribution. Tempe Formation, Amadeus Basin, Northern Territory. Cambrian Series 2, Stage 4 (Ordian). Pinnally Formation and Wydjah Formation, Gnalta Group, New South Wales. Cambrian Series 2, Stage 4 (Ordian). Cape Melville Formation glacial erratic boulders, King George Island, Antarctica. Cambrian Series 2, Stage 4 (Toyonian-equivalent, ?Ordian).

Material. Over 100 specimens. Specimens range from 319.34 m to 272.85 m (Fig. 3) below the top of the drillcore.

Family CUPITHECIDAE Duan, 1984

Cupitheca Duan in Xing *et al.*, 1984

Type species. *Paragloborilus mirus* He in Qian, 1977.

Remarks. See Demidenko in Gravestock *et al.* (2001) for a full generic synonymy list for *Cupithec*a.

Cupitheca sp. (Fig. 5H–K, N)

Description. Conch length 1.9 mm in largest complete specimen, angle of divergence (AD) 8°, slightly to strongly curved in a single plane (dorsoventrally?) through about 40° from apex to aperture. Conch diameter 400–590 µm. Cross-section circular in outline. Internal sculpture smooth. Apex unknown; all specimens with preserved apertural ends of conch show septate termination characteristic of *Cupithec*a bound by smooth continuous, collar-like incised groove. Septa are planar to gently convex.

Remarks. Most specimens are preserved as steinkerns, commonly lacking the apertural region (Fig. 5I–K). The internally smooth, strongly curved conch and septate termination, with a collar-like incised groove (Fig. 5I, N) is very characteristic of *Cupithec*a (Duan 1984, Bengtson in Bengtson *et al.* 1990, Brock & Cooper 1993, Topper *et al.* 2009). Most are identical in size and form to specimens described as *Cupithec*a sp. from the Ordian of the Ord Basin by Kruse *et al.* (2004, p. 36, fig. 27C–E). As these conchs are strongly curved they differ from specimens described from the Toyonian-equivalent of South Australia (Brock & Cooper 1993, Demidenko in Gravestock *et al.* 2001), Ordian and Templetonian of Queensland (Kruse 2002) and Toyonian-equivalent of

Antarctica (Wrona 2003). Paterson *et al.* (2007) described a similar conch from the Cambrian Series 2, Stage 3, Koolyurtie Limestone Member (Parara Limestone) of South Australia, termed ‘curved orthothecides’. These hyoliths are generally similar in size and shape, albeit curved more dramatically through more than 180° compared with the specimens described from the Tempe Formation in the Hermannsburg 41 core (compare Fig. 5I, J to Paterson *et al.* 2007, fig. 5I, G).

Material. Over 100 specimens. Specimens range from 319.34 m to 273.00 m (Fig. 3) below the top of the drillcore.

Order HYOLITHIDA Sysoyev, 1957

Family UNCERTAIN

Hyolithida gen. et sp. indet. (Fig. 5E, F, L, M, O)

Description. Conch maximum length 4.2 mm, angle of divergence (AD) 17–19°, straight to very slightly curved towards the dorsum. Conch maximum height 590 µm, width 710 µm. Mean width/height ratio approximately 1.2. Cross-section rounded-triangular; dorsoventral margins smooth. Dorsum not bound by longitudinal sulci. Aperture with prominent smoothly rounded lip. Internal sculpture smooth.

Remarks. The majority of specimens preserve only limited detail. The possible lack of longitudinal sulci on the dorsum (Fig. 5E, O) may exclude this taxon from the Hyolithidae Nicholson in Nicholson & Lydekker, 1889 (Kruse 2002). However, since most specimens are either compressed or distorted (Fig. 5L) this may be a preservational artefact. Most conchs have a rounded-triangular cross-section (Fig. 5O) and smooth lateral margins (Fig. 5E) similar to unnamed hyoliths from the Northern Territory, including ‘hyolithide indet’ described from the Ordian of the Daly Basin (Kruse 1990, pl. 22) and ‘?notabilid indet’ from the Ordian of the Wiso Basin (Kruse 1998, fig. 37C, D). The Tempe Formation specimens also resemble material described from the Toyonian-equivalent of Antarctica as *?Microcornus* ex gr. *M. eximius* Duan, 1984 (Wrona 2003, fig. 7). The poor preservational state of the Hermannsburg 41 specimens limits any further meaningful comparisons.

Material. Over 100 specimens. Specimens range from 319.02 m to 310.43 m (Fig. 3) below the top of the drillcore.

Phylum MOLLUSCA Cuvier, 1797

Class HELCIONELLOIDA Peel, 1991

Remarks. The higher-level classification and phylogeny of the Cambrian univalve molluscs remain uncertain (see Skovsted 2004 for a detailed review). No consensus has been reached owing to controversy over the original shell orientation, functional morphology and microstructure of these univalve shells with varying degrees of coiling (Runnegar & Jell 1976, Linsley & Keir 1984, Peel 1991, Geyer 1994, Runnegar 1996,

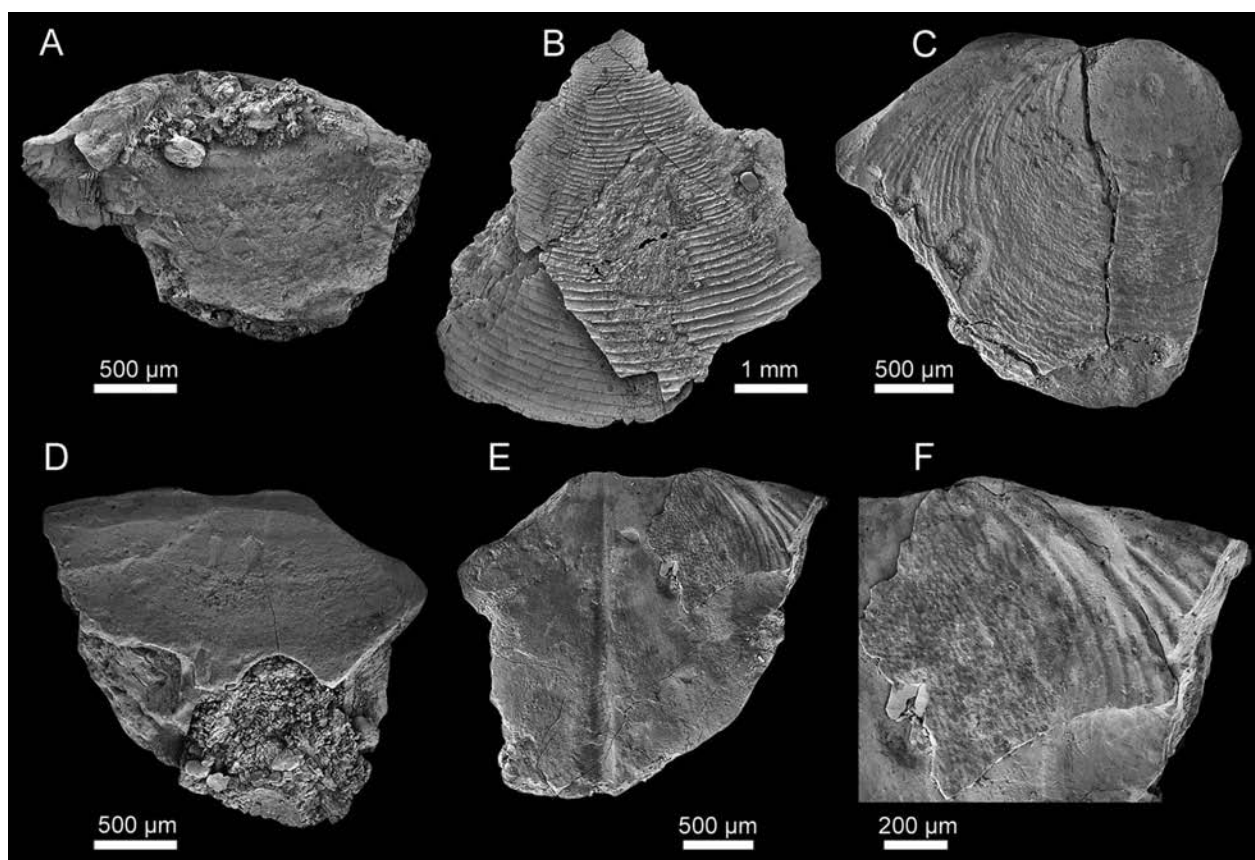


Fig. 7. *Linguloidea* gen. et sp. indet. from the Ordian Tempe Formation in the Hermannsburg 41 drillcore (all measurements denote depth from top of the drillcore). **A**, CPC41841, sample 71, 319.02 m, interior view of ventral valve showing pedicle groove. **B**, CPC41842, sample 71, 319.02 m be, valve fragment with distinct concentric ornament. **C**, CPC41843, sample 40, 293.40 m, exterior view of partial ventral valve. **D–F**, CPC41844, sample 71, 319.02 m. **D**, interior view of dorsal valve. **E**, exterior view of dorsal valve. **F**, enlargement of **E** showing external ornament of concentric growth lines and raised pustules.

Gubanov & Peel 2000, Skovsted 2004, Parkhaev 2008, Parkhaev & Demidenko 2010, Devaere *et al.* 2013). We follow Skovsted (2004) in limiting taxonomic description to genus and species level only.

Dorispira Parkhaev in Parkhaev & Demidenko, 2010

Type species. *Helcionella terraaustralis* Runnegar & Jell, 1976.

Dorispira sp. cf. **D. terraaustralis** (Runnegar & Jell, 1976) (Fig. 6A–G)

cf. 1976 *Helcionella terraaustralis*; Runnegar & Jell, p. 126, fig. 9C. 1–10.

Description. Tall (maximum height 1.5 mm), moderately cyrtconic univalve. Shell laterally compressed and expanding from the apex. Aperture oval in outline, mean length-to-width ratio approximately 1.45, with a pair of radial ridges on internal posterior surface; aperture planar or with a slight anterior gape. Apex overhanging posterior border, swollen in a few specimens (Fig. 6A) possibly representing an inflated protoconch. External ornament consists of sharply rounded concentric rugae at the aperture gradually transitioning to uniformly rounded concentric rugae towards the apex. Concentric rugae only present on the lateral and anterior surface of shell.

Remarks. The Tempe Formation material includes a few silicified specimens (Fig. 6A, B, D) from a single stratigraphic horizon (319.02 m below surface) and numerous steinkerns (Fig. 6C, F). Assignment to *Dorispira terraaustralis* (Runnegar & Jell, 1976), known previously from the Ordian ‘first discovery limestone’ of the Coonigan Formation, New South Wales is supported by the moderate lateral compression of the shell, apex overhanging the posterior shell margin, oval apertural outline, broadly spaced narrow subrounded rugae, a pair of radial ridges on the internal posterior surface and weak coiling. Parkhaev (in Parkhaev & Demidenko 2010) recently assigned this taxon as the type species of *Dorispira*, after revising *Latouchella* Cobbold, 1921 and *Helcionella* Grabau & Shimer, 1909, in line with suggestions made by several authors (Missarzhevskiy 1989, Esakova & Zhegallo 1996), with this placement being used in recent investigations (e.g., Devaere *et al.* 2013). Other Australian species of *Dorispira* share numerous features with *D. terraaustralis*, for example: radial ridges on the internal posterior surface are also present in *Dorispira merino* (Runnegar & Jell, 1976) from the Ordian ‘first discovery limestone’ of the Coonigan Formation; *Dorispira accordionata* (Runnegar & Jell, 1976) from the Ordian of the Gnalt Shelf and the Daly, Georgina, Ord and Wiso basins, together with the

Floran–Undillan of the New England Fold Belt; and *Dorispira aliciae* (Brock, 1998) from the Floran–Undillan allochthonous blocks in the New England Fold Belt. *Dorispira terraaustralis* differs from all these species in being less tightly coiled with narrower, less prominent rugae.

The Tempe Formation specimens vary only slightly from *D. terraaustralis* from the ‘first discovery limestone’ of the Coonigan Formation, being almost half the overall size. At least one specimen has a slightly swollen protoconch (Fig. 6A), which has not been reported previously in the species. There are a few forms similar to *Dorispira* that exhibit a slightly swollen protoconch, in many cases represented by a constriction followed by a swelling at the apex. These include *Igorella* (*Latouchella*) cf. *I. iacobinica* (Geyer, 1986) from the Cambrian Series 3 of Morocco (Geyer 1986) and *Igorella* (*Latouchella*) aff. *I. iacobinica* (Geyer, 1986) from the Toyonian-equivalent of South Australia (Brock & Cooper 1993). However, these species are less curved and have a greater taper towards the apex, which leads to a more pronounced apical constriction.

Lack of larger specimens with the flared, unornamented aperture seen in the holotype specimen (Runnegar & Jell 1976, fig. 9C, 1–5) and the indifferent nature of preservation in the Tempe Formation material make precise taxonomic assignment difficult. Therefore, these specimens are only tentatively compared with *D. terraaustralis*.

Distribution. Tempe Formation, Amadeus Basin, Northern Territory. Cambrian Series 2, Stage 4 (Ordian). Possibly the Coonigan Formation (‘first discovery limestone’), Gnalta Group, New South Wales. Cambrian Series 2, Stage 4 (Ordian).

Material. Eighteen near-complete specimens. Specimens range from 321.28 m to 316.15 m (Fig. 3) below the top of the drillcore.

Protowenella Runnegar & Jell, 1976

Type species. *Protowenella flemingi* Runnegar & Jell, 1976.

Remarks. See Brock (1998) for a comprehensive discussion of the genus.

Protowenella sp. (Fig. 6H, J, K)

Description. Microscopic, globose, planispiral univalve. Shell gradually expanding from the apex. Aperture average length-to-width ratio of 1.0, approximately circular in outline. Lateral umbilical channels originate after first half whorl. External ornament unknown.

Remarks. This taxon is represented by a single steinkern in the Hermannsburg 41 core at 319.02 m (below the surface). The globose, planispiral form (Fig. 6H) and circular aperture (Fig. 6K) denote similarities with the type species, *Protowenella flemingi* Runnegar & Jell, 1976

from the Drumian Currant Bush Limestone, Georgina Basin. The possible presence of a circumbilical channel (Fig. 6H indicated with an arrow) strengthens the likely affinity with *P. flemingi*. The Hermannsburg 41 specimen differs slightly from the *P. flemingi* type in being less involute, making it similar to *Protowenella* sp. from the Ordian ‘first discovery limestone’ of the Coonigan Formation, New South Wales (Runnegar & Jell 1976).

Kruse (1998) included *Protowenella* sp. described by Runnegar & Jell (1976) within *P. flemingi* based on collections from the Ordian of the Georgina and Wiso basins, indicating the Coonigan material could be accommodated within the known spectrum of intraspecific variation for this taxon. Although assignment to the type species is a possibility, the presence of a single steinkern obviously limits comparison. The circular aperture suggests that this specimen could also belong to several other taxa including: *Protowenella* sp. from Floran–Undillan erratic blocks in the Murrawong Creek Formation, New South Wales (Brock 1998); *Protowenella cobbensis* Mackinnon, 1985 from the Boomerangian Tasman Formation, New Zealand (Mackinnon 1985); *Protowenella primaria* Zhou & Xiao 1984 and *Protowenella huainanensis* Zhou & Xiao 1984 from the lower Cambrian Yutaishan Formation, China (Zhou & Xiao 1984). Given incomplete preservation of the material presented here, we prefer to take a conservative approach to the taxonomic identification of the Hermannsburg 41 steinkern. The specimen is thus left under open nomenclature.

Material. One specimen from 319.02 m below the top of the drillcore.

Pelagiella Matthew, 1895

Type species. *Crytolithes atlantoides* Matthew, 1894.

Remarks. For a complete list of species in the genus, see Parkhaev in Gravestock *et al.* (2001). The recent discovery of purported chaetae-like structures in specimens of *Pelagiella* from the lower Cambrian Kinzer Formation, USA (Thomas & Vinther 2012) has raised questions about the affinities of this taxon (see Dzik & Mazurek 2013).

Pelagiella sp. (Fig. 6I, L, M)

Description. Dextral, asymmetrical, helically coiled univalve with a flattened dorsal surface and a subtriangular to oval aperture. Internal mould is composed of approximately a 0.75 rapidly expanding whorl with the apex broken away. The exterior ornament is unknown.

Remarks. Material consists of a single steinkern from 310.43 m (below the top of the drillcore). The Tempe Formation specimen shows the distinctive shell curvature, helical spire (Fig. 6I), flattening of the dorsal surface (Fig. 6L) and simple aperture (Fig. 6M) characteristic of *Pelagiella*. The material resembles

specimens described as *Pelagiella* cf. *P. adunca* (He & Pei in He *et al.*, 1984) by Brock & Cooper (1993, fig 13.11–13.18) from the Toyonian-equivalent Wirrealpa Limestone in South Australia and *Pelagiella madianensis* (Zhou & Xiao, 1984) described by Wrona (2003, fig. 13C–E) from the Toyonian-equivalent of Antarctica. Brock & Percival (2006) also described a comparable form with a similar outline and degree of involution as *P. madianensis* from the Ordian Pincally and Wydjah formations, New South Wales and in doing so placed *Pelagiella* cf. *P. adunca* described by Brock & Cooper (1993) under *P. madianensis*. Skovsted (2004) and Topper *et al.* (2009) warned that specific discrimination within *Pelagiella* is problematic when based entirely on internal moulds, so we refrain from attempting definitive species assignment.

Material. One specimen from 310.43 m below the top of the drillcore.

Phylum BRACHIOPODA Duméril, 1806
Subphylum LINGULIFORMEA Williams, Carlson, Brunton, Holmer & Popov, 1996
Class LINGULATA Goryanskiy & Popov, 1985
Order LINGULIDA Waagen, 1885
Superfamily and Family UNCERTAIN

Linguloidea gen. et sp. indet. (Fig. 7)

1990 Linguloid indet. Roberts & Jell, pp. 305–307, fig. 37A–M.

Description. Very large, thick (>500 µm), dorsibiconvex shell. Post-larval shell ornamented with evenly distributed fine pustules and concentric growth ridges. Pseudointerarea of both valves unknown. Dorsal valve with medium septum, which extends anteriorly from posterior margin at an angle of 5–10° from the median plane of symmetry. Length of septum unknown owing to fragmentary nature of material. Ventral valve interior with deep pedicle groove that narrows towards the delthyrium.

Remarks. Material consists of numerous large (>4–5 mm), thick-shelled fragments, which lack pseudointerareas and other diagnostic characteristics in many cases (e.g., Fig. 7B). Roberts & Jell (1990, p. 305, fig. 37) described a very similar taxon from the Ordian ‘first discovery limestone’ of the Coonigan Formation, New South Wales, based on 13 relatively complete specimens. They assigned the taxon to the superfamily Linguloidea based on its phosphatic valve composition and the possession of a pseudointerarea that formed a flat to slightly concave apical plate, which is also apparent in the Tempe material (Fig. 7A, D). The high degree of fragmentation makes taxonomic assignment difficult, and so the taxon is left under open nomenclature until more complete material can be recovered.

Material. One dorsal and two ventral valves with over 100 fragments. Specimens range from 319.34 m to 293.18 m (Fig. 3) below the top of the drillcore.

Family BOTSFORDIIDAE Schindewolf, 1955

Karathele Koneva, 1986

Type species. *Karathele coronata* Koneva, 1986.

Karathele napuru (Kruse, 1990) (Fig. 8A–F, I)

1990 *Eothele napuru*; Kruse, p. 31, fig. 16, pl. 12.

1991 *Eothele napuru* Kruse; Kruse, p. 178, fig. 7A–E.

1993 *Eothele napuru* Kruse; Brock & Cooper, p. 782, fig. 15.1–15.4.

1996 *Karathele napuru* (Kruse); Holmer, Popov & Wrona, p. 45, pl. 11, figs 1–8, pl. 12, figs 1–5, text-fig. 3C–D.

1998 *Karathele napuru* (Kruse); Kruse, p. 37, fig. 31A–I. (cum syn.)

Description. See Kruse (1990, p. 31).

Remarks. This species is represented by both dorsal (Fig. 8E, F, I) and ventral valves (Fig. 8A–C, D). The characteristic pustulose post-larval shell ornament of the taxon is preserved on several specimens (Fig. 8A, B, E). The open delthyrium (Fig. 8A–D) with evidence of narrowing through ontogeny (Fig. 8B, D), absence of a pedicle tube and two distinctly separated low, rounded swellings located immediately anterior of the ventral valve apex (Fig. 8C) strongly supports assignment to *Karathele napuru* (Kruse, 1990). The specimens from the Tempe Formation are almost identical to those reported previously from Ordian strata of the Northern Territory, including the type material from the Tindall Limestone (compare Fig. 8A–F, I with Kruse 1990, pl. 12; 1991, fig. 7A–E; 1998, fig. 31A–H) and the Toyonian-equivalents of South Australia (Brock & Cooper 1993) and Antarctica (Holmer *et al.* 1996).

The type species, *Karathele coronata* Koneva, 1986 from the Drumian of Kazakhstan, differs from *K. napuru* in having a less elongate pedicle groove. *Karathele yorkensis* Ushatinskaya & Holmer in Gravestock *et al.*, 2001 from the lower Cambrian of the Arrowie and Stansbury basins of South Australia can be differentiated by the presence of a distinct concentric ridge in front of the ventral valve apex as opposed to *K. napuru*, which has two distinct larval swellings in front of the ventral valve apex. *Karathele yorkensis* also has a wider triangular delthyrial opening (e.g., width-to-length ratio of mature delthyrium in *K. yorkensis* = 2.7 versus Tempe Formation *K. napuru* = 0.4) and a smaller maximum size (Gravestock *et al.* 2001). *Karathele quadrituberculum* Percival & Kruse, 2014 from the Ordian Thornton Limestone (=Hay River Formation) is contemporaneous with *K. napuru* and almost indistinguishable based on the ventral valve. *Karathele quadrituberculum* differs only in having two pairs of tubercles on the dorsal larval shell and lacking divergent ridges on the dorsal valve interior. *Karathele kurtuju* Kruse, 1998 from younger Templetonian Point Wakefield beds, Wiso Basin, can be distinguished by having a

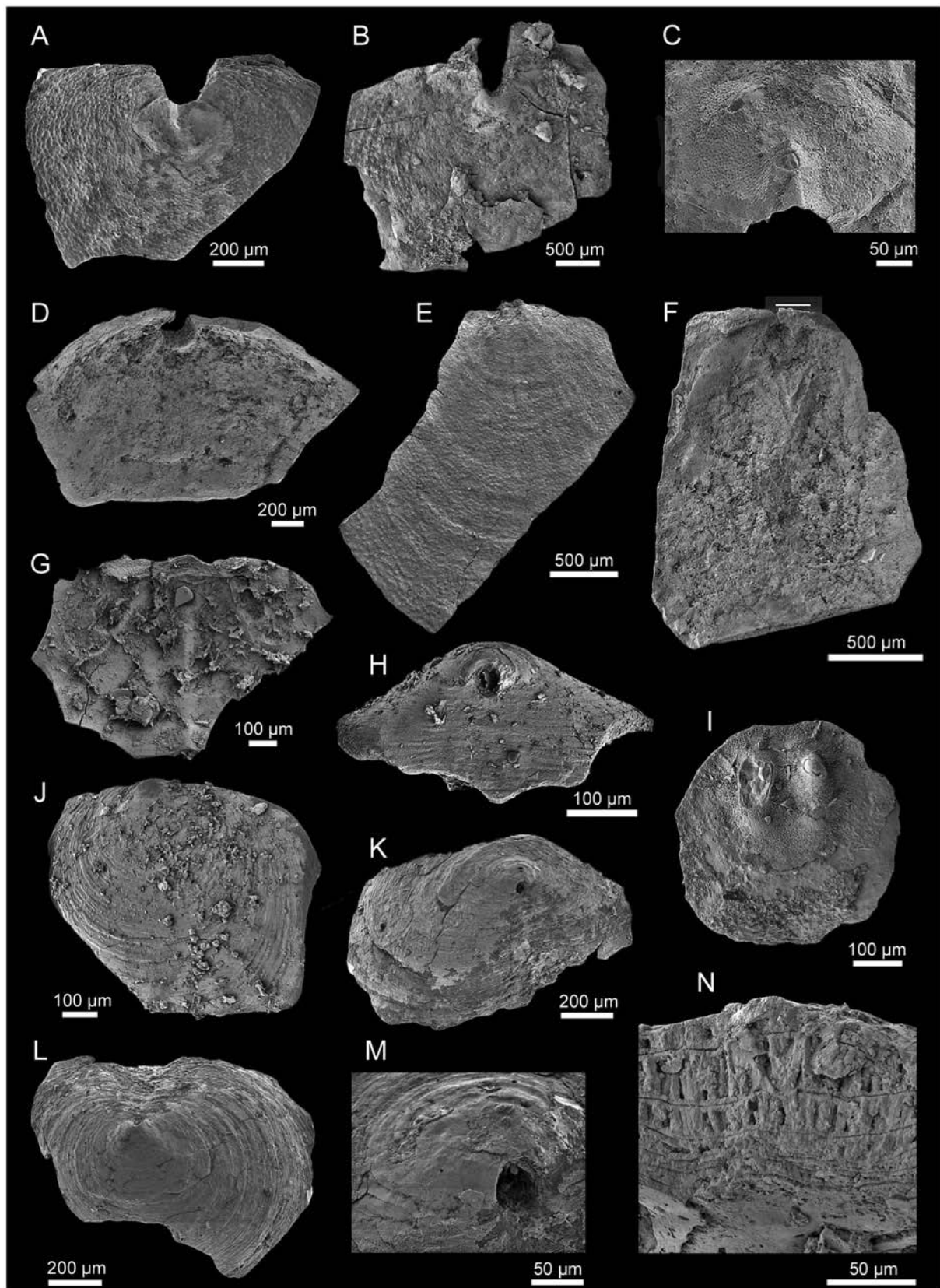


Fig. 8. Brachiopods from the Ordian Tempe Formation in the Hermannsburg 41 drillcore (all measurements denote depth from top of the drill-core). A–F, I, *Karathele napuru* (Kruse, 1990). A, C, CPC41845, sample 71, 319.02 m. A, exterior view of partial ventral valve. C, enlargement of larval shell showing two separate larval swellings anterior of apex. B, CPC41846, sample 67, 316.15 m, exterior view of partial ventral valve. D, CPC41847, sample 70, 316.43 m, interior view of partial ventral valve. E, CPC41848, sample 71, 319.02 m, exterior view of partial dorsal valve. F, CPC41849, sample 71, 319.02 m, interior view of partial and abraded dorsal valve. I, CPC41850, sample 67, 316.15 m, enlargement of larval shell of the dorsal valve. G, H, J–N, *Kostjubella djaoran* (Kruse, 1990). G, CPC41851, sample 67, 316.15 m, interior view of partial dorsal

persistently widening pedicle slit and slightly larger overall size.

Karathele (and the closely related *Botsfordia*) are distinguished from *Eothele* by the presence of a slit-like pedicle opening that never closes to form a complete foramen during adulthood. All specimens of *K. napuru* from the Tempe Formation in the Hermannsburg 41 core have a slit-like foramen, which contrasts with taxa such as *Eothele granulata* (Roberts & Jell 1990, fig. 28A–P; Brock & Percival 2006, fig. 8A–I) from the Ordian of New South Wales, which have complete fusion of the ventral pseudointerareas to form an elliptical pedicle tube.

Distribution. Tempe Formation, Amadeus Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Gum Ridge Formation and Top Springs Limestone, Georgina Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Tindall Limestone, Daly Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Montejinni Limestone, Wiso Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Wirrealpa Limestone, Arrowie Basin, South Australia; Cambrian Series 2, Stage 4 (Toyonian-equivalent, ?Ordian). Cape Melville Formation glacial erratic boulders, King George Island, Antarctica; Cambrian Series 2, Stage 4 (Toyonian-equivalent, ?Ordian).

Material. Three dorsal and ten ventral valves plus over 100 fragments. Specimens range from 319.34 m to 272.85 m (Fig. 3) below the top of the drillcore.

Order ACROTRETIDA Kuhn, 1949

Superfamily ACROTRETOIDEA Schuchert, 1893

Family ACROTRETIDAE Schuchert, 1893

Kostjubella Popov, Holmer & Goryanskiy, 1996

Type species. *Kostjubella relaxata* Popov, Holmer & Goryanskiy, 1996.

Remarks. See Percival & Kruse (2014, pp. 370–371) for a comprehensive discussion of the similarities of *Kostjubella* with the closely allied genera *Hadrotreta* Rowell, 1966, *Vandalotreta* Mergl, 1988, *Luhotreta* Mergl & Šlehoferová, 1990, *Iberotreta* Wotte & Mergl, 2007 and *Genetreta* Wotte & Mergl, 2007. In particular, Percival & Kruse (2014) outlined the taxonomic relationships of *Kostjubella djagoran* (discussed below) with both *Hadrotreta* and *Vandalotreta*. We acknowledge that all three taxa are very similar to one another, but that many of the differences (e.g., subtle differences in depth of the median sulcus in the dorsal valve and extent of convexity and location of maximum valve height) have dubious taxonomic significance at the

generic level. Although clearly beyond the scope of this paper, a detailed investigation of the type material of *Kostjubella*, *Hadrotreta* and *Vandalotreta* is required to substantiate the taxonomic validity of these taxa.

We follow Percival & Kruse (2014, p. 371) who formally reassigned *Vandalotreta djagoran* to *Kostjubella* based on the presence of a shallow sulcus and distinct median ridge in the dorsal valve. However, we note that the original generic diagnosis of *Kostjubella* by Popov *et al.* (1996) describes the presence of a ‘deep intertrough’ in the ventral valve. The specimens described herein from the Tempe Formation (Fig. 8H, K, L) and those figured by Brock & Cooper (1993, fig. 14.1–14.4, 14.7), Gravestock *et al.* (2001, pl. 18, figs 7, 8, 13a, 13b), Holmer *et al.* (1996, pl. 13, figs 1b–5b, 6a–6c, 9), Kruse (1990, pl. 11, fig. 15A–D, F; 1991, fig. 6H, I; 1998, fig. 34A–D) and Percival & Kruse (2014, fig. 12L, S, W, Y) have a relatively shallow, wide intertrough, which places some doubt on the generic assignment and on the taxonomic importance of this particular character.

Kostjubella djagoran (Kruse, 1990) (Fig. 8G, H, J–N)

1990 *Hadrotreta djagoran*; Kruse, p. 29, pl. 11, fig. 15. (cum. syn.).

1991 *Hadrotreta djagoran* Kruse; Kruse, p. 178, fig. 6H–L.

1993 *Hadrotreta primaeva* (Walcott); Brock & Cooper, p. 782, fig. 14.1–14.13.

1996 *Vandalotreta djagoran* (Kruse); Holmer, Popov & Wrona, p. 47, pl. 13, figs 1–9, text-fig. 4.

1998 *Vandalotreta djagoran* (Kruse); Kruse, p. 39, fig. 34.

2001 *Vandalotreta djagoran* (Kruse); Ushatinskaya & Holmer in Gravestock *et al.*, p. 132, pl. 18, figs 7–14.

2014 *Kostjubella djagoran* (Kruse); Percival & Kruse, p. 371, figs 12–13.

Description. See Percival & Kruse (2014, p. 371) for emendation of the original description by Kruse (1990, p. 29).

Remarks. The material from the Tempe Formation consists of a few specimens, mostly ventral valves (Fig. 8H, K, M), although two dorsal valves were also recovered (Fig. 8G, J). Some valves have been highly abraded such that the outer shell layers have been removed, commonly displaying the columnar shell microstructure beneath (Fig. 8N). Interiors of the ventral valves are mostly filled with sediment or phosphatized debris, completely obscuring the apical process.

The transversely oval shell with a procline to catacline ventral pseudointerarea, foramen not enclosed

valve. **H**, CPC41852, sample 60, 310.43 m, posterior external view of ventral valve. **J**, CPC41853, sample 60, 310.43 m, exterior view of partial dorsal valve. **K–M**, CPC41854, sample 71, 319.02 m. **K**, oblique posterolateral external view of ventral valve. **L**, external ventral view of ventral valve. **M**, enlargement of larval shell and foramen in oblique posterolateral view. **N**, CPC41855, sample 60, 310.43 m, valve showing vestigial columnar shell microstructure.

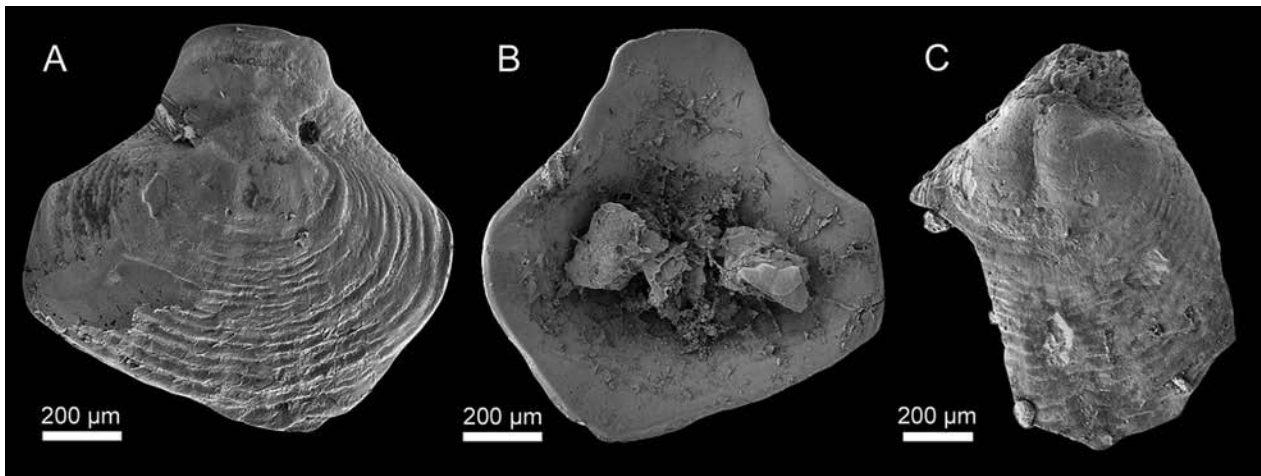


Fig. 9. *Micromitra nerranubawu* Kruse, 1990 from the Ordian Tempe Formation in the Hermannsburg 41 drillcore (all measurements denote depth from top of the drillcore). A, B, CPC41856, sample 78A, 321.28 m. A, exterior view of ventral valve. B, interior view of ventral valve. C, CPC41857, sample 71, 319.02 m, exterior view of ventral valve.

within the larval shell (Fig. 8M), dorsal valve pseudointerarea with a broadly triangular median groove and a low median ridge (Fig. 8G) supports assignment to *Kostjubella* as recently outlined by Percival & Kruse (2014). Specimens from the Tempe Formation appear to closely match *Kostjubella djagoran* (Kruse, 1990) from the Ordian Tindall Limestone in both overall form and size (compare Fig. 8G, H, J–N with Kruse 1990 pl. 11), with the ventral valve beak slightly overhanging the pedicle foramen (Fig. 8L), maximum height at the valve apex, and in the dorsal valve possessing a weak median ridge, which would exceed 1 mm in length if complete (Fig. 8G). We follow Percival & Kruse (2014) and recognize other described specimens of *K. djagoran* from the Georgina (Kruse 1998), Arrowie (Brock & Cooper 1993) and Stansbury basins (Holmer & Ushatinskaya in Gravestock *et al.* 2001) in Australia and from Antarctica (Holmer *et al.* 1996) as conspecific.

Kostjubella djagoran differs from the type species, *Kostjubella relaxata* Popov, Holmer & Goryanskiy 1996 from the Cambrian Series 2–3 boundary of Kazakhstan, in having: the dorsal valve lacking a sulcus; a lower, less developed to indistinct medium ridge and the maximum height of the ventral valve being at the apex. The only other species currently included in the genus is *Kostjubella robusta* Percival & Kruse, 2014, from the Ordian Thornton Limestone (=Hay River Formation), Georgina Basin. It differs in having a lower ventral valve profile (lower conical shape), which is distinctly more procline than those of *Kostjubella djagoran*.

Distribution. Tempe Formation, Amadeus Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Gum Ridge Formation, Thornton Limestone (=Hay River Formation) and Top Springs Limestone, Georgina Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Tindall Limestone, Daly Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Montejinni Limestone, Wiso Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Wirrealpa Limestone,

Arrowie Basin, South Australia; Cambrian Series 2, Stage 4 (Toyonian-equivalent, ?Ordian). Ramsay Limestone, Stansbury Basin, South Australia; Cambrian Series 2, Stage 4 (Toyonian-equivalent, ?Ordian). Cape Melville Formation glacial erratic boulders, King George Island, Antarctica; Cambrian Series 2, Stage 4 (Toyonian-equivalent, ?Ordian).

Material. Two dorsal and two ventral valves collected. Specimens range from 316.30 m to 310.43 m (Fig. 3) below the top of the drillcore.

Class PATERINATA Williams, Carlson, Bruton, Holmer & Popov, 1996

Order PATERINIDA Rowell, 1965

Superfamily PATERINOIDEA Schuchert, 1893

Family PATERINIDAE Schuchert, 1893

***Micromitra* Meek, 1873**

Type species. ?*Iphidea scutilis* (Meek, 1873).

***Micromitra nerranubawu* Kruse, 1990 (Fig. 9)**

1990 *Micromitra nerranubawu*; Kruse pp. 35–36, pl. 13, figs A–J, pl. 14, figs A–F (cum. syn.).

1990 *Micromitra nerranubawu* Kruse; Roberts in Roberts & Jell, pp. 297–298, figs 30, 31.

?1991 *Micromitra nerranubawu* Kruse; Kruse, p. 179, fig. 7F–H.

?1998 *Micromitra ?nerranubawu* Kruse; Kruse, p. 41, fig. 35.

2006 *Micromitra nerranubawu* Kruse; Brock & Percival, pp. 95–97, fig. 10F–L, O.

Description. See Kruse (1990, pp. 35–36) and Roberts in Roberts & Jell (1990, pp. 297–298).

Remarks. This species is represented by ventral valves (Fig. 9A–C) with no dorsal valves recovered from the drillcore. Despite extensive fragmentation, the broadly flaring homeodeltidium lacking delthyrial ridges and the closely spaced undulose concentric ornament are characteristic of *Micromitra nerranubawu* Kruse, 1990 allowing

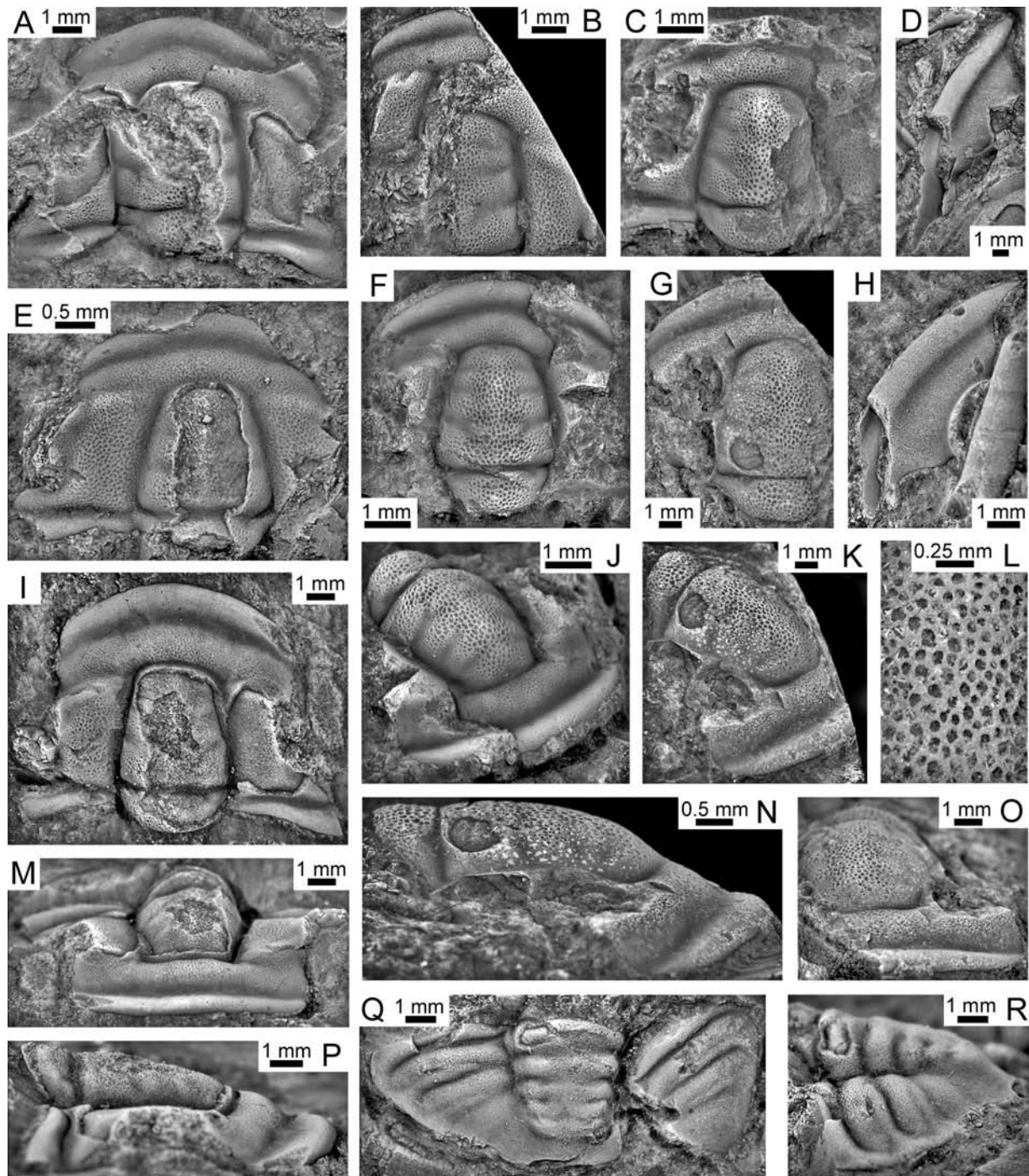


Fig. 10. *Gunnia fava* sp. nov. from the Ordian Tempe Formation in the Hermannsburg 41 drillcore (all measurements denote depth from top of the drillcore). **A**, paratype CPC41859, sample T1, 292.75 m, dorsal view of fractured partial cranidium. **B**, paratype CPC41860, sample T1, 292.75 m, dorsal view of fractured partial cranidium. **C**, paratype CPC41861, sample T3, 292.92 m, dorsal view of partial cranidium. **D**, paratype CPC41862, sample T1, 292.75 m, dorsal view of partial librigena. **E**, paratype CPC41863, sample T4, 293.07 m, dorsal view of small partial cranidium. **F**, **J**, paratype CPC41864, sample T3, 292.92 m. **F**, dorsal view of partial cranidium. **J**, oblique anterolateral view of partial cranidium. **G**, **K**, **L**, **N**, **O**, paratype CPC41865, sample T2, 292.85 m. **G**, dorsal view of partial cranidium. **K**, oblique anterolateral view of partial cranidium. **L**, enlargement of characteristic reticulate ornament covering prosopon. **N**, lateral view of partial cranidium. **O**, anterior view of partial cranidium. **H**, Paratype CPC41866, sample T2, 292.85 m. dorsal view of partial librigena. **I**, **M**, **P**, holotype CPC41858, sample T6, 293.15 m. **I**, dorsal view of partial cranidium. **M**, anterior view of partial cranidium. **P**, lateral view of partial cranidium. **Q**, **R**, paratype CPC41867, sample T1, 292.75 m. **Q**, dorsal view of partial pygidium. **R**, lateral view of partial pygidium.

for confident taxonomic assignment (Fig. 9A–C). The material from the Hermannsburg 41 core is very similar to specimens of *M. nerranubawu* described by Brock & Percival (2006) from the Ordian Pincally and Wydjah formations, New South Wales. Both share a similar size

range, distinctiveness of the larval shell and dimensions of the homeodeltidium. *Micromitra nerranubawu* is possibly conspecific with material recorded as *Micromitra* sp. from the Thornton Limestone (=Hay River Formation), Georgina Basin (Williams *et al.* 1998, Percival & Kruse 2014),

although this taxon appears to differ in the distinctiveness of the larval shell (Percival & Kruse 2014).

Micromitra nerranubawu differs from the type species *Micromitra sculptilis* from Cambrian Series 3 of the USA (Meek 1873) in its longer homeodeltidium and lack of delthyrial ridges (compare Fig. 9A and Kruse 1990, pl. 13 to Bell 1941, pl. 28, figs 1–26). Several younger species are also known from Australia: *Micromitra georginaensis* Percival & Kruse, 2014 from the Floran of the Arthur Creek Formation, Georgina Basin (Percival & Kruse 2014; see Laurie 2012 for an age determination); *Micromitra* sp. cf. *M. modesta* (Lochman, 1940) and an informal *Micromitra* species from late Floran–Boomerangian allochthonous blocks of the Murrawong Creek Formation, New South Wales (Engelbretsen 1996); *Micromitra modesta* (Lochman, 1940) and two informal *Micromitra* species from the late Mindyallan–Idamean Dolodrook River limestones, Victoria (Engelbretsen 2004). All these younger species differ in having a much shorter homeodeltidium and much coarser ornamentation.

Distribution. Tempe Formation, Amadeus Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Top Springs Limestone and possibly the Gum Ridge Formation, Georgina Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Tindall Limestone, Daly Basin, Northern Territory; Cambrian Series 2, Stage 4 (Ordian). Coonigan Formation ('first discovery limestone'), Pincally Formation and Wydjah Formation, Gnalta Group, New South Wales; Cambrian Series 2 and 3, Stage 4 (Ordian).

Material. Four ventral valves and over 30 fragments. Specimens range from 321.28 m to 272.85 m (Fig. 3) below the top of the drillcore.

Phylum ARTHROPODA von Siebold, 1848

Class TRILOBITA Walch, 1771

Family PTYCHOPARIIDAE Matthew, 1887

Gunnia Gatehouse, 1968

Type species. *Gunnia lutea* Gatehouse, 1968.

Remarks. See Kruse (1990) and Peng *et al.* (2009) for detailed discussions of the genus; the latter also provided a comprehensive generic synonymy and species list.

***Gunnia fava* sp. nov.** (Fig. 10)

Etymology. Latin *fava*, honeycomb, in reference to the beautiful reticulated ornament of this trilobite.

Diagnosis. Cranidium moderately convex, length-to-width ratio of 74%. Prosopon covered by well-developed reticulated ornament, but with smooth anterior and posterior cranial borders. Glabella width-to-length ratio of 60–75% (mean 68%), occupying about 69–74% (mean 71%) of cranial length (sag.). Eye ridges moderately defined, palpebral lobe about 32% of total cranial

length. Border equal in length to the preglabellar field, 13–17% (mean 15%) of sagittal length of cranidium.

Pygidium transversely semiellipsoidal, with length-to-width ratio of 38%, axis strongly convex, moderately tapered posteriorly with a width-to-length ratio of 93%, occupying 88% of pygidial length; four axial rings and a very short (sag., exsag.) terminal piece.

Type material. Holotype: CPC41858 (Fig. 10I, M, P), partial cranidium from sample T6, 293.15 m below the top of the drillcore. Paratypes: CPC41859 (Fig. 10A), CPC41860 (Fig. 10B), CPC41862 (Fig. 10D) and CPC41867 (Fig. 10Q, R); two partial cranidia, a librigenae and a pygidium from sample T1, 292.75 m below the top of the drillcore. CPC41865 (Fig. 10G, K, L, N, O) and CPC41866 (Fig. 10H); partial cranidium and librigenae from sample T2, 292.85 m below the top of the drillcore. CPC41861 (Fig. 10C) and CPC41864 (Fig. 10F, J); two partial cranidia from sample T3, 292.92 m below the top of the drillcore. CPC41863 (Fig. 10E); small holaspis cranidium from sample T4, 293.07 m below the top of the drillcore. All type specimens were recovered from the Hermannsburg 41 drillcore, Tempe Formation.

Description. Largest cranidium 12.0 mm long (sag.) (Fig. 10G, K), subquadrate in outline, length-to-width ratio of 74%, maximum width across posterior limbs of fixigena; prosopon of cephalon covered by well-developed reticulate ornament over most of the surface apart from the smooth anterior and posterior borders. Narrowest point of cranidium forward of the palpebral lobes (γ – γ), where it is about 68% of maximum cranial width. Cranidium moderately convex sagittally, less so transversely. Anterior and posterior margins strongly curved anteriorly, Sutures diverge anteriorly from γ – γ point at about 70° from one another for short distance, then curve abruptly towards the midline at about the border furrow before they intersect the anterior margin. The ε – ω segments of the facial suture diverge strongly from one another at or near 110° before they intersect the posterior margin. Glabella subconical in outline with a truncated anterior margin, width-to-length ratio of 60–75% (mean 68%), occupying about 69–74% (mean 71%) of cranial length; moderately tapering forward, width across anterior of 60–73% (mean 65%) of the maximum width. Moderately convex sagittally and transversely, with maximum convexity along midwidth, lateral portions gently curved. Axial furrows deep and narrow (tr.). S1 weakly defined, intersecting axial furrow at glabellar midlength and from there are directed posteromedially, bifurcating adaxially. S2 straight, transverse to slightly posteromedially directed. S3 straight and of similar width (tr.) to S2, directed slightly anteromedially. Occipital ring of moderate width (sag.), strongly tapering abaxially, with strongly bowed posterior margin; SO slightly bowed posteriorly, of equal depth across entire width.

Preglabellar field downsloping, slightly convex, 13% of cranial length (sag.). Preocular field downsloping, slightly convex, similar to prelabellar field. Anterior border broad, equal in length to the prelabellar field (sag.), slightly convex (sag., exsag.), about 13–17% (mean 15%) of sagittal length of cranium and narrowing very slightly abaxially; anterior border furrow moderately deep and wide (sag., exsag.). Palpebral lobe about 32% of total cranial length, slightly curved, defined by shallow palpebral furrow anteriorly, becoming deeper posteriorly; anterior tip roughly opposite S2, posterior tip opposite L1. Eye ridges moderately defined, extending posterolaterally from anterolateral corners of glabella in a slight curve towards the anterior tip of palpebral lobe. Palpebral area of fixigena slightly convex, gently sloping towards glabella. Postocular area of fixigena slightly downsloping towards posterolateral corners. Posterolateral projections of fixigena downsloping, gently tapering abaxially, directed slightly posterolaterally. Posterior border moderately narrow (exsag.), slightly widening abaxially, separated from fixigenal field by moderately deep, narrow border furrow.

Librigenae of moderate size, largest is 8 mm (Fig. 10D) with a length-to-width ratio of 57% excluding the genal spine. Lateral margins curved, continuing onto genal spine. Genal field slightly convex, subtrapezoidal in outline, maximum width 71% of entire librigenae (tr.). Lateral borders moderately convex, 29% librigenae width, lateral border furrow moderately deep and slightly wide (tr.). Surface of librigenal field covered by fine reticulated ornament, but with smooth lateral borders. Genal spine relatively straight and strongly tapering posteriorly, total length unknown.

Largest pygidium 5.7 mm long (sag.) (Fig. 10Q), transversely semi-ellipsoidal, convex, with a length-to-width ratio of 38%, with a strongly convex, moderately tapered axis, which has a width-to-length ratio of 93% and occupies 88% of pygidial length (sag.). Pleural field moderately convex, sloping down from axial furrow to poorly defined border. Articulating half-ring incompletely known, separated from anteriormost axial ring by shallow, narrow, articulating furrow. Axis with four axial rings and a very short (sag.) terminal piece. First (anteriormost) axial ring posteriorly delimited by straight inter-ring furrow, which is wider and shallower sagittally. Second and third axial rings defined posteriorly by straight inter-ring furrows that are shallow medially and deep exsagittally. Fourth axial ring separated from terminal piece by faint inter-ring furrow. Axial furrow clearly developed adjacent to ring furrows, becoming shallower posteriorly. Pleural furrows variably developed. First anterior pleural furrow deep across most of pleural field, extending from near anterior extremity of axial furrow and gently curving posteriorly. Second pleural furrow arises opposite first inter-ring furrow and is similarly developed and runs parallel with the first pleural furrow. Third pleural furrow is weakly developed and arises from the second inter-ring furrow

and runs parallel to the second pleural furrow. Interpleural furrows are faintly visible for the first two pleural ribs, with the anterior band of each pleura being widest (exsag.) at the axis and narrowing abaxially, with the opposite being true of the posterior band, both bands being approximately the same width at the border. Border poorly defined by gradual break in slope near terminations of pleural furrows.

Hypostome, rostral plate and thorax unknown.

Remarks. This taxon is known from a small collection of 14 cranidia, four librigenae and two pygidia. Most specimens are fragmented, at least in part (e.g., Fig. 10A, B, Q), attesting to the high-energy conditions during deposition. The distinctive reticulate ornamentation (Fig. 10L) is unique among all previously reported species of *Gunnia*, making these specimens immediately distinguishable. The cranial, librigenal and pygidial morphology of the Hermannsburg 41 material is very similar to most previously described members of the genus. The type species, *Gunnia lutea* Gatehouse, 1968, was described from the Ordian Tindall Limestone, Daly Basin and differs from *G. fava* sp. nov. mainly in having a longer (sag., exsag.), slightly flatter anterior cranial border, granulose and tuberculate ornament, and a pygidium with only two axial rings (Kruse 1990). *Gunnia jixianensis* (Zhang in Zhang *et al.*, 1995) from Series 3, Stage 5 of China is also similar, but can be distinguished by a longer (sag.), more strongly curved anterior cranial border (Zhang *et al.* 1995). *Gunnia smithi* Peng & Hughes in Peng *et al.*, 2009 from the Cambrian Series 3, Stage 5 Parahio Formation of India differs markedly from the Hermannsburg 41 material in possessing a wider (tr.) cranium with a longer (sag.) anterior cranial border, prelabellar field and occipital ring, in addition to less distinct axial, lateral glabellar and occipital furrows, and a narrower (exsag.) posterior border. The pygidium of *G. smithi* also has a distinct border, three axial rings, and short anterior pleural bands. Likewise, *Gunnia* sp. 1 and *Gunnia* sp. 2 described by Peng *et al.* (2009) differ in having wider (tr.) cranidia that possess a strongly tapered glabella with a more rounded frontal lobe.

Gunnia sp. cf. *G. concava* (Deiss, 1939) from the Tindall Limestone (see Kruse 1990, pl. 6) is also distinguishable based on the cranial ornament consisting of fine granules interspersed with larger tubercles, slightly longer (sag., exsag.) and flatter anterior cranial border, shorter (sag.) occipital ring and a much shorter (sag.) pygidial axis with three axial rings. Peng *et al.* (2009) suggested that *Gunnia* sp. cf. *G. concava* would be better assigned to *Xingrenaspis* Yuan & Zhou in Zhang *et al.*, 1980, but provided no further comment. The only other species currently within the genus is *Gunnia yiliangensis* (Luo in Luo *et al.*, 1994) from Cambrian Series 2, Stage 4 of China. However, given the poor preservation of the holotype, comparison is difficult.

Distribution. Tempe Formation, Amadeus Basin, Northern Territory. Cambrian Series 2, Stage 4 (Ordian).

Material. Fourteen cranidia, four librigenae and two pygidia. Specimens range from 292.75 m to 293.15 m (Fig. 3) below the top of the Hermannsburg 41 drill-core.

Xingrenaspis Yuan & Zhou in Zhang *et al.*, 1980

Type species. *Xingrenaspis xingrenensis* Yuan & Zhou in Zhang *et al.*, 1980.

Remarks. See Peng *et al.* (2009) for a detailed discussion of the genus including a comprehensive generic synonymy and species list. See also Sundberg *et al.* (2011) regarding the synonymy of *Xingrenaspis hobo*i (Resser & Endo in Endo & Resser, 1937) and the type species (contra Peng *et al.* 2009, pp. 63–66).

Xingrenaspis sp. (Fig. 11)

?1990 *Tongshania* cf. *tongshanensis* Qiu & Lin in Qiu *et al.*; Kruse, p. 21, pl. 7, figs A–O.

?2009 *Xingrenaspis* cf. *tongshanensis* (Qiu & Lin in Qiu *et al.*); Peng *et al.*, p. 63.

Description. Largest cranidium 17 mm long (sag.). Subquadrate in outline. Maximum width across posterior limbs of fixigena. Narrowest point of cranidium at the anterior border furrow (β – β). Cranidium strongly convex sagittally and transversely. Anterior margin strongly curved. Posterior margin incompletely known. Anterior branches of the facial sutures converge (anterior of the γ – γ point) at 34° to one another, before they intersect the cephalic margin. The ε – ω segments of the cephalic suture, incompletely known, appear to diverge strongly from one another. Glabella wide, pyriform in outline with a truncated anterior margin, strongly tapered anteriorly; highly convex (sag., tr.), maximum convexity along midwidth, lateral portions gently curved. Axial furrows deep, relatively wide (tr.), and straight. S1 weakly defined, shallow, intersecting axial furrow adjacent to posterior third of palpebral lobe, directed posteromedially. S2 very slightly directed posteromedially, intersecting axial furrow adjacent to anterior tip of palpebral lobe. S3 furrow directed anteromedially from axial furrow. Occipital ring and furrow unknown. Preglabellar field strongly downslowing, slightly convex, the same length (exsag.) as the anterior border. Preocular field strongly downslowing and slightly convex, similar to preglabellar field. Anterior border slightly convex (exsag.), tapering abaxially. Anterior border furrow deep and narrow (exsag.), becoming deeper abaxially. Palpebral lobe narrow (tr.), 35% glabellar length. Eye ridges obscured, but may be indistinct and strongly directed posterolaterally from frontal lobe of glabella. Palpebral area relatively flat, downslowing slightly towards palpebral lobe. Postocular area downslowing steeply towards posterior border furrow. Posterolateral projections of fixigena narrow (tr.), downslowing, tapering abaxially,

directed posterolaterally. Posterior border moderately narrow (exsag.), slightly widening abaxially, separated from fixigenal field by clearly defined, moderately deep, narrow border furrow that terminates at the distal tip of the posterolateral projection.

Librigenae of medium size, largest 4.2 mm long, excluding spine. Lateral margins strongly curved, continuing onto spine. Posterior margin very narrow (tr.), strongly curved onto genal spine. Genal field strongly convex, subtrapezoidal in shape, 75% of librigenal width (tr.). Lateral border convex, 39% of librigenal width (tr.), lateral border furrow deep, moderately wide (tr.). Posterior border drawn out into a long genal spine. Genal spine long, length 4 mm in largest specimen, only very slightly curved. Doublure extends only under lateral border of librigenae.

Thorax with unknown number of segments. Axial lobe clearly defined, highly convex. Deep and narrow (sag.) articulating axial furrow. Pleura with anterior and posterior bands of equal length (exsag.), well-developed fulcrum; pleural furrow shallow near the axial furrow, becoming deeper and narrower abaxially before terminating just before the pleural extremities. Pleural tips are either falcate or spatulate.

Pygidium small, up to 2 mm long (sag.), transversely subovate, convex, with a length-to-width ratio of 36%, with a strongly convex, slightly tapered axis, which has a length-to-width ratio of 85% and occupies 77% of pygidial length (sag.). Pleural field highly convex, strongly downslowing from axial furrow to poorly defined border. Articulating half-ring short (sag., exsag.) and wide (tr.), separated from anterior axial ring by deep, narrow, articulating furrow. At least three axial rings present, anteriormost axial ring posteriorly delimited by narrow, straight inter-ring furrow. Second and third axial rings similarly defined posteriorly. Axial furrow clearly developed adjacent to inter-ring furrows, but becoming shallower posteriorly. Pleural furrows variably developed. First anterior pleural furrow well developed, extending from near anterior extremity of axial furrow and gently curving posteriorly, following the curvature of the anterior margin. Second pleural furrow arising slightly posterior of the first inter-ring furrow and running parallel to the first pleural furrow. Third pleural furrow arising slightly posterior to the second inter-ring furrow and running parallel to the second pleural furrow. Interpleural furrows indistinct. Border poorly defined by gradual break in slope near terminations of pleural furrows.

Entire prosopon covered with closely spaced tubercles; although these are much fainter on the librigenae and pygidium. Hypostome and rostral plate unknown.

Remarks. The material from Hermannsburg 41 is largely represented by silicified thoracic segments. Only two partially complete cranidia (Fig. 11A–F, I), four librigenae (Fig. 11G, J–L, P, Q) and two pygidia (Fig. 11V–A¹) were recovered.

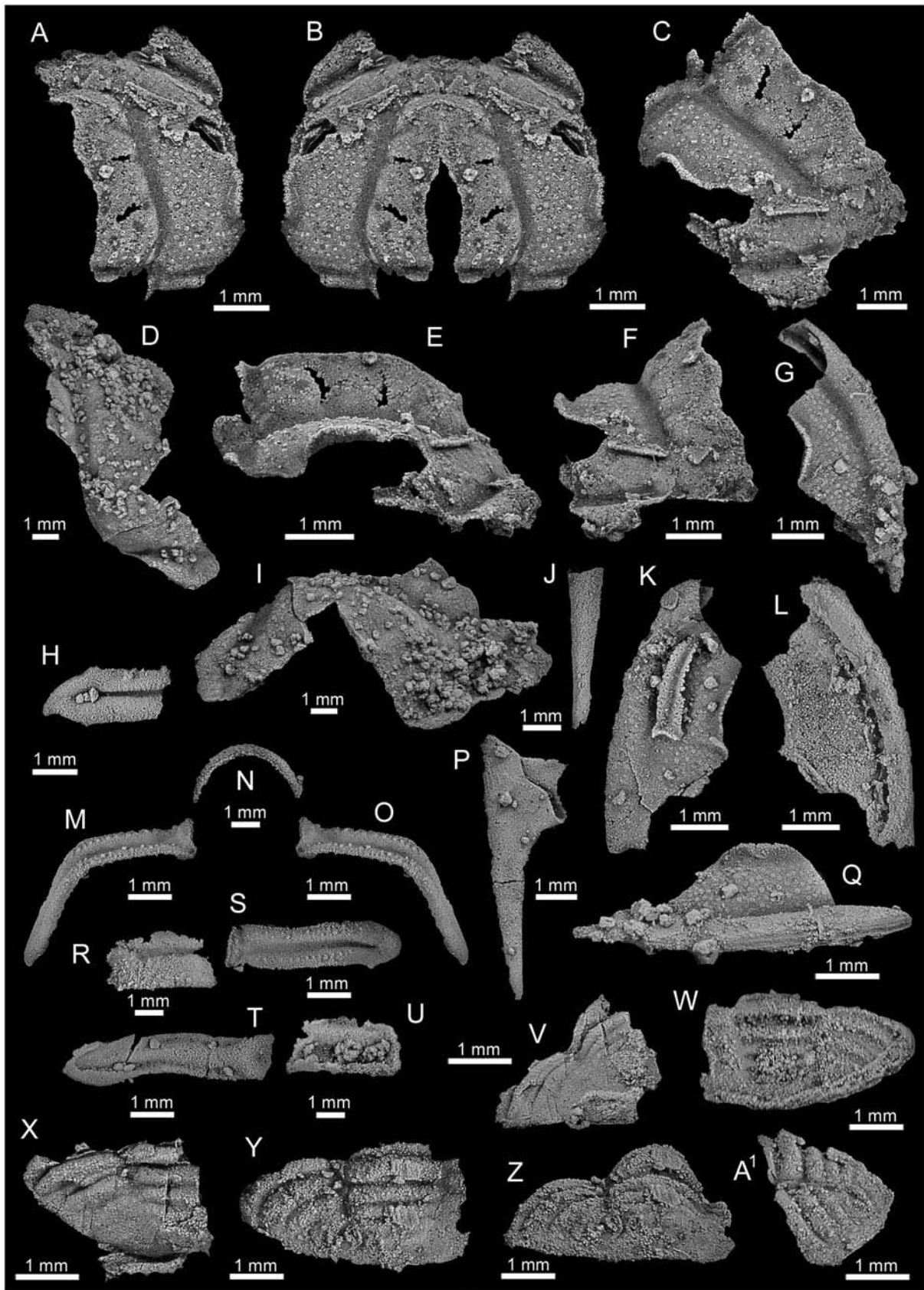


Fig. 11. *Xingrenaspis* sp. Silicified specimens from the Ordian Tempe Formation in the Hermannsburg 41 drillcore (all measurements denote depth from top of the drillcore). A–C, E, F, CPC41868, sample 71, 319.02 m. A, dorsal view of partial cranium. B, reconstruction of partial cranium using mirrored image. C, oblique anterolateral view of partial cranium. E, lateral view of partial cranium. F, anterior view of partial cranium. D, I, CPC41869, sample 71, 319.02 m. D, dorsal view of partial cranium. I, lateral view of partial cranium. G, Q, CPC41870, sample 71, 319.02 m. G, dorsal view of right librigena. Q, lateral view of librigena. H, CPC41871, sample 71, 319.02 m, dorsal view of thoracic pleura

The cranidia resemble a species described as *Tongshania* cf. *tongshanensis* Qiu & Lin in Qiu *et al.*, 1983 by Kruse (1990) from the Ordian Tindall Limestone in the Daly Basin. Jell & Hughes (1997) suggested that *Tongshania* is a junior subjective synonym of *Douposiella* Lu & Chang in Lu *et al.*, 1974, but the former genus was subsequently reassigned as a junior synonym of *Xingrenaspis* by Peng & Hughes in Peng *et al.* (2009)—a view followed herein. The material from Hermannsburg 41 is similar to the Tindall Limestone specimens in having a subquadrate cranidium, a preglabellar field that is shorter (sag., exsag.) than or equal to the anterior border, an anterior border furrow that appears to deepen abaxially, narrow (tr.) posterolateral projections of the fixigenae, a pyriform glabella, which appears to bulge at L1, and a coarse tuberculate ornament (compare Fig. 11A–F with Kruse 1990, pl. 7, figs A–C, F–K, N, O). The Hermannsburg 41 specimens differ, however, in having anterior branches of the facial suture that are either parallel or convergent and in the pygidia having three axial rings rather than two and no medial recess in the posterior margin. Given these minor differences, it is possible that the Tempe Formation material may represent the same species. However, as cranidia and pygidia are rare in collections from Hermannsburg 41, synonymy remains questionable.

The Hermannsburg 41 material also strongly resembles a species from the Coonigan Formation (possibly from the ‘first discovery limestone’) of western New South Wales that was documented in an unpublished Honours thesis (Leu 1980, pl. 17, figs 4–14, pl. 18, figs 1–5, pl. 19, figs 1–10). The only major difference is a slightly more rounded anterior margin of the glabella in the Coonigan Formation specimens. This is probably ontogenetic variation as the Tempe Formation cranidia are smaller in overall size.

Material. Two cranidia, four librigenae, two pygidia, and over 100 thoracic axial segments and pleurae in total. Specimens range from 319.02 m to 316.93 m (Fig. 3) below the top of the drillcore.

Class UNCERTAIN

Order BRADORIIDA Raymond, 1935

Family MONGOLITUBULIDAE Topper, Skovsted, Harper & Ahlberg, 2013

Mongolitubulus Missarzhevskiy, 1977.

Type species. *Mongolitubulus squamifer* Missarzhevskiy, 1977.

Remarks. See Topper *et al.* (2013) and Smith *et al.* (2014) for comments on the features that facilitate identification of isolated spines to *Mongolitubulus* and its affinities within the Bradoriida.

Mongolitubulus sp. (Fig. 12)

Description. Valve extensively folded, outline incompletely known. Surface covered with raised, subcircular, flat-topped disc structures (diameter 11 µm) that are regularly dispersed over the entire surface of the valve, being similar to the ornament on the spine base (Fig. 12F). Spines relatively long (max 1.1 mm length), slender, straight to very gently curved with a circular to slightly oval cross-section (110–200 µm diameter), tapering gently to closed apex. Most spines detached from valves and broken into fragments of the spine base. Some spine tips show a blunt, recurved apex that is rounded and hook-like in appearance. Abapical region broken in all specimens. Spine ornament varies dramatically between specimens. Tops of the spine have semi-regularly arranged rhombic scale-like protuberances (about 14 µm in diameter; Fig. 12A). External spine surface consists of three distinct laminated layers, each about 4 µm thick.

Remarks. The isolated hooked spine tips and fragmentary spine bases (Fig. 12G–M) are relatively common, whereas valves (Figs 12B–D) are exceedingly rare in the Hermannsburg 41 core. Most valves are fragmentary or highly deformed (Fig. 12B, D). No spines were recovered attached directly to the valves, but similarity in ornament between the fragmentary spine bases and the valve (compare Fig. 12A and Fig. 12F) suggest that they are associated elements.

The distinctive slightly raised, subcircular discs on the valves (Fig. 12C) of *Mongolitubulus* sp. are closest to the ornament of *M. aspermachaera* Topper *et al.*, 2013 from the Furongian (Cambrian) of Sweden. The possible presence of only a single spine on the valve surface in the Tempe Formation specimens (Fig. 12D) also resembles the arrangement seen in *M. aspermachaera*. The ornament on the fragmentary spine bases, alternatively, resembles that of the type species, *Mongolitubulus squamifer* Missarzhevskiy, 1977 (pl. 31, figs 1, 3). The spines in *M. squamifer* typically show a high degree of surface ornament variation, ranging from rounded, diamond-shaped scales to the more rhombic scale-like protuberances, such as those evident in the Tempe Formation material. Spines of *Mongolitubulus* species, however, typically show numerous types of

showing falcate spine. **J**, CPC41872, sample 71, 319.02 m, partial genal spine. **K, L**, CPC41873, sample 71, 319.02 m. **K**, dorsal view of left librigena. **L**, ventral view of left librigena. **M, O**, CPC41874, sample 71, 319.02 m. **M**, mirrored image of anterior view of thoracic pleura. **O**, anterior view of thoracic pleura. **N**, CPC41875, sample 71, 319.02 m, anterior view of axial ring. **P**, CPC41876, sample 71, 319.02 m, ventral view of genal spine. **R, U**, CPC41877, sample 71, 319.02 m. **R**, dorsal view of axial ring. **U**, ventral view of axial ring. **S, T**, CPC41878, sample 71, 319.02 m. **S**, dorsal view of thoracic pleura. **T**, ventral view of thoracic pleura. **V, X**, CPC41879, sample 71, 319.02 m. **V**, posterior view of partial pygidium. **X**, dorsal view of partial pygidium. **W, Y, Z, A¹**, CPC41880, sample 71, 319.02 m. **W**, ventral view of partial pygidium. **Y**, dorsal view of partial pygidium. **Z**, posterior view of partial pygidium. **A¹**, lateral view of partial pygidium.

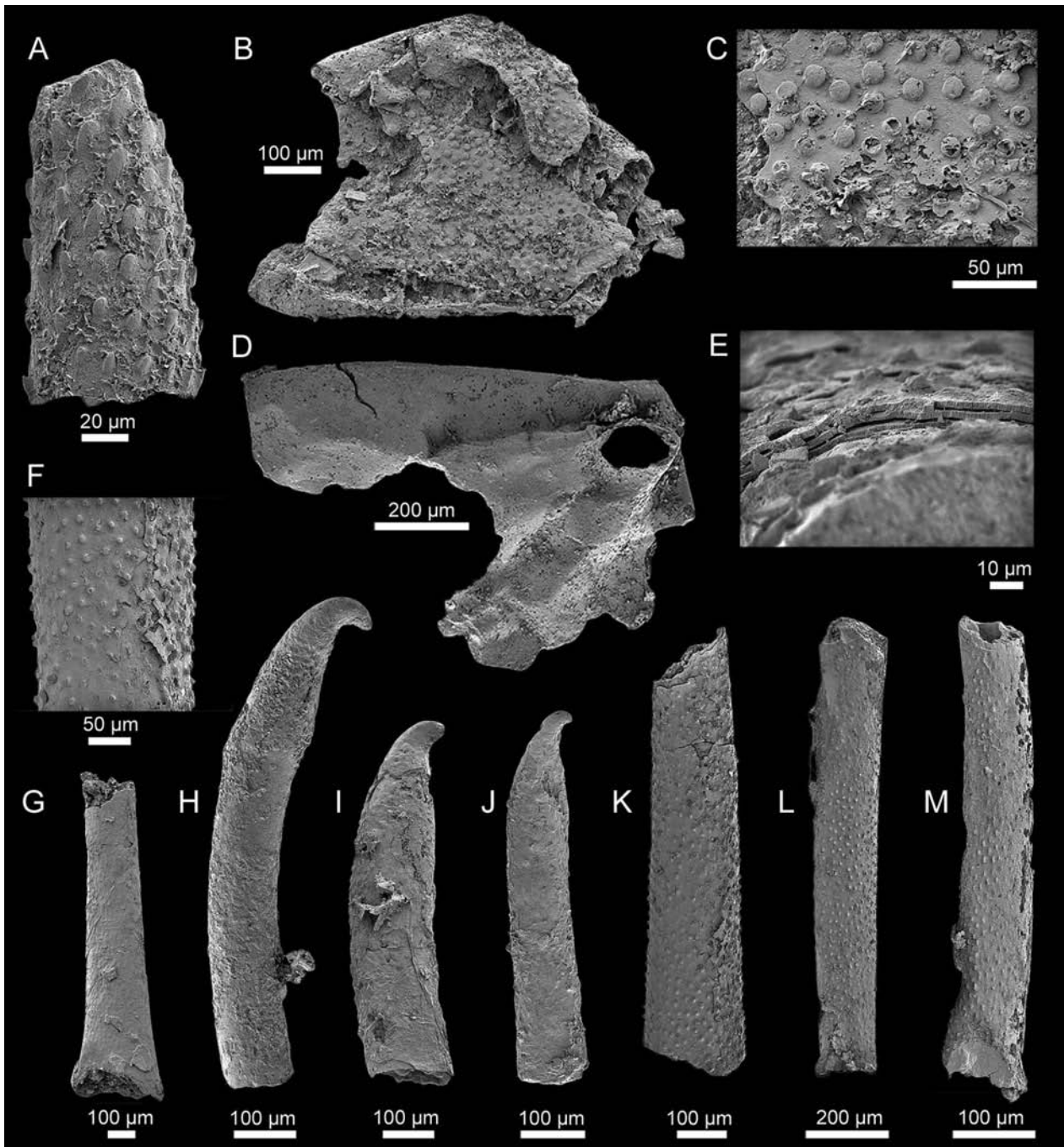


Fig. 12. *Mongolitubulus* sp. spine and valve material from the Ordian Tempe Formation in the Hermannsburg 41 drillcore (all measurements denote depth from top of the drillcore). A, CPC41881, sample 38, 292.68 m, enlargement of ornament on spine. B, C, CPC41882, sample 70, 316.43 m. B, highly folded valve material. C, enlargement of valve external ornament. D, CPC41883, sample 70, 316.43 m, valve material showing straight hinge and only single spine base. E, CPC41884, sample 67, 316.15 m, cross-section of spine showing three-layered microstructure. F, K, CPC41885, sample 67, 316.15 m. F, enlargement of spine ornament. K, section from a large broken spine. G, CPC41886, sample 70, 316.43 m, spine showing flaring at base. H, CPC41887, sample 68, 316.30 m, long spine with hooked tip. I, CPC41888, sample 67, 316.15 m, spine with hooked tip. J, CPC41889, sample 39, 293.18 m, spine with hooked tip. L, CPC41890, sample 67, 316.15 m, section from a large broken spine. M, CPC41891, sample 67, 316.15 m, section from a large broken spine.

ornamentation; hence, it is not considered a taxonomically diagnostic character (Topper *et al.* 2007).

None of the hooked spine tips examined in the Tempe Formation possesses the ornament of the associated *Mongolitubulus* valves, hence it is difficult to be sure that the two belong together. However, numerous species assigned to *Mongolitubulus* have been described with

similar hook structures, including *M. aspermachaera*, *Mongolitubulus reticulatus* Kouchinsky *et al.*, 2011 and *Mongolitubulus tulpere* Smith, Brock, Paterson & Topper, 2014. Comparable hooked spines have also been reported from the Ordian Gum Ridge Formation and Thornton Limestone (=Hay River Formation) of the Georgina Basin and the Montejinni Limestone of the

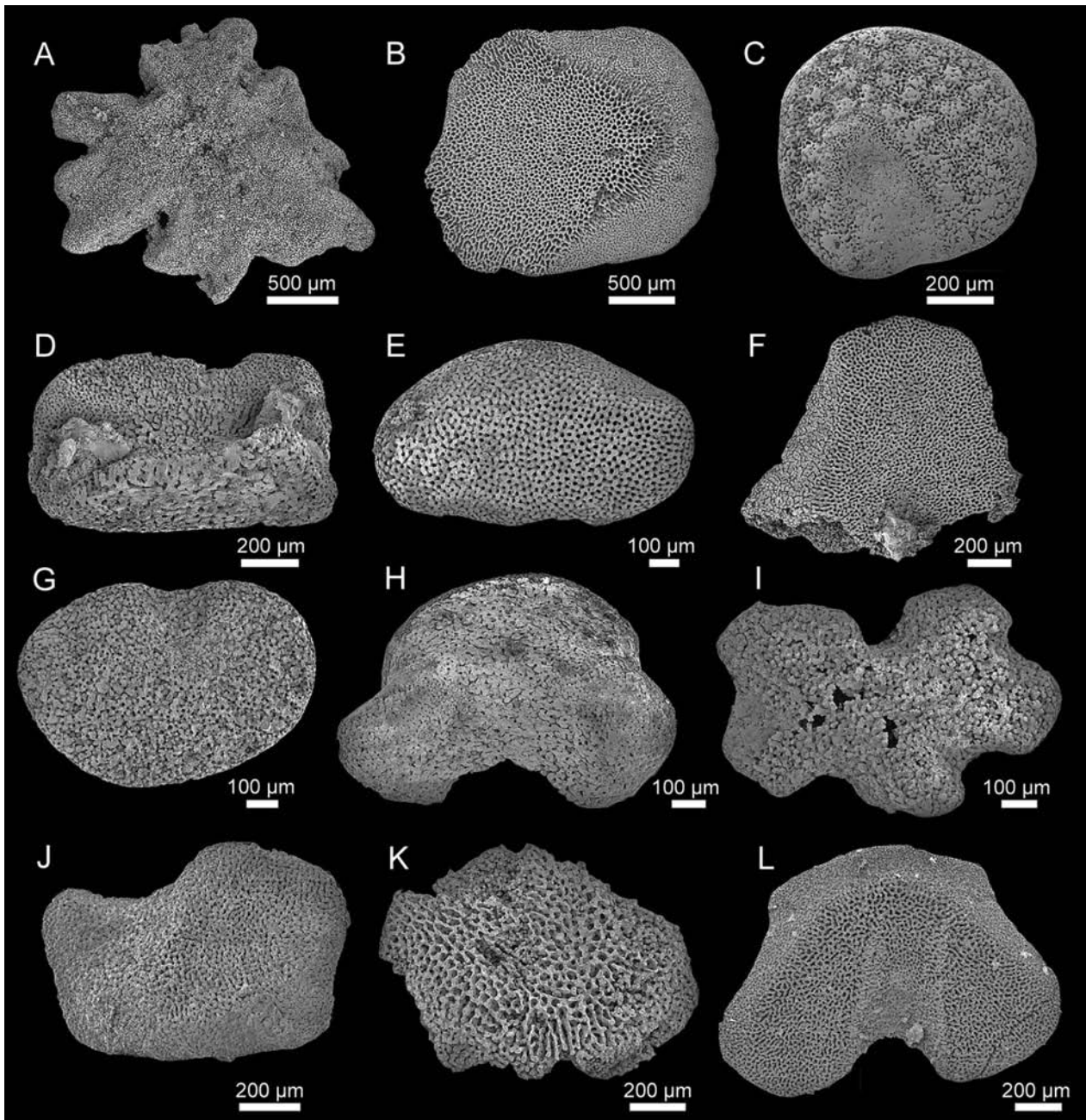


Fig. 13. Echinoderm fragments from the Ordian Tempe Formation in the Hermannsburg 41 drillcore (all measurements denote depth from top of the drillcore). **A**, CPC41892, sample 13, 272.85 m, possible interambulacral plate. **B**, CPC41893, sample 13, 272.85 m, aboral plate. **C**, CPC41894, sample 75, 320.19 m, highly rounded aboral surfacing plate. **D**, CPC41895, sample 13, 272.85 m, fragmentary, possible ambulacral flooring plate. **E**, CPC41896, sample 13, 272.85 m, highly rounded aboral surface plate. **F**, CPC41897, sample 13, 272.85 m, fragmentary plate. **G**, CPC41898, sample 14, 273.00 m, highly rounded aboral plate. **H**, CPC41899, sample 14, 273.00 m, highly rounded plate. **I**, CPC41900, sample 14, 273.00 m, possible interambulacral plate. **J**, CPC41901, sample 70, 316.43 m, fragmentary plate. **K**, CPC41902, sample 13, 272.85 m, fragmentary plate. **L**, CPC41903, sample 70, 316.43 m, possible interambulacral plate.

Wiso Basin (Kruse 1998, fig. 48C–F; Jones & Kruse 2009, fig. 13). Smith *et al.* (2014) suggested that this material may be conspecific with *M. tunpere* and, therefore, belong to *Mongolitubulus*.

Given the occurrence in the same stratigraphic levels as the valves and ornamented spine bases, similar diameter to the associated spine bases and the close comparison with three other *Mongolitubulus* species, it seems highly plausible that these hooked spine tips in the

Hermannsburg 41 core belong to the same species of *Mongolitubulus* as the other identified elements.

Because the Tempe Formation valve material is indifferently preserved and scarce, we take a tentative taxonomic approach and leave this taxon under open nomenclature. The similar age and close geographic proximity of the hooked spines originally described from the Georgina and Wiso basins suggest the material described herein may be conspecific.

Material. Two valves and more than 100 spines collected. Specimens range from 319.34 m to 292.68 m (Fig. 3) below the top of the drillcore.

Phylum ECHINODERMATA Klein, 1734
Class EDRIOASTEROIDEA Billings, 1858

Edrioasteroid plates (Fig. 13)

Remarks. Silicified and phosphatized isolated echinoderm ossicles are uncommon and have a sporadic distribution in Cambrian deposits from the Northern Territory (Kruse *et al.* 2004), South Australia (Brock & Cooper 1993), New South Wales (Smith & Jell 1990) and elsewhere in the world (Skovsted & Holmer 2006, Skovsted & Peel 2007, 2010, Kouchinsky *et al.* 2011). The large number of plates from the Tempe Formation in the Hermannsburg 41 core is noteworthy. A few rare plates resemble interambulacral plates with epispires (indentations in the plate margin, e.g., Fig. 13A, H, I, L), but the majority of plates are aboral (dorsal) plates and ossicles. An ambulacral flooring plate may also be present (Fig. 13D), though it is incomplete. Taxonomic identification of individual disarticulated plates is notoriously difficult, particularly when many specimens are well rounded by high-energy conditions (e.g., Fig. 13C, E, G). The presence of interambulacral plates with epispires is characteristic of various groups including eocrinoids, edrioasteroids, cinctans (e.g., cornutes and stylophorans) and blastozoans (Ubaghs 1975, Paul & Smith 1984). The presence of only aboral surfacing plates and absence of other diagnostic plates, apart from possible ambulacral flooring plates, suggests edrioasteroid affinities for these echinoderm ossicles. Further support for this affinity comes from the similarity of the Hermannsburg 41 material to disarticulated plates previously reported from edrioasteroids of a similar age from the 'first discovery limestone' of the Coonigan Formation in western New South Wales (Jell *et al.* 1985), the Panton Formation in the Northern Territory (Kruse *et al.* 2004), and Kuonamka Formation of northern Siberia (Kouchinsky *et al.* 2011).

In Australia, there are two named species of edrioasteroids from the Ordian; *Edriodiscus primoticus* (Henderson & Shergold, 1971) and *Stromatocystites reduncus* Smith & Jell, 1990, both from the 'Yelvertoft Bed', Thornton Limestone (=Hay River Formation), Georgina Basin. It is entirely possible that one or both of these species are represented in the present collection of ossicles.

Material. Over 100 specimens collected, ranging from 321.28 m to 272.85 m (Fig. 3) below the top of the drillcore.

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PAPER 2

New bradoriid arthropods from the Giles Creek

Dolostone (Cambrian Series 3, Stage 5; Templetonian),

Amadeus Basin, central Australia.

SMITH, P.M., BROCK, G.A., PATERSON, J.R., & TOPPER, T.P., 2014. New bradoriid arthropods from the Giles Creek Dolostone (Cambrian Series 3, Stage 5; Templetonian), Amadeus Basin, central Australia. *Memoirs of the Association of Australasian Palaeontologists* 45, 233–248.

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Smith, P. M., Brock, G. A., Paterson, J.R. & Topper, T. P. (2014) New bradoriid arthropods from the Giles Creek Dolostone (Cambrian Series 3, Stage 5; Templetonian), Amadeus Basin, central Australia. *Memoirs of the Association of Australasian Palaeontologists*, vol. 45, pp. 233-248.

PAPER 3

Trilobites from the Giles Creek Dolostone (Cambrian
Series 3, Stage 5; Templetonian) Amadeus Basin,
central Australia.

SMITH, P.M., PATERSON, J.R. & BROCK, G.A., 2015. Trilobites from the Giles Creek Dolostone (Cambrian Series 3, Stage 5; Templetonian) Amadeus Basin, central Australia. *Papers in Palaeontology* 1, 167–200.

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PAPER 4

Linguliformean brachiopods from the early Templetonian (Cambrian Series 3, Stage 5) Giles Creek Dolostone, Amadeus Basin, Northern Territory.

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PAPER 5

Trilobites and agnostoid arthropods from the Goyder
Formation (Cambrian Series 3, Guzhangian;
Mindyallan), Amadeus Basin, central Australia.

SMITH, P.M., PATERSON, J.R. & BROCK, G.A., 2016. Trilobites and agnostoid arthropods from the Goyder Formation (Cambrian Series 3, Guzhangian; Mindyallan), Amadeus Basin, central Australia. (Draft manuscript to be submitted to *Zootaxa*).

Trilobites and agnostoid arthropods from the Goyder Formation (Cambrian Series 3, Guzhangian; Mindyallan), Amadeus Basin, central Australia

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Abstract

A new assemblage containing twenty-two species of trilobites and agnostoid arthropods are described from the Goyder Formation in the Ross River Syncline and Gardiner Ranges of the Amadeus Basin, Northern Territory, central Australia. New trilobite taxa described include the genus, *Trephina* gen. nov., and four new species *Adelogonus prichardi* sp. nov., *Hebeia stewarti* sp. nov., *Liostracina joyceae* sp. nov. and *Trephina ranfordi* gen. et sp. nov.

Additionally, two agnostoid taxa previously known only from Antarctica, *Ammagnostus antarcticus* Bentley, Jago & Cooper, 2009 and *Hadragnostus helixensis* Jago & Cooper, 2005, are also documented. Of the two agnostoid species, *H. helixensis* is the most age diagnostic; previously reported from the Cambrian Series 3 (Guzhangian; late Mindyallan; *Glyptagnostus stolidotus* Zone) Spurs Formation in Northern Victoria Land. This age is supported by the co-occurrence of the trilobites *Biaverta reineri* Öpik, 1967, *Blackwelderia repanda* Öpik, 1967, *Henadoparia integra* Öpik, 1967, *Monkaspis* cf. *travesi* (Öpik, 1967), *Nomadinis pristinus* Öpik, 1967, *Paraacidaspis priscilla* (Öpik, 1967) and *Polycyrtaspis* cf. *flexuosa* Öpik, 1967, also known from the late Mindyallan (*G. stolidotus* Zone) successions of the neighbouring

Georgina Basin (Northern Territory and Queensland). The generic assemblage of the Goyder Formation is also similar to those from the Guzhangian (Mindyallan) of other parts of Australia (New South Wales, South Australia and Western Australia), in addition to East Antarctica and China.

Key words: Trilobita, Agnostida, middle Cambrian, Northern Territory, Australia, East Gondwana.

Introduction

The diversity of trilobites and agnostoid arthropods in East Gondwana increased dramatically during the mid-Cambrian (Series 3; ~509–497 Ma). The greatest diversification occurred during the Guzhangian (158 genera), with the increase more than doubling the number of known genera from the underlying Drumian Stage. A large part of this diversity in Australia occurs in the Georgina Basin, which contains 101 of the 158 known Guzhangian genera (Hally & Paterson 2014). Guzhangian trilobites and agnostoids from the neighbouring Amadeus Basin have been reported from the Goyder Formation, but never formally described.

Faunas from the Goyder Formation were first observed by Prichard & Quinlan (1962, p. 17), who noted the presence of ‘upper Cambrian trilobites’. Faunal elements of the Goyder Formation were also mentioned by numerous other regional mappers at the Bureau of Mineral Resources (now Geoscience Australia) in successive reports, often citing the collections of Miss Joyce Gilbert-Tomlinson (e.g., Ranford & Cook 1964; Ranford *et al.* 1965; Wells *et al.* 1967). Öpik (1967, appendix 2, p. 16), in particular, reported two fossiliferous horizons in the Goyder Formation from one locality (NT187, near AS256) in the Ross River Gorge area, approximately 64 km east of Alice Springs (Fig. 1A-C). The first of these horizons contained

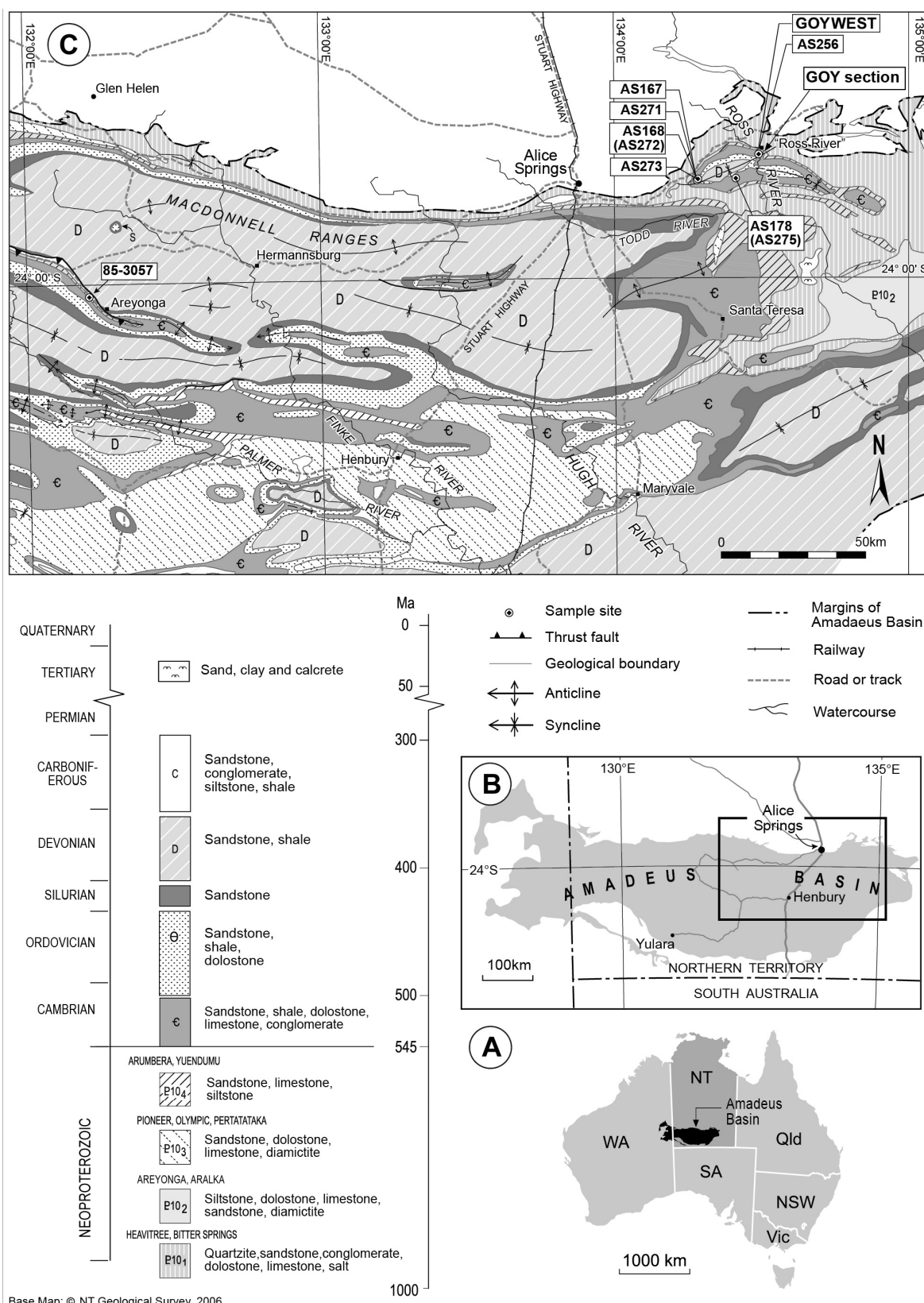


FIGURE 1. Geology of the northeastern portion of the Amadeus Basin. A, map of Australia showing the location of the Amadeus Basin. B, map of the Amadeus Basin; rectangular outline represents the study region. C, Geological map of study area showing the positions of the GOY section, 85-3057, AS167, AS271, AS168, AS273, AS178, AS256 and GOYWEST spot localities. Geological map modified from Alice Springs SF5314. © Copyright Google Earth 2014 and Commonwealth of Australia (Geoscience Australia) 1996.

a low diversity fauna with only *Auritama* sp. nov., *Liostracina* cf. *volens* and damesellid fragments. The second horizon contained a higher diversity, including *Liostracina* cf. *krausei*, *Metopotropis* sp. nov., *Plectrifer?* sp. nov. (pygidia) and what Öpik (1967) assumed was a new genus of trilobite. Subsequently, Gilbert-Tomlinson (in Pojeta *et al.* 1977, p. 34), added to this list '*Homagnostus*' sp. nov. from the second locality (termed the 'lower bed'). Shergold & Laurie (in Shergold *et al.* 1991) later recorded sixteen other localities with trilobites and agnostoids on the northern limb of the Ross River Syncline (representing the Fergusson Range), as well as areas in the Gardiner Ranges. The exact position of these localities were not provided in Shergold *et al.* (1991), but a taxonomic list included the genera *Liostracina* Monke, 1903, *Henadoparia* Öpik, 1967, *Lophoholcus* Öpik, 1967, *Nomadinis* Öpik, 1967, *Metopotropis* Öpik, 1967, *Palaeadotes* Öpik, 1967 and other indeterminate damesellids, pagodiids and agnostoids, particularly of the *Ammagnostus*-type (Shergold 1986).

Interestingly, Shergold & Laurie (in Shergold *et al.* 1991, p. 104) commented that another fauna, which they term the 'parabolinoïd assemblage', occurred in the misidentified 'Shannon Formation' in the Gaylad Syncline and the 'upper Goyder Formation' in the Fergusson Syncline, the Waterhouse Range Anticline, and the Gardiner Range Anticline, near Areyonga. The 'parabolinoïd assemblage' is possibly the same as the 'late Franconian trilobites' reported by Öpik (in Joklik 1955) and Gilbert-Tomlinson (in Wells *et al.* 1967) from two levels near the top of the apparent 'upper Goyder Formation' (Jones *et al.* 1971). Uncertainty in the geographic locality of any of these samples makes it difficult to suggest that they belong to the Goyder Formation *sensu stricto*. Most likely the 'parabolinoïd assemblage' belongs to either another formation or a currently unrecognised unit between the Goyder Formation and Pacoota Sandstone.

The main aims of this study are to: (1) provide the first detailed systematic description of the trilobite and agnostoid assemblages from the Goyder Formation in the Ross River Syncline and Gardiner Ranges of the Amadeus Basin; (2) contribute the first biostratigraphic

range data for the Goyder Formation; and (3) assess biostratigraphical correlations within and outside the Amadeus Basin.

Geological setting and locality

The Amadeus Basin is a large intracratonic depocentre of Neoproterozoic to Carboniferous sedimentary rocks located in central Australia (Fig. 1A-B). The eastern and western boundaries of the basin are buried under younger sedimentary deposits, and the northern and southern limits are structural and/or erosional rather than depositional (Edgoose 2012). Within the basin, the late Ediacaran–Cambrian Pertaoorrta Group has traditionally has been divided into five stratigraphic sequences (€1–€5). The lower three sequences (€1–€3), incorporating the Arumbera Sandstone, Todd River Dolostone, Tempe Formation and Giles Creek Dolostone, have been previously documented palaeontologically (e.g., see Laurie 1986; Shergold 1986; Smith *et al.* 2014, 2015a, b, 2016). Sequence €4 is represented by the mid-Cambrian Hugh River Shale, Jay Creek Limestone, Illara, Petermann and Cleland sandstones, as well as the Deception, Shannon and Goyder formations. Lower parts of the Pacoota Sandstone—initially referred to the ‘upper Goyder Formation’—make up sequence €5, which is latest Cambrian in age (Kennard & Lindsay 1991).

The Goyder Formation was originally described as beds Df and Dg of (Madigan 1932) and was later defined as an independent formation by Prichard & Quinlan (1962). Subsequently, the Goyder Formation was redefined as a member of the ‘Pertaoorrta Formation’ (Wells *et al.* 1965) before being reinstated as a separate formation by Ranford *et al.* (1965). The formation is known to occur in the northern part of the Amadeus Basin, stretching from the Mt. Winter 1 core in the west (Gorter *et al.* 1982), the Fergusson Ranges in the east (Wells, *et al.* 1967) and extends as far as the Seymour Range in the south (Ranford & Cook 1964). However, the formation may be more widely distributed, since outcrop exposure is typically poor and there is confusion in the field as to which rock units belong to

the Goyder Formation *sensu stricto* (Gorter & Nicoll in Kennard *et al.* 1986). Prichard & Quinlan (1962) nominated the type section for the Goyder Formation at a location “half a mile west of Ellery Creek”, but their publication did not provide a map or any other geographic information. According to the International Commission on Stratigraphy (ICS) guidelines, a type section (stratotype) must be associated with a detailed map and/or aerial photograph to define the unit. Therefore the Goyder Formation currently needs a well defined and documented type section. Prichard & Quinlan’s (1962) initial description of the Goyder Formation implied a bipartite package with a lower, predominantly carbonate succession and an upper, mostly clastic succession. The base of the Goyder Formation appears to conformably overlie the Hugh River Shale, Jay Creek Limestone, Petermann Sandstone and Shannon Formation—all of which are supposedly lateral equivalents across the basin (at least in part)—whilst the upper boundary of the unit is said to be disconformably overlain by the Pacoota Sandstone (Shergold 1991).

The trilobites and agnostoid arthropods described herein come from a measured stratigraphic section (GOY) through the Goyder Formation in Ross River Gorge, supplemented by eight spot localities around the basin (Figs 1C, 2). The GOY section (Fig. 2D, base at 23°36’46” S, 134°29’21” E), was measured from the last exposed bed of Shannon Formation; the exposed contact with the Goyder Formation was identified 2 km west at the GOYWEST locality (Fig. 2D). The stratigraphic section (Fig. 3) intersects 297.3 m (true thickness) of the Goyder Formation; the lower 49.4 m (true thickness) is covered by alluvium. Between 49.4 and 138.2 m, the lithology consists of sandy and shaley limestone parasequences capped by progressively thicker dolostone and sandy dolostone benches. Large, elongate (2 to 5 cm diameter) pisoids, ooids, sandy microbial clasts and shelly fossil remains (including trilobites, agnostoids, echinoderms, gastropods, rostroconchs, phosphatic brachiopods and hyoliths) are common in this interval. The dolostone and sandy dolostone benches contain classic herringbone cross-bedding, microbialites and centimeter to metre

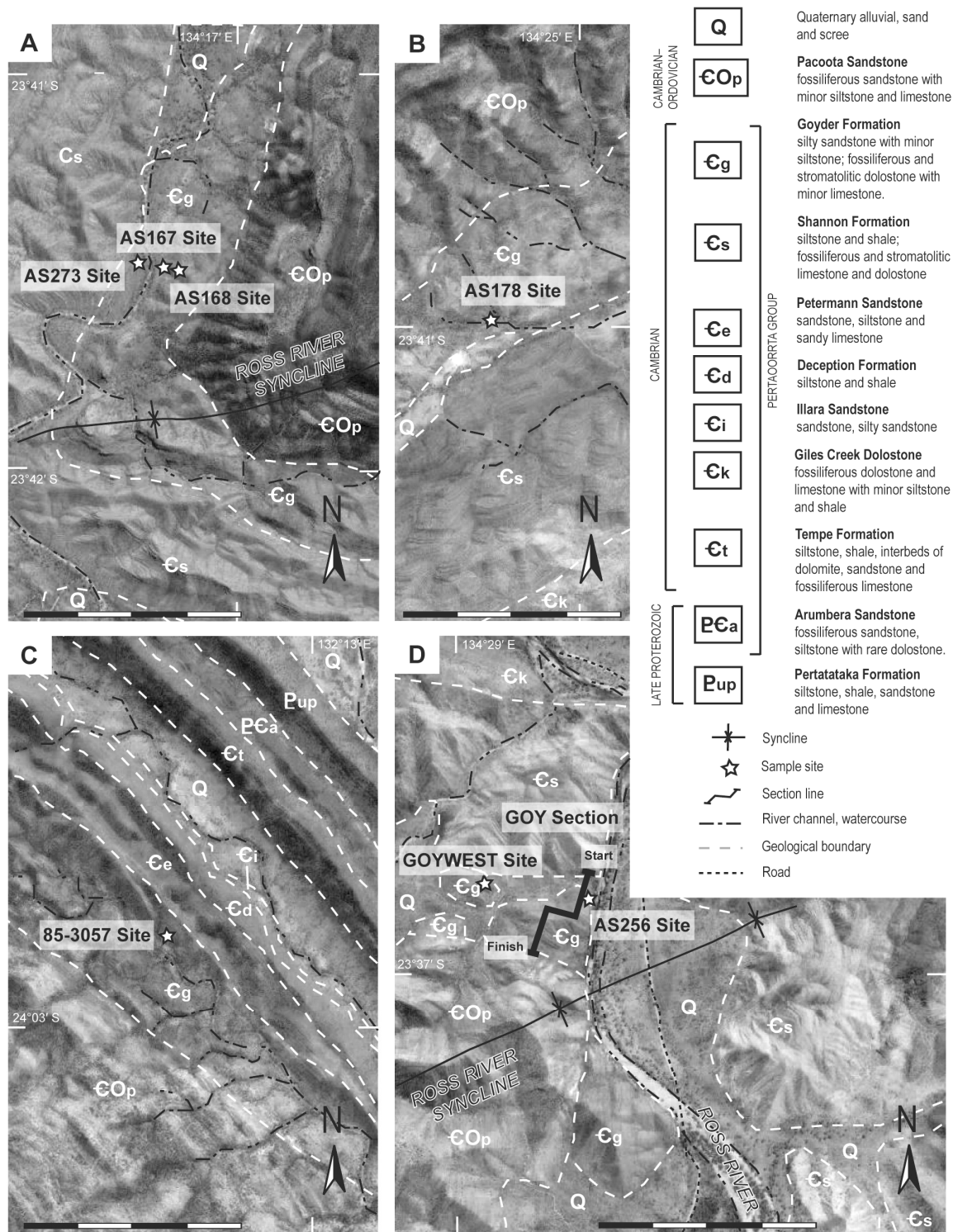


FIGURE 2. Detailed maps of the Goyder Formation localities. A, Spot localities AS167, AS168 and AS273 near the western limb of the Ross River Syncline. B, Spot locality AS178 on the southern face of the Ross River Syncline. C, Spot locality 85-3057 in the Gardiner Rangers. D, The GOY section near the eastern limb of the Ross River Syncline along with the spot localities AS256 and GOYWEST, Northern Territory. All scale bars are 1 km long and are divided into 250 m gradations. Geological map modified from Alice Springs SF5314. © Copyright Google Earth 2015 and Commonwealth of Australia (Geoscience Australia) 1996.

scale domal stromatolites. Two disconformity surfaces were recorded at 76.4 m and 101.7 m above the base of the section; both immediately overlain by microbial laminations and

domal stromatolites. The interval from 138.2 to 198.1 m (true thickness) is dominated by sandy dolostone. Oolitic dolostones with sandy microbial clasts occur interbedded with herringbone crossbeds in cyclically repeated layers. The top of this interval is covered by two thick sandy dolostone benches with crossbedding. The lower of these benches contains numerous lenticular clasts, whilst the upper bench is dominated by metre scale domal stromatolites. Shelly fossils were not recovered above 150 m from the base of the section (Fig. 3). The upper package, between 198.1 and 297.3 m, consists of interbedded dolostones, cross-bedded, sandy dolostone and red-brown, fine grained sandstone. Deci-centimeter domal stromatolites are prominent in the sandy dolostone at 284.0 m, near the defined top of the section. The GOY section terminates at the sharp transition from dolomitic sandstones to the white, coarser grained, *Skolithos*-bearing, feldspathic sandstone of the basal Pacoota Sandstone (Fig. 3).

The GOY section only intersects carbonate-dominated units, previously identified as part of the ‘lower Goyder Formation’ (Wells *et al.* 1967, p.42, 43). The succession of white sandstones above the GOY section was traditionally interpreted as ‘upper Goyder Formation’ (see Kennard & Nicoll in Kennard *et al.* 1986, p. 75). However, detailed study of the Pacoota Sandstone in the Ross River area by Shergold (1991) showed that these white sandstones, ranging up to 190 m in thickness, are lithologically distinct and likely belong to the basal Pacoota Sandstone. Thus, the Goyder Formation represented in the GOY section is considerably shorter than the original section measured by Wells *et al.* (1967, pl. 12). The carbonate-dominated succession represented in the GOY section also conforms to the suggestion by Gorter (1991) that the ‘upper Goyder Formation’ be united with the lower Pacoota Sandstone, in what he termed the ‘Wallaby sequence’. Gorter (1991) also suggested the ‘lower Goyder Formation’ should be combined with the conformably underlying Shannon Formation, a suggestion which is not supported here.

Supplementary trilobite material collected from spot localities come from the northeastern portion of the basin, around the Ross River Syncline (Figs 1C, 2). These include:

AS167 (23°41'31" S, 134°16'48" E), AS168 (= AS272) (23°41'32" S, 134°16'57" E), AS178 (=AS275) (23°41'14" S, 134°24'46" E), AS256 (23°36'48"S, 134°29'22"E), AS273 (23°41'27"S, 134°16'41"E) and GOYWEST (23°36'48"S, 134°29'2"E) (Fig. 2). Two other spot localities produced collections, one from the central part of the basin in the Gardiner Range, 85-3057 (24° 2'13.73"S, 132°12'45.55"E; Fig. 2C) and the other, 87-008, from a poorly located area originally collected by J. H. Shergold (a red-cream colour sandstone).

Biostratigraphy and correlation

Following the first reports of fossils from the 'lower Goyder Formation', the unit was given a Mindyallan age, specifically within the *Glyptagnostus stolidotus* Zone (Öpik 1967, p. 32). This interpretation was based on the apparent similarity of reported genera (see above) to taxa described in Öpik's (1967) monograph on Mindyallan trilobites and agnostoids from the Georgina Basin. However, none of the reported trilobites and agnostoids from the 'lower Goyder Formation' were formally described (or even illustrated), making this age assessment difficult to substantiate. The only previously described fossils from the unit are rostroconchs (Pojeta *et al.* 1977), which have little biostratigraphic utility. Thus, the trilobites and agnostoids reported herein provide the first definitive age assessment for the formation since its initial description.

Two successive assemblages, each with a characteristic agnostoid taxon, occur in the Goyder Formation at the GOY section (Fig. 3). The lowest assemblage, herein dubbed the *Hadragnostus helixensis* assemblage, includes the eponymous agnostoid and the trilobites *Adelogonus prichardi* sp. nov., *Biaverta?* sp., *Blackwelderia repanda* Öpik, 1967, *nepeidae* gen. et sp. indet., *Hebeia stewarti* sp. nov., *Henadoparia integra* Öpik, 1967, *Liostracina joyceae* sp. nov., *Monkaspis cf. travesi* (Öpik, 1967), *Paraacidaspis priscilla* (Öpik, 1967), *Proceratopyge* sp. and *Trephina ranfordi* gen. et sp. nov. (Fig. 3). Elements of this assemblage at AS178 and AS168 suggest that *Liostracina* sp. and *Protaitzehoia?* sp. also

belong to the *H. helixensis* assemblage (Fig. 3). Overlying this is the *Ammagnostus antarcticus* assemblage, which includes the eponym and the trilobites *Biaverta reineri* Öpik, 1967, *Blackwelderia repanda* Öpik, 1967 (continuing from the assemblage below), catillicephalidae gen. et sp. indet., *Nomadinis pristinus* Öpik, 1967, *Paradistazeris* sp., and *Polycyrtaspis* cf. *flexuosa* Öpik, 1967 (Fig. 3). The close similarity of *Nomadinis* cf. *pristinus* Öpik, 1967 from 85-3057 to *N. pristinus* in the GOY section may suggest that the former taxon, along with the co-occurring *Liostracina* cf. *kaulbacki* Shergold, Laurie & Shergold, 2007, also belong to the *A. antarcticus* assemblage (Fig. 3).

Hadragnostus helixensis is the more age diagnostic taxon of the two agnostoids in the Goyder Formation. It has only been described previously from the Spurs Formation at the head of Carryer Glacier in Antarctica (Jago & Cooper 2005), within a 10 m interval with the eponym of the *G. stolidotus* Zone. In contrast, *Ammagnostus antarcticus* is potentially longer ranging. Originally, *A. antarcticus* was only reported to co-occur with the age diagnostic taxon *Acmahachis quasivespa* Öpik, 1967 (= *Acmahachis typicalis* Resser, 1938 in Bentley *et al.* 2009) in the eponymous zone from the Spurs Formation, 2.7 km north of Jago & Cooper's (2005) Carryer Glacier locality (Bentley *et al.* 2009). However, *Agnostoglossa bassa* Öpik, 1967 from the Mungerebar Limestone of the Georgina Basin (Öpik 1967) and *Ammagnostus* sp. indet. (Wang *et al.* 1989) from the Boshy Formation in the Koonenberry Belt of western New South Wales may be conspecific. If this is the case, *A. antarcticus* would extend down to the *Erediaspis eretes* Zone and also higher up into the overlying *G. stolidotus* Zone, expanding its range to the entire Mindyallan stage. Given the potential ranges of these taxa and their relative positions in the Goyder Formation at the GOY section, the entire fauna likely belongs to the late Mindyallan *G. stolidotus* Zone (Fig. 4).

The trilobites from the Goyder Formation also support a late Mindyallan age. The strongest faunal connections appear to be with the Georgina Basin where at least six, possibly seven, taxa are shared. The Goyder Formation assemblage has the most in common with that of the O'Hara Shale, with *Blackwelderia repanda*, *Henadoparia integra*, *N. pristinus*,

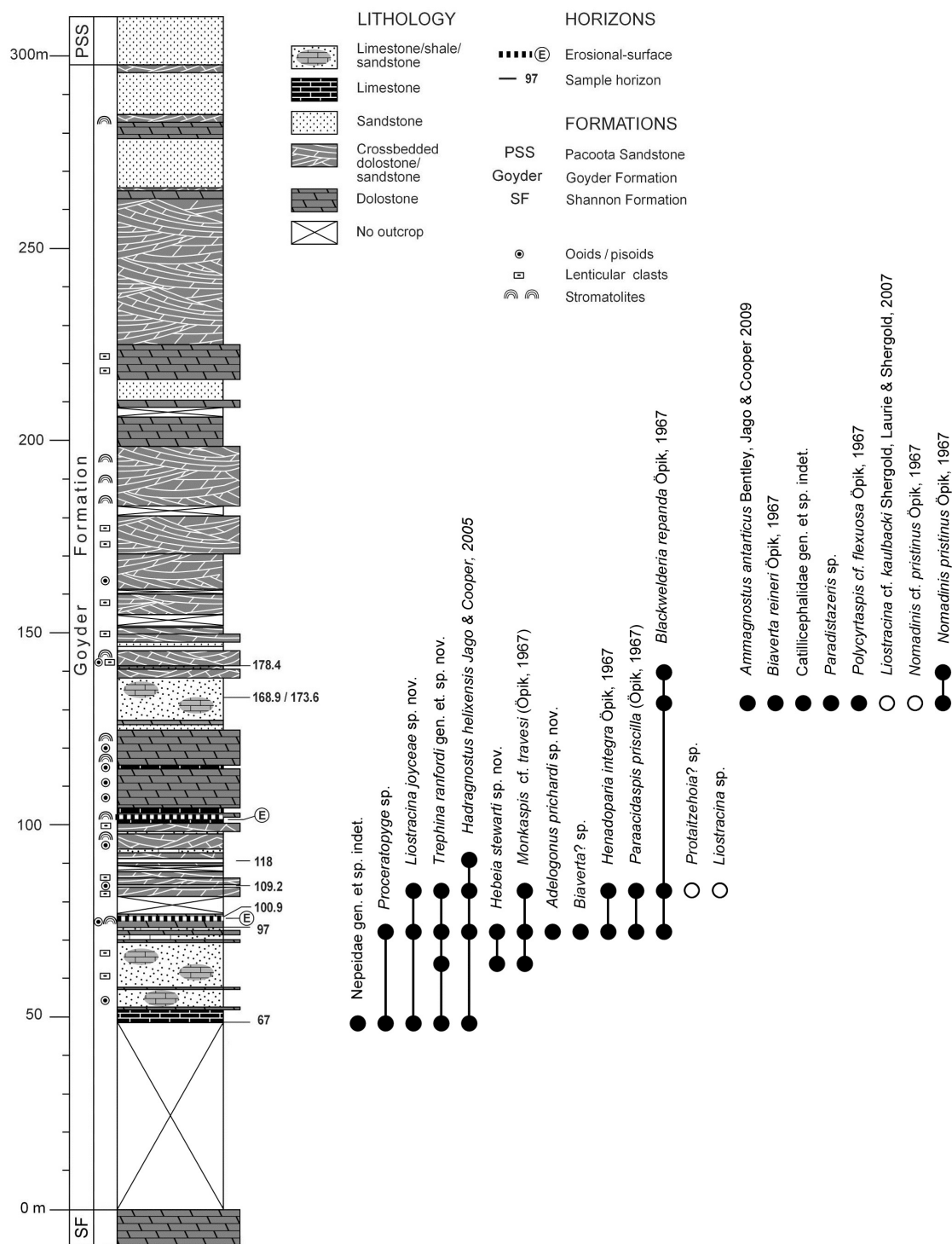


FIGURE 3. Generalized lithostratigraphy and taxon ranges through the Goyder Formation at the GOY section. Sampled horizons are indicated on the right side of the columns, with sample numbers on the GOY section representing tape meterage along the section line (see Fig. 2). Measurements on the left side of each column are in meters (true thickness) from the base of the Goyder Formation. SF = Shannon Formation, PSS = Pacoota Sandstone. Black filled-in circles represent the ranges of taxa present in the GOY section. Hollow circles represent the range of taxa found only at spot localities. N.B. Ranges of taxa found only at spotspot localities is approximate, and has been inferred using lithological, faunal and geographical information.

Paraacidaspis priscilla and *Polycyrtaspis flexuosa* Öpik, 1967 (similar to *Polycyrtaspis* cf. *flexuosa*) all co-occurring. These same taxa, with the exception of *Blackwelderia repanda* and addition of *Monkaspsis travesi* (Öpik, 1967) (similar to *Monkaspsis* cf. *travesi* Öpik, 1967), are

also known in the Georgina Limestone (Öpik 1961). Both of these formations in the Georgina Basin also host *Glyptagnostus stolidotus* Öpik, 1961, further strengthening a *G. stolidotus* Zone age for the Goyder Formation (Öpik 1967). *Biaverta reineri* is also found in the Georgina Basin from the Mungerebar Limestone, but it only occurs with a *G. stolidotus* Zone-like fauna rather than with the eponym itself (Öpik 1967). The trilobite and agnostoid faunas from other coeval units in the Georgina Basin, such as the Selwyn Range and Pomegranate limestones, are either poorly known (Öpik 1961) or contain dissimilar taxa (Öpik 1967). The Pomegranate Limestone, in particular, is partially represented by a flaggy-bedded, bituminous, micritic limestone containing a diversity of agnostoids (Öpik 1960, 1967), suggesting a slightly deeper facies than represented by the Goyder Formation.

Outside of the Georgina Basin, the Goyder Formation fauna is similar to the *G. stolidotus* Zone assemblages of the Boshy Formation in western New South Wales (NSW), and possibly the Skewthorpe Formation of the Bonaparte Basin in Western Australia (WA). The Boshy Formation shares *Blackwelderia repanda* (referred to as *Blackwelderia* sp. cf. *B. repanda* by Wang *et al.* 1989) and *Biaverta* sp. (possibly synonymous with *Biaverta reineri*) (Wang *et al.* 1989). The Skewthorpe Formation also has two similar taxa, *Blackwelderia* sp. cf. *B. repanda* (comparable to *Blackwelderia repanda* in the Goyder Formation) and *Liostracina kaulbacki* (similar to *Liostracina* cf. *kaulbacki*) (Shergold *et al.* 2007). The Goyder Formation may also correlate with the Kalladeina Formation of the Warburton Basin in the Northern Territory (NT) and South Australia (SA). The trilobite genera *Blackwelderia* Walcott, 1906 and *Liostracina* Öpik, 1967 are shared between the two formations, but the taxa from the Kalladeina Formation remain undescribed (Gatehouse 1986). Tasmania is also host to several Mindyallan faunas (Jago 1973; Jago & Daily 1974; Jago 1979; Shergold *et al.* 1985), but they appear distinctly different to the Goyder Formation taxa, perhaps as a result of their association with outer shelf to upper slope facies.

Stage	Northern Territory biostratigraphic Zones	Amadeus Basin (NT)		Warburton Basin (NT&SA)	Georgina Basin (NT&Qld)		West NSW	Bonaparte Basin (WA)	Antartica
		Carmichael sub-basin	Ooraminna sub-basin	Gidgealpa 1	Toko Syncline	Burke River Structural Belt	Koonenberry Belt	Pretlove Hills	Nth Victoria Land
Idamean	<i>Stigmatia diloma</i>								
	<i>Erixanum sentum</i>								
	<i>Proceratopyge cryptica</i>								
	<i>Glyptagnostus reticulatus</i>								
Mindyallan	<i>Glyptagnostus stolidotus</i>	Goyder Formation	Goyder Formation	Kalladeina Formation	Georgina Limestone	Pomegranate Limestone	Watties Bore Formation	Pretlove Sandstone	Spurs Formation
	<i>Acmahachis quasivespa</i>				Mungerebar Limestone	O'Hara Shale	Boshy Formation	Skewthorpe Formation	
	<i>Erediaspis eretes</i>								
Boomerangian	<i>Lejopyge laevigata</i>				Steamboat Sandstone	Selwyn Range Limestone	Morden Formation	Hart Spring Sandstone	Edlin Formation
	III	Cleland Sandstone	Petermann Sandstone		Arthur Creek Formation	Devoncourt Limestone			
	II				Quila Formation	Roaring Silstone			
	I								

FIGURE 4. Correlation of Cambrian successions in the Amadeus, Bonaparte, Georgina and Warburton Basins, in addition to western New South Wales and Antarctica. Based on data presented by Shergold (1986), Shergold et al. (1991) and herein for the Amadeus Basin; Gatehouse (1986) for the Warburton Basin; Öpik (1967), Shergold et al. (1985), Laurie (2012) and Smith et al. (2013) for the Georgina Basin; Wang et al. (1989) for western New South Wales; Shergold et al. (2007) for the Bonaparte Basin and Cooper et al. (1976), Shergold et al. (1976), Cooper et al. (1983), Cooper et al. (1990), Cooper et al. (1996), Jago and Cooper (2005), Bentley et al. (2009) and Jago et al. (2011) for Antarctica.

International correlations using the trilobite species from the Goyder Formation are largely with Antarctica. *Henadoparia integra* occurs with *G. stolidotus* in the uppermost beds of the Spurs Formation near Carryer Glacier (Jago & Cooper 2005), and it potentially ranges down into the *A. quasivespa* Zone (cf. Bentley et al. 2009). Other links to Antarctica are through generic associations including *Liostracina* Monke, 1903, *Paraacidaspis* Poletaeva, 1960 (under *Coosia*? sp. 1 and 2 and *Nganasanella*? sp.) and *Proceratopyge* Wallerius, 1895 (Cooper et al. 1996; Jago & Cooper 2005; Bentley et al. 2009). The Goyder Formation also shows similar generic and family-level associations to *G. stolidotus* Zone faunas on other continents along the Asia-Australia margin of Gondwana at lower palaeolatitudes (Brock et al. 2000). In particular, the North and South China blocks have almost all of the genera reported from the Goyder Formation, with the exception of *Biaverta* Öpik, 1967 and *Polycyrtaspis* Öpik, 1967 (Peng et al. 2004a,b; Zhu 2008; Yuan et al. 2012). This similarity

would be expected given the large eustatic transgressive event that peaked during *G. stolidotus* Zone Chron, allowing widespread faunal exchange to other parts of the Cambrian world (Hally & Paterson 2014).

Systematics

Morphological terminology follows Whittington & Kelly (1997). Photographed specimens have been stained with black, water-based acrylic paint or Indian ink and then coated with ammonium chloride. All described specimens are provided with CPC numbers and are held at the Commonwealth Palaeontological Collection (prefix CPC), Geoscience Australia, Canberra. Stratigraphic ranges for all taxa are given in terms of true thickness above the base of the Goyder Formation at Ross River Gorge.

Class Uncertain

Order Agnostida Salter, 1864

Family Agnostidae M'Coy, 1849

Subfamily Ammagnostinae Öpik, 1967

***Ammagnostus* Öpik, 1967**

Type species. *Ammagnostus psammius* Öpik, 1967.

Discussion. For comprehensive discussion of the genus, see Peng & Robison (2000, p. 25).

***Ammagnostus antarcticus* Bentley, Jago & Cooper, 2009**

Fig. 5

?1967 *Agnostoglossa bassa*; Öpik, p. 146, pl. 60, figs 6–14, text-fig. 44.

?1989 *Ammagnostus* sp. indet.; Wang, Mills, Webby & Shergold, p. 111, fig. 4A–D.

2009 *Ammagnostus antarcticus*; Bentley, Jago & Cooper, p. 171, 172, fig. 4A–I.

Holotype. (Original designation) CPC5878, pygidium from the Mindyallan Mungerebar Limestone, Loc. G150.

Other Material. Nineteen cephalons and eight pygidia figured, CPC42177–CPC42203.

Twenty-six cephalons and eleven pygidia not figured (mostly fragments).

Description. Cephalon and pygidium each attaining about 2.6 mm in length; nonscrobiculate; surface smooth. Cephalon subquadrate in outline, about 94% as long as wide, nonspinose, moderately convex; border reasonably wide (sag., exsag.), flattened; border furrow well developed; preglabellar median furrow faintly developed or absent. Glabella 70 to 73% (mean 71%, $n = 4$) as long (sag.) as cephalon. Small anterior lobe clearly defined, semioval in shape, obtusely angular anteriorly, occupying 29 to 30% (mean 30%, $n = 4$) of glabellar length. F3 transglabellar furrow deeply incised, strongly bowed rearward in a V-shape. Posterior glabellar lobe wider (tr.) than anterior lobe, parallel sided with slight taper, convexity similar between anterior and posterior lobe. F2 furrows at glabellar mid-length (sag.), moderately developed as distinct notches, gently directed anteriorly for a short distance. F1 furrows effaced. Glabellar node indistinct, located slightly posteriorly of F2 furrows; basal lobes very small, subtriangular in outline.

Pygidium rounded to weakly quadrate in outline, 90% as long as wide, moderately convex, with short (exsag.) posterolateral spines, situated inline with widest point in pygidial axis; border flattened, very wide (sag., exsag.) and narrows distinctly toward anterior; border furrow moderately deep and wide (sag., exsag.). Axis wide (tr.) and long (sag., exsag.), intersecting posterior border furrow; about 64 to 70% (mean 67%, $n = 5$) as wide as long and

occupying 73% of pygidial length (sag.); slightly constricted across M2 and expanding to become wider after F2; posteriorly rounded to obtusely rounded and wide (tr.), moderately convex. F1 and F2 furrows effaced. M1 lobe very broad (tr.), lateral margins slightly convex. M2 lobe only distinguished from M1 by constriction. Axial node well developed, of moderate size, crossing slightly over onto posteroaxis. Posteroaxis occupying about 58 to 63% (mean 60%, $n = 3$) of axial length, with maximum width slightly posterior of posteroaxis mid-length. Small secondary axial node developed on some specimens, located a short distance posterior to the maximum width of the posteroaxis.

Hypostome and thorax unknown.

Discussion. The larger cephalon and pygidia from the Goyder Formation most closely resemble those of *Ammagnostus antarcticus* Bentley, Jago & Cooper, 2009 described from the Mindyallan-equivalent Spurs Formation in Antarctica. Both share a long (sag.) anterior border with a shallow border furrow, a glabella that is approximately 70% the length (sag.) of the cephalon, an F3 that is strongly bowed rearward in a V-shape, an indistinct glabellar node, a pygidium that has a greater width (tr.) than length (sag.), a well developed axial node that encroaches onto the posteroaxis, and a posterior border that is very wide (sag.) with small posterolateral spines. The holotype cephalon of *A. antarcticus* (Bentley *et al.* 2009, fig. 4E) is 8.1 mm in length (sag.), which is well beyond the largest specimen from the Goyder Formation (at 2.6 mm; Fig. 5A). The other cephalon figured by Bentley *et al.* (2009, fig. 4A–C, F) are closer in size to the specimens reported herein. Given the close morphological similarity to *A. antarcticus*, we consider it likely that the Goyder Formation material represents a collection of mostly juvenile specimens or perhaps a geographic variant. Smaller cephalon from the Goyder Formation are reminiscent of *Ammagnostus laiwuensis* (Lorenz, 1906) and *Ammagnostus quadratiformis* (Guo & Luo in Guo *et al.*, 1996)—both of which are synonymous according to Peng & Robison 2000—based on the presence of a shorter (sag.)

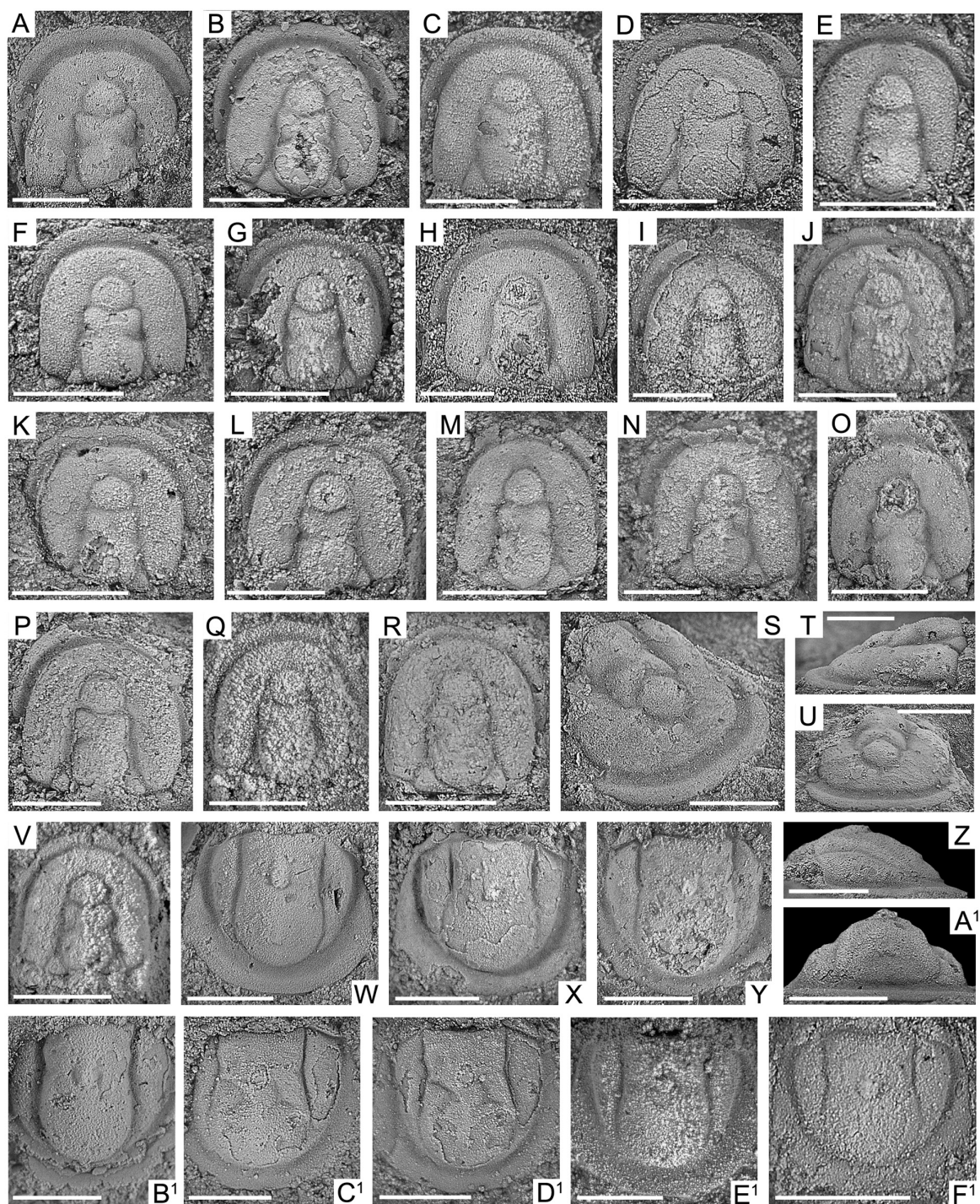


FIGURE 5. *Ammagnostus antarcticus* Bentley, Jago & Cooper 2009 from the Mindyallan Goyder Formation. All specimens come from sample GOY/173.6 in the GOY section. A, S, T, U, CPC42177, partial cephalon; A, dorsal view; S, oblique anterolateral view; T, lateral view; U, anterior view. B, CPC42178, partial cephalon. C, CPC42179, partial cephalon. D, CPC42180, partial cephalon. E, CPC42181, partial cephalon. F, CPC42182, partial cephalon. G, CPC42183, partial cephalon. H, CPC42184, partial cephalon. I, CPC42185, partial cephalon. J, CPC42186, partial cephalon. K, CPC42187, partial cephalon. L, CPC42188, partial cephalon. M, CPC42189, partial cephalon. N, CPC42190, partial cephalon. O, CPC42191, partial cephalon. P, CPC42192, partial cephalon. Q, CPC42193, partial cephalon. R, CPC42194, partial cephalon. V, CPC42195, partial cephalon. W, Z, A1, CPC42196, partial pygidium; W, dorsal view; Z, lateral view; A1, posterior view. X, CPC42197, partial pygidium. Y, CPC42198, partial pygidium. B1, CPC42199, partial pygidium. C1, CPC42200, partial pygidium. D1, CPC42201, partial pygidium. E1, CPC42202, partial pygidium. F1, CPC42203, partial pygidium. All scale bars are 1 mm.

anterior border and a more transverse F3 furrow (e.g. compare Fig. 5K, P with Peng & Robison 2000, fig. 20.1–20.5 and Yuan *et al.* 2012, pl. 2, figs. 7, 12). This suggests that it is difficult to distinguish species of *Ammagnostus* Öpik, 1967 based on small specimens, prompting taxonomic caution with juvenile material.

Ammagnostus bassa (= *Agnostoglossa bassa*) Öpik, 1967 from the Mindyallan Mungerebar Limestone of the Georgina Basin resembles the Goyder Formation material in sharing a moderately long (sag.) anterior border, an F3 that is slightly bowed rearward, an indistinct glabellar node, and a pygidium with a posterior border that is relatively long (sag.). However, the coarsely silicified material of *A. bassa* makes it difficult to ascertain if *A. antarcticus* is synonymous.

Ammagnostus sp. indet. from the Mindyallan Boshy Formation of NSW (Wang *et al.* 1989) also resembles *A. antarcticus* in having a posterior glabellar lobe that is wider (tr.) than the anterior lobe, an F3 that is slightly bowed rearward, an indistinct glabellar node, and a long (sag.) posterior border on the pygidium. The limited amount of material from the Boshy Formation and its poor preservation only allows a tentative assignment to *A. antarcticus*. All other known species of *Ammagnostus* differ from *A. antarcticus* in having a shorter (sag.) anterior border, more transverse (or only slightly posteriorly bowed) F3, and a shorter (sag.) posterior pygidial border.

Occurrence. GOY section horizon 132.7 m (Fig. 3).

Distribution. Goyder Formation, Amadeus Basin, Northern Territory; Spurs Formation, Northern Victoria Land, Antarctica. Possibly the Mungerebar Limestone, Georgina Basin, Northern Territory and Queensland, and the Boshy Formation, Koonenberry Belt, New South Wales. All occurrences are Cambrian Series 3, Guzhangian (Mindyallan) in age.

***Hadragnostus* Öpik, 1967**

Type species. *Hadragnostus las* Öpik, 1967.

Discussion. For a comprehensive discussion of the genus, see Jago & Cooper (2005, p. 663).

We agree with their assessment and consider *Formosagnostus* Ergaliev, 1980

(=*Kunshanagnostus* Qian & Zhou, 1984) to be distinct from *Hadragnostus* Öpik, 1967

(*contra* Peng & Robison 2000, p. 30–32). We also agree with Jago & Cooper (2005, p. 663)

in recognising that *H. las* and *H. modestus* (Lochman in Lochman & Duncan, 1944) are separate species.

***Hadragnostus helixensis* Jago & Cooper, 2005**

Fig. 6

2005 *Hadragnostus helixensis*; Jago & Cooper, p. 665, fig. 2A–L.

Holotype. (Original designation) AR1570, pygidium from the Mindyallan Spurs Formation, Antarctica, Loc. RS 397.

Other Material. Eleven cephalon and nine pygidia figured, CPC42204–CPC42223. Fifty-three cephalon and thirty-six pygidia not figured (mostly fragments).

Description. Cephalon and pygidium each attaining about 3.5 mm in length; nonscrobiculate; surface finely granulose. Cephalon subquadrate to subcircular in outline, about 87% as long as wide, nonspinose, strongly convex; border wide (sag., exsag.), flattened; border furrow well developed, moderately narrow (sag., exsag.); preglabellar median furrow shallow, short (sag.), moderately narrow (tr.) extending along the mid-line from the anterior most portion of axial furrow to the anterior border furrow. Glabella

71 to 75% (mean 72%, n = 5) as long (sag.) as cephalon. Small anterior lobe clearly defined, subpentagonal to semioval in shape, obtusely angular anteriorly, occupying 32 to 38% (mean 36%, n = 6) of glabellar length. F3 transglabellar furrow shallowly incised, bowed moderately rearward; posterior glabellar lobe very weakly tapered, highly convex in its posterior half, less so anteriorly. F2 furrows slightly anterior of glabellar mid-length (sag.), weakly developed as faint notches, gently directed anteriorly for a short distance. F1 furrows effaced to very weakly developed; glabellar node indistinct, located slightly posteriorly of F2 furrows; basal lobes small, subtriangular in outline.

Pygidium rounded to weakly quadrate in outline, 80% as long as wide, strongly convex, with very short (exsag.) posterolateral spines; border flattened, wide (sag., exsag.) and narrows distinctly toward anterior; border furrow deep and wide (sag., exsag.). Axis wide (tr.) and long (sag., exsag.), intersecting posterior border furrow; about 68 to 72% (mean 72%, n = 3) as wide as long and occupying 81 to 88% (mean 86%, n = 3) of pygidial length (sag.); slightly constricted across M2 and expanding to become much wider after F2; posteriorly very rounded and wide (tr.); highly convex. F1 furrow only very faintly developed as weak lateral indentations in axial margin; where visible, furrow is bent strongly forward. M1 lobe very broad (tr.) being 38% of pygidial width, lateral margins convex, converging posteriorly. F2 furrow effaced to weakly developed, indentations in axial margin develop in a few individuals into a faint furrow crossing the axis; where visible, F2 is straight. M2 lobe constricted, margins variably convex and converging posteriorly. Axial node well developed, of moderate size, elongate, crossing slightly over F2. Posteroaxis occupying about 63% of axial length, with maximum width near posteroaxis mid-length. Secondary axial node absent.

Hypostome and thorax unknown.

Discussion. The Goyder Formation specimens are very similar to *Hadragnostus helixensis* Jago & Cooper, 2005 described from the Mindyallan-equivalent Spur Formation in Antarctica. The Goyder material appears to share a wide anterior border furrow, an effaced to

faintly developed median preglabellar furrow, a large anteroglabella, an F3 that is slightly curved posteriorly, a posteroglabella that is raised above the anteroglabella, a wide (tr.)

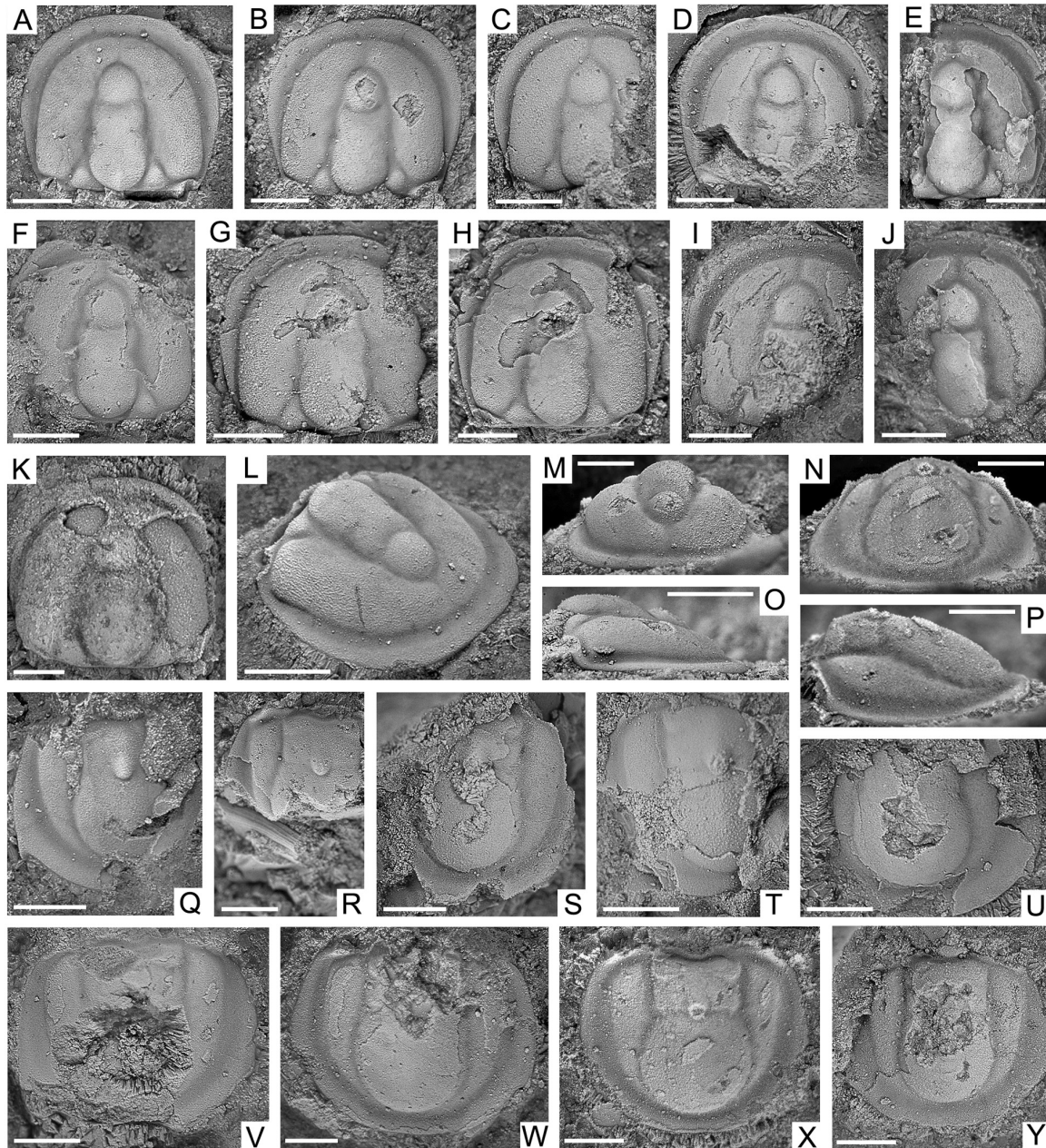


FIGURE 6. *Hadragnostus helixensis* Jago & Cooper, 2005 from the Mindyallan Goyder Formation. All specimens come from sample GOY/97 in the GOY section. A, L, CPC42204, partial cephalon; A, dorsal view; L, oblique anterolateral view. B, M, O, CPC42205, partial cephalon; B, dorsal view; M, anterior view; O, lateral view. C, CPC42206, partial cephalon. D, CPC42207, partial cephalon. E, CPC42208, partial cephalon. F, CPC42209, partial cephalon. G, CPC42210, partial cephalon. H, CPC42211, partial cephalon. I, CPC42212, partial cephalon. J, CPC42213, partial cephalon. K, CPC42214, partial cephalon. N, P, X CPC42215, partial pygidium; N, posterior view; P, lateral view; X, dorsal view. Q, CPC42216, partial pygidium. R, CPC42217, partial pygidium. S, CPC42218, partial pygidium. T, CPC42219, partial pygidium. U, CPC42220, partial pygidium. V, CPC42221, partial pygidium. W, CPC42222, partial pygidium. Y, CPC42223, partial pygidium. All scale bars are 1 mm.

pygidial axis greater than 50% the pygidial width (tr.), an F1 and F2 on the pygidium that are essentially effaced except in exfoliated specimens (e.g. Fig. 6P, X), a pygidial axis constricted (tr.) around M2 and expands (tr.) in the posteroaxis, and a wide posterior border furrow. Only the absence of a node just posterior to F2 on the posteroglabella and the presence of a finely granulose ornament differentiate the Goyder Formation material. Given that the posteroglabellar node and ornament is often difficult to observe in the considerably smaller Antarctic specimens (Jago & Cooper 2005, fig. 2A, B, E, F, H, I), we consider it likely that these differences represent ontogenetic variation. The posteroaxis on the pygidium in the holotype and a second specimen (Jago & Cooper 2005, fig. 2C, D) also appears less rounded posteriorly than those of the Goyder Formation material (Fig. 6Q, S, T, U, W, X, Y). Two smaller pygidia figured by Jago & Cooper (2005, fig. 2G, K) demonstrate that this feature is also variably developed

Hadragnostus helixensis differs from the type species, *H. las* Öpik, 1967, in having a much wider anterior border, a narrower (tr.) median preglabellar furrow, a pygidium that is longer (sag.) than it is wide (tr.), a wider (tr.) posteroaxis, and a much wider posterior border. Likewise, *H. helixensis* differs from *H. edax* Fortey & Rushton, 1976, described from the Guzhangian of Iran, in having a much wider anterior border, a narrow (tr.) pygidium that is longer sagittally, a greater expansion (tr.) after M2 of the posteroaxis, and a much wider posterior border. *Hadragnostus helixensis* is closest to *H. modestus* from the Guzhangian of China (Peng & Robison 2000, p. 32, fig. 23), but the former differs in possessing a moderately wider anterior border, a narrower (tr.) pygidial axis, and a slightly more posteriorly situated pygidial axial node.

Occurrence. GOY section horizons 49.4, 73.2, 83.9 and 91.9 m (Fig. 3). Also found at AS167, AS168, AS178, AS256 and GOYWEST.

Distribution. Goyder Formation, Amadeus Basin, Northern Territory; Spurs Formation, Northern Victoria Land, Antarctica. All occurrences are Cambrian Series 3, Guzhangian (Mindyallan) in age.

Class Trilobita Walch, 1771

Family Leiestegiidae Bradley, 1925

***Trephina* gen. nov.**

Type species. *Trephina ranfordi* gen. et sp. nov.

Etymology. After Trephina Creek, near Ross River Gorge.

Diagnosis. Subtrapezoidal in outline, length:width ratio of 60%. Anterior branches of facial suture (γ – β) diverge at 24°. Glabella truncate, sub-quadrate in outline, width:length ratio of 60% to 68%. Anterior of glabella merges with anterior border, preglabellar furrow effaced; axial furrows are narrow (tr.) and very deep. S1 moderately well defined, bifurcating; S2 faintly defined, bifurcating; S3 relatively faint, S4 variably developed. SO bowed backwards. Anterior cranial border narrow, 5% to 10% of sagittal cranial length. Preocular field 28% of sagittal cranial length. Palpebral lobes 33% of total cranial length, reniform in outline. Palpebral area of fixigena 60% adjacent glabellar width. Posterolateral projections at posterior of palpebral lobe 13% total cranial length. Librigenal genal field 76% of librigenal width. Genal spine blade-like, reaching 41% the length of the librigena. Pygidium up to 5.2 mm long (sag.), moderately convex, length:width ratio of 50% to 51%. Axis occupying about 72% of sagittal length of pygidium. Two well defined axial rings, a third faintly developed. Prosopon comprising closely spaced granules over most of the cephalon, except the posterolateral corners of the glabella, palpebral lobes and librigenal

borders which are covered by small, closely spaced pits. Anterior cranidial border and the librigenal border also covered by well defined terrace ridges. Pygidium covered by small, closely spaced pits, with slightly larger and more widely spaced pits and small granules closer to the axis on the pleural ribs.

Discussion. This new genus has similarities to various leiostrigoids, such as *Pagodia*, *Chuangia* and *Lophoholcus*. Cranidia of the Goyder taxon and some species of *Pagodia* (cf. Öpik 1967, pl. 17, figs 1, 2, 4; Shergold 1975, pl. 29, figs 5, 6; Shergold 1982, pl. 13, figs 1, 2, 4; Zhang & Jell 1987, pl. 94, figs 8, 10, 11, pl. 95, figs 2, 4, 5) possess a truncate, sub-quadrangle glabella that slightly constricts at or anterior of the mid-length, a very short (sag., exsag.) anterior border, an anterior border furrow that is often obscured medially by the encroaching anterior glabellar lobe, and prominent, reniform palpebral lobes. However, the Goyder cranidia mainly differ in showing medial effacement of the anterior border furrow through fusion of the anterior glabellar lobe with the anterior border, and have distinctly incised glabellar furrows (particularly the bifurcated S1). The Goyder pygidia possess a more tapered axis with fewer axial rings compared to most species of *Pagodia*; one exception is *P. (Idamea) baccata* from the Pomegranate Limestone in the Georgina Basin, which appears to have 3–4 axial rings (Öpik 1967, pl. 17, figs 5–7; Shergold 1982, pl. 13, figs 6, 7).

Chuangia also shows some similarities in the cranidial features mentioned above, although species typically have an effaced and more anteriorly tapered glabella (cf. Zhang & Jell 1987, pl. 89, figs 8, 9, pl. 90, figs 1, 3, 5, 12, pl. 91, figs 2, 6, 7, 8, pl. 92, figs 1, 3, 5, 7, 11, 12, pl. 93, figs 1–8; Peng *et al.* 2004a, pl. 20, figs 1–8; Choi *et al.* 2008, figs 15.1, 15.2, 15.4–15.7). Like the Goyder pygidia, some species of *Chuangia* exhibit 3–4 axial rings, and sometimes show a distinct postaxial ridge (e.g., Zhang & Jell 1987, pl. 89, fig. 10, pl. 90, figs 7–10, pl. 91, figs 1, 9; Choi *et al.* 2008, figs 15.8, 15.11). Some pygidia of *Chuangia* also show a similar pitted ornament, at least on exfoliated specimens (e.g., Zhang & Jell 1987, pl.

90, fig. 10, pl. 91, figs 1, 11, pl. 94, figs 1, 2), but generally differ in having weakly developed furrows on the pleural field.

The new genus also shares features with the monotypic genus *Lophoholcus* (type species: *Lophoholcus asper* Öpik, 1967) from the Mindyallan O'Hara Shale in the Georgina Basin. Both have a similar cranidial and glabellar outline, glabellar furrows, and extent of the anterior border. *Lophoholcus* differs from *Trephina* in having an anterior border separated from the glabella by a deep border furrow, lower glabellar convexity, an occipital node, narrower (tr.) palpebral areas, longer (exsag.) and narrower (tr.) palpebral lobes, and a pygidium with a much wider (tr.) axis.

***Trephina ranfordi* gen. et sp. nov.**

Figs 7, 8

Etymology. In honour of L.C. Ranford, for his work on the geology of the Amadeus Basin.

Holotype. CPC42225, cranidium from the Goyder Formation at spot locality AS178 (Fig. 7B, N, O, Q).

Paratypes. One cranidium: CPC42224 (Fig. 7A), from sample GOY/67.0, 49.4 m above the base of the formation. Seven cranidia: CPC42226 (Fig. 7C, L, M); CPC42227 (Fig. 7D); CPC42228 (Fig. 7E); CPC42229 (Fig. 7F); CPC42230 (Fig. 7G); CPC42231 (Fig. 7H); and CPC42232 (Fig. 7I); three librigena: CPC42233 (Fig. 7J); CPC42234 (Fig. 7K); and CPC42235 (Fig. 7P); eight pygidia: CPC42236 (Fig. 8A, H, I); CPC42237 (Fig. 8B); CPC42238 (Fig. 8C); CPC42240 (Fig. 8E); CPC42241 (Fig. 8F); and CPC42242 (Fig. 8G), from sample GOY/97.0, 73.2 m above the base of the formation. One pygidium: CPC42239 (Fig. 7D), from sample GOY/109.2, 83.9 m above the base of the formation.

Material. Nine cranidia, three librigenae and seven pygidia figured, CPC42224–CPC42242. Forty-nine cranidia, twenty-seven librigenae and eleven pygidia not figured (mostly fragments).

Diagnosis. As for genus.

Description. Cephalon semicircular, up to 9 mm long (sag.). Cranidium subtrapezoidal in outline, length:width ratio of 60%, maximum width across posterolateral projections of fixigenae, narrowest point of cranidium at the anterior margin; highly convex (sag., tr.). Anterior margin rounded. Posterior margin straight to slightly bowed anteriorly. Anterior branches of facial suture (γ – β) diverge slightly from one another at 24° , then curve abruptly towards the midline at the β point, slightly behind the border furrow, before they reach the anterior margin. Glabella truncate, sub-quadrate in outline often with near to parallel sides; glabellar anterior merges with anterior border; wide (tr.) and highly convex, with maximum convexity across midwidth, lateral slopes gently convex; width:length ratio of 60% to 68% (mean 65%; $n = 3$), occupying entire cranidial length. Preglabellar furrow effaced, axial furrows are narrow (tr.) and very deep. S1 moderately well defined, intersecting axial furrow approximately in line with the δ point, directed posteromedially for a short distance, before bifurcating with the anterior branch directed anteromedially and the posterior branch continuing posteromedially. S2 faintly developed, intersecting axial furrow just anterior to the γ point, directed transversely for a short distance, before bifurcating with the anterior branch directed slightly anteromedially and the posterior branch slightly posteromedially. S3 very faint, directed anteromedially for a short distance before becoming indistinct. S4 variably developed, but when present is directed anteromedially (more so than S3) for half the width (tr.) of S2 and S3. Short (sag.) occipital ring, becoming slightly narrower abaxially, posterior margin strongly bowed backwards. SO bowed backwards, moderately deep (sag.) and

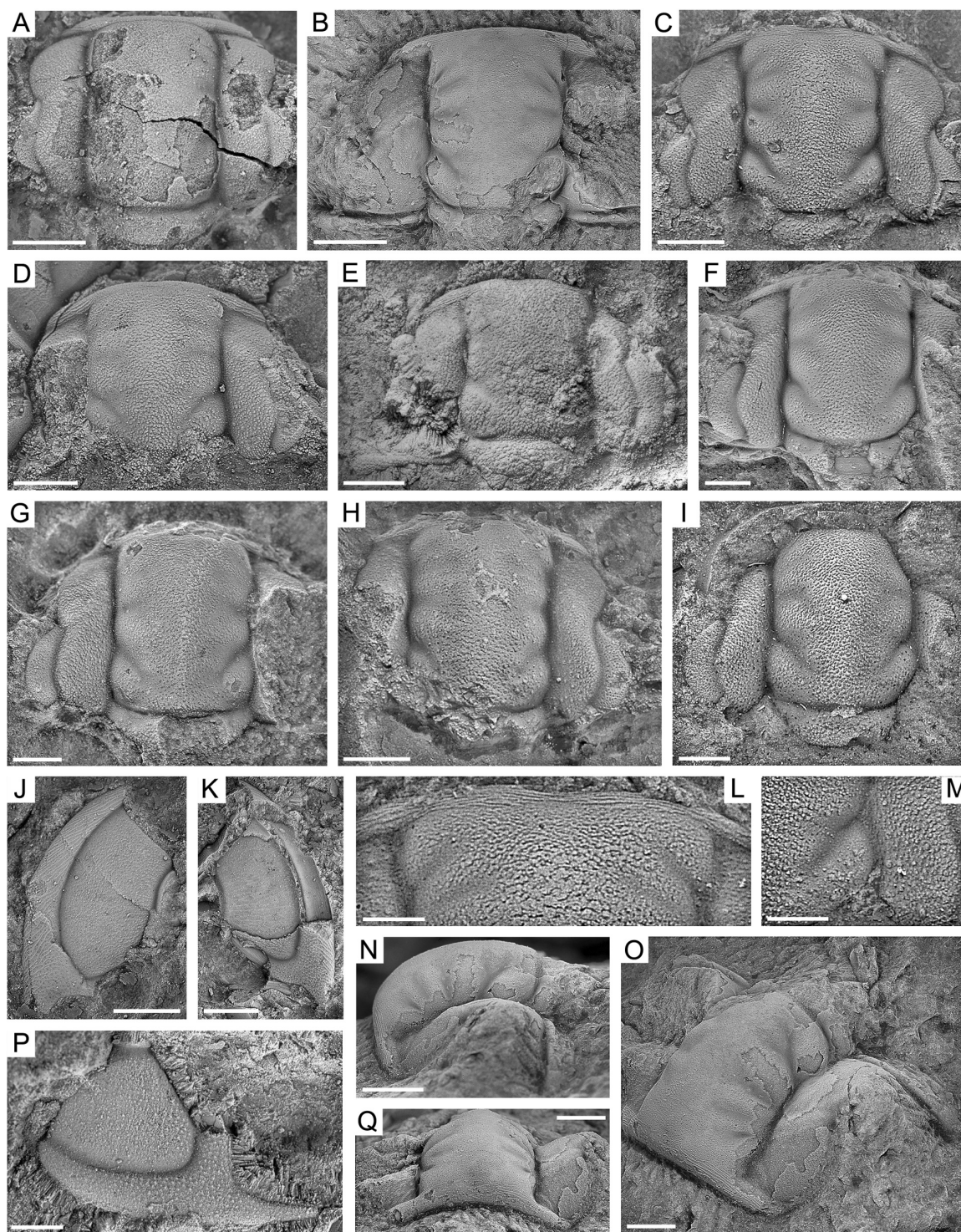


FIGURE 7. *Trephina ranfordi* gen. et sp. nov. from the Mindyallan Goyder Formation. A comes from sample GOY/67 in the GOY section; C–M, P come from sample GOY/97 in the GOY section; and B, N, O, Q come from spot locality AS178. A, paratype, CPC42224, partial cranidium. B, N, O, Q, holotype, CPC42225, partial cranidium; B, dorsal view; N, lateral view; O, oblique anterolateral view; Q, anterior view. C, L, M, paratype, CPC42226, partial cranidium; C, dorsal view; L, close up on fused anterior border; M, close up on ornament. D, paratype, CPC42227, partial cranidium. E, paratype, CPC42228, partial cranidium. F, paratype, CPC42229, partial cranidium. G, paratype, CPC42230, partial cranidium. H, paratype, CPC42231, partial cranidium. I, paratype, CPC42232, partial cranidium. J, paratype, CPC42233, partial librigena. K, paratype, CPC42234, partial librigena. P paratype, CPC42235, lateral view of partial librigena. All scale bars are 1 mm, except B, J, K, N, Q = 2 mm, and L, M = 0.5 mm.

deepening abaxially. Anterior cranial border narrow (sag., exsag.) and convex, occupying about 5% to 10% (mean 8%; n = 4) of sagittal cranial length, narrowing abaxially, obscured medially by fusion with glabella. Anterior border furrow deep and narrow (sag., exsag.), except where obscured by glabella. Preocular field slightly convex, moderately downsloping toward the anterior border furrow, 28% of sagittal cranial length. Palpebral lobes wide (tr.), long (exsag.), approximately 33% of total cranial length, reniform in outline, defined by a narrow (tr.) palpebral, anterior tip situated opposite the mid-point of L2, posterior tip situated slightly anterior to SO in smaller specimens and slightly posterior to SO in larger specimens. Eye ridge very weakly defined on external surface, better defined on exfoliated surfaces, extending posterolaterally from axial furrow opposite L3 in an almost straight line towards the anterior tip of palpebral lobe. Palpebral area of fixigena slightly convex, maximum width (tr.) is 60% adjacent glabellar width. Postocular area short (exsag.) and strongly downsloping toward the posterior border furrow. Posterolateral projections of fixigena strongly downsloping in a similar manner to the postocular area, maximum length (exsag.) at posterior of palpebral lobe 13% total cranial length (sag.). Posterior border narrow (exsag.), separated for the most part from fixigenal field by very deep, moderately narrow (exsag.) border furrow.

Librigena up to 9 mm in length excluding spine. Lateral margin, including that of genal spine, evenly curved. Posterior margin curved distally. Genal field subtrapeziform, 76% of librigenal width (tr.), moderately convex. Lateral border very well defined, gradually becoming wider (tr.) towards genal angle. Lateral and posterior border furrows narrow and deep; furrows coalesce in an even curve. Distinct, short eye socle present, separated from genal field by wide eye socle furrow. Genal spine blade-like, reaching approximately 41% the length of the librigena. Doublure approximately the same width (tr.) as the lateral border.

Pygidium up to 5.2 mm long (sag.), transversely semicircular, moderately convex, length:width ratio of 50% to 51% (mean 50%; n = 3). Anterior margin straight to slightly rounded; anterolateral corners sharply defined and moderately well rounded. Posterior margin strongly rounded. Axis prominent, of moderate width (tr.), strongly tapered posteriorly,

width:length ratio of 86%, occupying about 72% of sagittal length of pygidium. Very narrow (sag.), articulating half-ring, well defined by a shallow, narrow (sag.) inter-ring furrow. Two well defined axial rings, a third faintly developed, separated by shallow, narrow (sag.) inter-

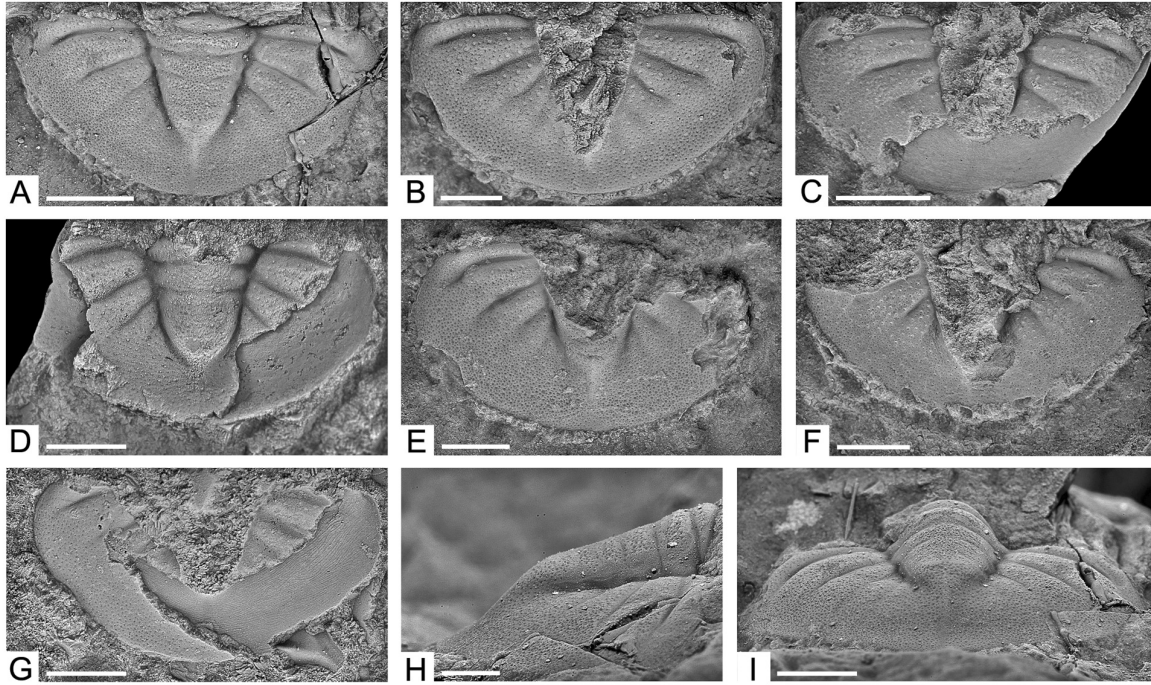


FIGURE 8. *Trephina ranfordi* gen. et sp. nov. from the Mindyallan Goyder Formation. A–C, E–I come from sample GOY/97 in the GOY section; and D comes from sample GOY/109 in the GOY section. A, H, I, paratype, CPC42236, partial pygidium; A, dorsal view; H, lateral view; I, posterior view. B, paratype, CPC42237, partial pygidium. C, paratype, CPC42238, partial pygidium. D, paratype, CPC42239, partial pygidium. E, paratype, CPC42240, partial pygidium. F, paratype, CPC42241, partial pygidium. G, paratype, CPC42242, partial pygidium. All scale bars are 2 mm, except B, H = 1 mm.

ring furrows; furrows only faintly visible medially. Terminal piece of moderate length (sag.), defined posteriorly by abrupt change in slope; small, narrow postaxial ridge present, almost extending to posterior margin. Axial furrows very deep and narrow (tr.). Pleural regions moderately convex, with four narrow, variably developed pleural furrows that become shorter and fainter posteriorly and terminate well before the pygidial margin; furrows become more posterolaterally directed towards the posterior. Border not clearly differentiated by furrow.

Prosopon comprising closely spaced granules over most of the cephalon, except the posterolateral corners of the glabella, palpebral lobes and librigenal borders which are covered by small, closely spaced pits. Anterior cranial border and the librigenal border also covered

by well defined terrace ridges. Pygidium covered by small, closely spaced pits, with slightly larger and more widely spaced pits and small granules closer to the axis on the pleural ribs.

Hypostome, rostral plate and thorax unknown.

Discussion. Association of the different sclerites (cranidia, librigenae and pygidia) was based on their similarity in ornamentation and on their stratigraphic co-occurrence. The cranidia from the Goyder Formation show a vast degree of size variation, with specimens ranging from approximately 2–10 mm in length (sag.). . The smaller specimens appear to show a faint vestigial anterior border furrow at the front of the glabella (Fig. 7A), whilst in larger specimens this furrow is almost completely effaced (Fig. 7C, L). Individuals with a vestigial anterior border furrow also appear to show fainter glabellar furrows and smaller palpebral lobes than those which lack the anterior furrow.

Occurrence. GOY section horizons 49.4, 64.9, 73.2 and 83.9 m (Fig. 3). Also found at AS168, AS178 and GOY WEST.

Distribution. Goyder Formation, Amadeus Basin, Northern Territory. Cambrian Series 3, Guzhangian (Mindyallan) in age.

Family Damesellidae Kobayashi, 1935

***Blackwelderia* Walcott, 1906**

Type species. *Calymmene? sinensis* Bergeron, 1899.

Discussion. This genus has been discussed exhaustively by numerous authors (e.g., Walcott 1913; Kobayashi 1942; Lu *et al.* 1965; Öpik 1967), yet the generic concept is still poorly

understood. Recently, Park *et al.* (2013) suggested this problem stems from a number of species erected on poorly preserved specimens, including the lectotype (Peng *et al.* 2004a), which come from weathered material in North China (Peng *et al.* 2004a; Peng 2007). This incomplete material has led to taxonomic confusion with morphologically similar genera such as *Damesella* Walcott, 1905 and over splitting of taxa in *Blackwelderia* (see Wang *et al.* 1989; Zhu & Wittke 1989; Guo *et al.* 1996 for expansive species lists). We agree with the suggestion of Park *et al.* (2013) that a detailed morphological and taxonomic assessment of *Blackwelderia* is needed to resolve the generic concept. A revision of this magnitude, however, is beyond the scope of this study.

***Blackwelderia repanda* Öpik, 1967**

Figs 9, 10

1967 *Blackwelderia repanda*; Öpik, p. 315–316, pl. 32, fig. 2, pl. 47, fig. 10.

1989 *Blackwelderia* sp. cf. *B. repanda* Öpik; Wang, Mills, Webby & Shergold, p. 114–115, figs. 4R–T, 5A–I.

?2007 *Blackwelderia* sp. cf. *B. repanda* Öpik; Shergold, Laurie & Shergold, p. 31–32, fig. 11A–F.

Holotype. (Original designation) CPC5736, cranidium from the Mindyallan O'Hara Shale, Loc. D29.

Other material. Ten cranidia, three librigenae, two hypostomes and twelve pygidia figured, CPC42243–CPC42268. Twenty-six cranidia, sixty-two librigenae, nine hypostomes and one-hundred-and-two pygidia not figured (mostly fragments).

Description. Cephalon transversely subovate, up to 11 mm long (sag.). Cranidium trapezoidal in outline, length:width ratio approximately 53%, maximum width across posterior limbs of fixigenae, narrowest point of cranidium at the anterior margin; very strongly convex (sag., tr.). Anterior margin straight (tr.). Posterior margin bowed moderately anteriorly. Anterior branches of facial suture (γ - β) are difficult to distinguish. Glabella long (sag.), truncate, trapezoidal in outline, highly convex, with maximum convexity across midwidth, lateral slopes gently convex; width:length ratio of 71% to 74% (mean 72%; $n = 3$), occupying 89% of the cranidial length. Axial furrows are narrow (tr.) and very deep. S1 well defined, deep and narrow (exsag.), intersecting axial furrow approximately in line with the ϵ point, directed slightly posteromedially for a short distance, before bifurcating with the anterior branch traversing a small distance anteromedially before becoming indistinct and the posterior branch continuing posteromedially. S2 and S3 very short; S2 is directed posteromedially, whilst S3 is directed anteromedially. Short (sag.) occipital ring below the remaining glabella, becoming slightly narrower abaxially, posterior margin strongly bowed backwards. SO wide (exsag.), bowed backwards medially, moderately deep (sag.) and deepening abaxially. Anterior cranidial border narrow (sag.), moderately convex, slightly up-turned, occupying about 11% of sagittal cranidial length. Anterior border furrow deep and wide (sag., exsag.), with deeper (possibly apodemal) pits situated at the anterolateral corners of the glabella. Preocular field, highly convex, strongly downsloping toward the anterior border furrow, 21% of sagittal cranidial length. Palpebral lobes 26% of total cranidial length, reniform in outline, defined by a narrow (tr.), shallow palpebral furrow, anterior tip situated opposite S2, posterior tip situated opposite L1. Eye ridge very weakly defined on external surface, slightly more clearly defined on exfoliated surfaces, extending posterolaterally from just anterior to S2 in a slightly anteriorly curved line towards the anterior tip of palpebral lobe. Palpebral area of fixigena slightly convex, downsloping towards the axial furrows, maximum width (tr.) is 92% adjacent glabellar width. Postocular area moderately long (exsag.) and strongly downsloping toward the posterior border furrow. Posterolateral projections of fixigena strongly

downsloping in a similar manner to the postocular area. Posterior border very narrow (exsag), widening abaxially, separated for the most part from fixigenal field by very deep, wide (exsag.) border furrow.

Hypostome of moderate size, 5 mm in length (sag.), highly convex (sag., tr.), anterior margin weakly curved forward, lateral margins slightly curved, posterior margin strongly rounded. Middle body width 4 mm, anterior lobe strongly convex and ovale in outline. Posterior lobe moderately convex, narrow (sag., exsag.), strongly crescentic; anterior wings short (tr.), subtriangular in outline. Middle furrow slit-like and shallow. Lateral and posterior border flat and of relatively consistent width (sag., tr.).

Librigena up to 10 mm in length excluding spine. Lateral margin, including that of genal spine, evenly curved. Posterior margin curved slightly forward distally before intercepting the genal spine. Genal field subtrapeziform, 75% of librigenal width (tr.), moderately convex. Lateral border moderately well defined, 2 mm at the widest point near the posterior border. Lateral and posterior border furrows slightly wide (exsag.), deep, and coalesce in an even curve. Short eye socle present, separated from librigenal field by very wide, shallow eye socle furrow. Genal spine blade-like, reaching approximately the same length as the librigenal field.

Pygidium large, up to 10 mm long (sag.), subtrapezoidal in outline excluding spines, moderately convex, length:width ratio of 47% to 54% (mean 50%; n=4). Anterior margin straight. Posterior margin a broad parabolic curve. Axis prominent, moderately narrow (tr.), moderately tapered posteriorly, width:length ratio of 70%, occupying about 85% of sagittal length of pygidium. Articulating half-ring incompletely preserved, appears to have been very short (sag.). Four well defined axial rings present, separated by deep, wide (sag., exsag.) inter-ring furrows; a faint fifth axial ring present in some specimens, separated from the terminal piece by a very poorly developed inter-ring furrow. Terminal piece short (sag.), defined posteriorly by abrupt change in slope. Axial furrows deep and wide (tr.). Pleural regions slightly convex, with four wide (exsag.), moderately deep pleural furrows. Furrows are in line

with the axial rings; roughly transverse anteriorly, and becoming shorter and more backwardly directed posteriorly, terminating before reaching margin. Pleural ribs highly convex. Very faint, shallow, narrow (exsag.) interpleural furrows on first and second pleural ribs, extending the entire length of the rib. Border of moderate width (sag., exsag.), defined by change in convexity from the pleural region; with seven pairs of spines, first and fifth pair are considerably longer and proximally wider (tr.); anterior spines extending posterolaterally and become progressively more backwards pointing until the sixth and seventh which are directed straight back.

Prosopon consists of granules of various sizes. Glabella, palpebral and postocular areas of fixigena as well as the posterolateral projections are densely covered in small granules with medium-sized granules randomly and equidistantly dispersed in-between. Occipital ring densely covered in small granules. Librigenal field densely covered in small and medium-sized granules with a faint anastomosing network of genal caeca also discernable, librigenal border and spine densely covered with small granules. Pygidial axis, ribs and spines densely covered with small granules, with medium-size granules interspersed on the axial rings and pleural ribs.

Rostral plate and thorax unknown.

Discussion. Limited material of this taxon from the Ross River Gorge at locality NT187 was reported by Öpik (1967, appendix 2, p. 16) as “Damesellinae, fragments”. The specimens from the GOY section and locality 87-008 are remarkably similar to one another, although librigenae from the GOY samples exhibit a slightly shorter genal spine. This minor difference, however, is either ontogenetic (as the 87-008 specimens are slightly larger) or taphonomic (with the GOY specimens preserved in limestone rather than a coarse sandstone). The GOY specimens also show minor variation in the degree of glabellar taper during ontogeny. The glabella of smaller holaspide specimens converges anteriorly at approximately

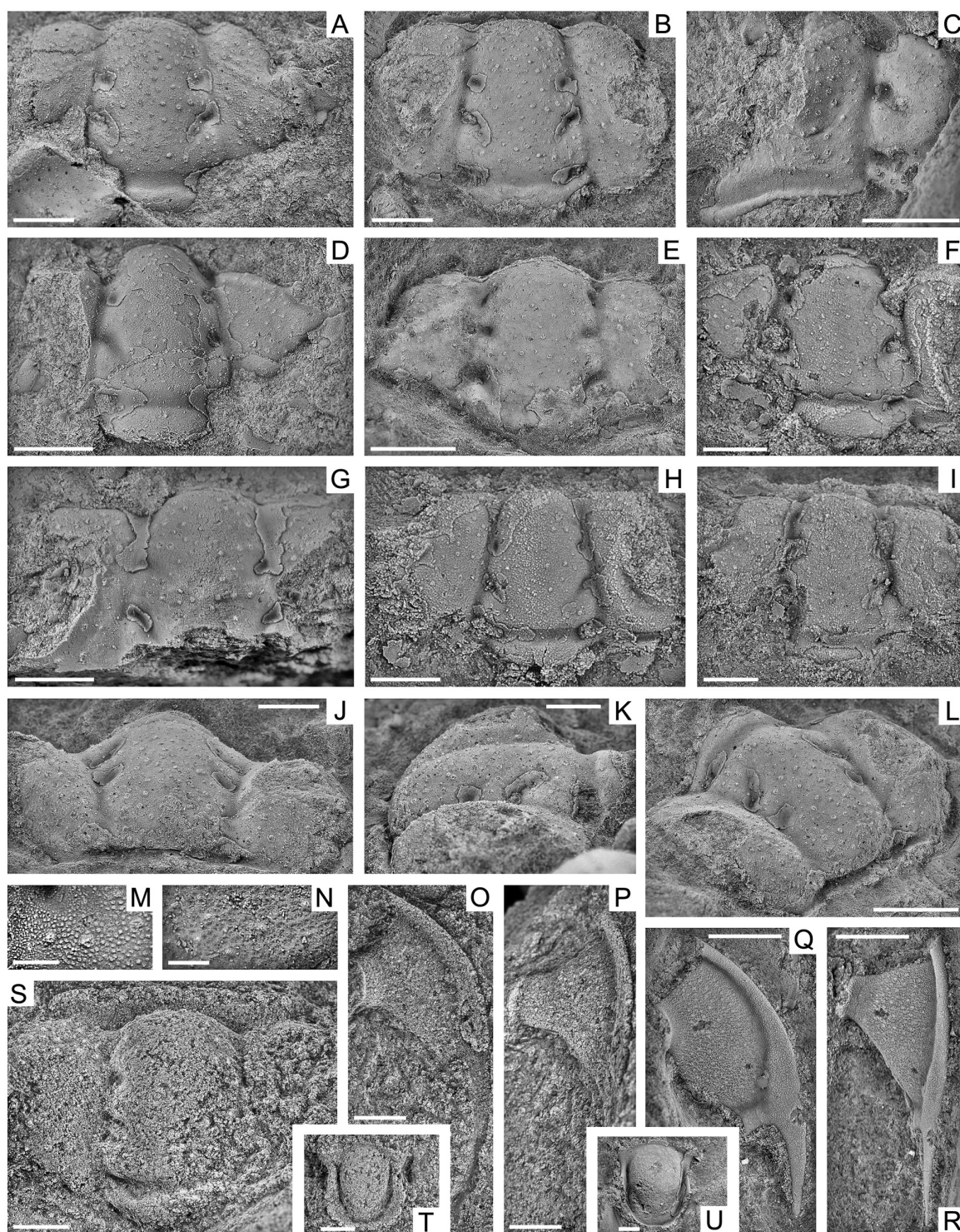


FIGURE 9. *Blackwelderia repanda* Öpik, 1967 from the Mindyallan Goyder Formation. A–N, Q, R, U come from sample GOY/173.6 in the GOY section; and O, P, S, T come from spot locality 85-008. A, B, J, K, L, CPC42243, partial cranidium; A, dorsal view, latex cast; B, dorsal view; J, anterior view; K, lateral view; L, oblique anterolateral view. C, CPC42244, partial cranidium. D, CPC42245, partial cranidium, latex cast. E, CPC42246, partial cranidium. F, CPC42247, partial cranidium. G, CPC42248, partial cranidium. H, CPC42249, partial cranidium. I, CPC42250, partial cranidium. M, CPC42251, close up on cranidium ornament. N, CPC42252, close up on librigena ornament. O, P, CPC42253, partial librigena; O, dorsal view; P, lateral view. Q, R, CPC42254, partial librigena; Q, dorsal view; R, lateral view. S, CPC42255, partial cranidium. T, CPC42256, partial hypostome. U, CPC42257, partial hypostome. All scale bars are 2 mm, except A–C, E, L, Q, R = 4 mm, F, H, I, U = 1 mm, and M, N = 0.5 mm.

20° (Fig. 9D, H and I), whilst larger specimens (Fig. 9A, B and E) have slightly less taper at approximately 12°.

Specimens from the Goyder Formation closely resemble *Blackwelderia repanda* Öpik, 1967 from the Georgina Basin in having a short (sag.) upturned anterior border, a relatively short (sag.) anterior border furrow, a slightly tapered glabella, narrow (tr.) S1 and S2 furrows, faint eye ridges, a pygidium with the first and fifth pair of spines being longer (exsag.) and wider (tr.), as well as a granulose prosopon. The Goyder Formation specimens are also similar to material identified as *Blackwelderia* sp. cf. *B. repanda* by both Wang *et al.* (1989) and Shergold *et al.* (2007) from the Mindyallan of NSW and WA, respectively. Although the specimens from NSW are distorted, they appear to have a short (sag.) anterior border, slightly tapered glabella, narrow (tr.), deep S1 and S2 furrows, faint to absent eye ridges, and a pygidium with the first and fifth pair of spines as described above (Wang *et al.* 1989, fig. 4R–T, 5A–I). Likewise, the WA specimens, although poorly preserved in coarse sandstone, exhibit these same distinctive features (Shergold *et al.* 2007, fig. 11A–F). The WA specimens differ slightly in having a slightly more tapered glabella with a rounder anterior, and fainter pleural furrows on the pygidium. However, this does not fall outside the scope of intraspecific variation seen in the Goyder Formation specimens. The synonymy of the WA material is only queried because of the incomplete and limited material illustrated by Shergold *et al.* (2007).

Blackwelderia repanda can be distinguished from other species attributed to this genus by its shorter (sag.) anterior border and anterior border furrow, a pygidial axis consisting of four (possibly five) axial rings, faint interpleural furrows on the first and second pleural ribs, seven pygidial spines, with the first and fifth being longer (exsag.) and wider (tr.) than the others, as well as a granulose prosopon. *Blackwelderia repanda* appears most similar to *B. gibberina* Öpik, 1967, which has similar cranidial and pygidial features (cf. Öpik 1967, pl. 48, figs 1–3). *Blackwelderia gibberina* differs only in having the first pygidial spines being slightly wider and longer and the fifth spines being narrower and shorter. Öpik (1967) also suggested that *B. gibberina* differed in having an almost horizontal anterior cranidial border

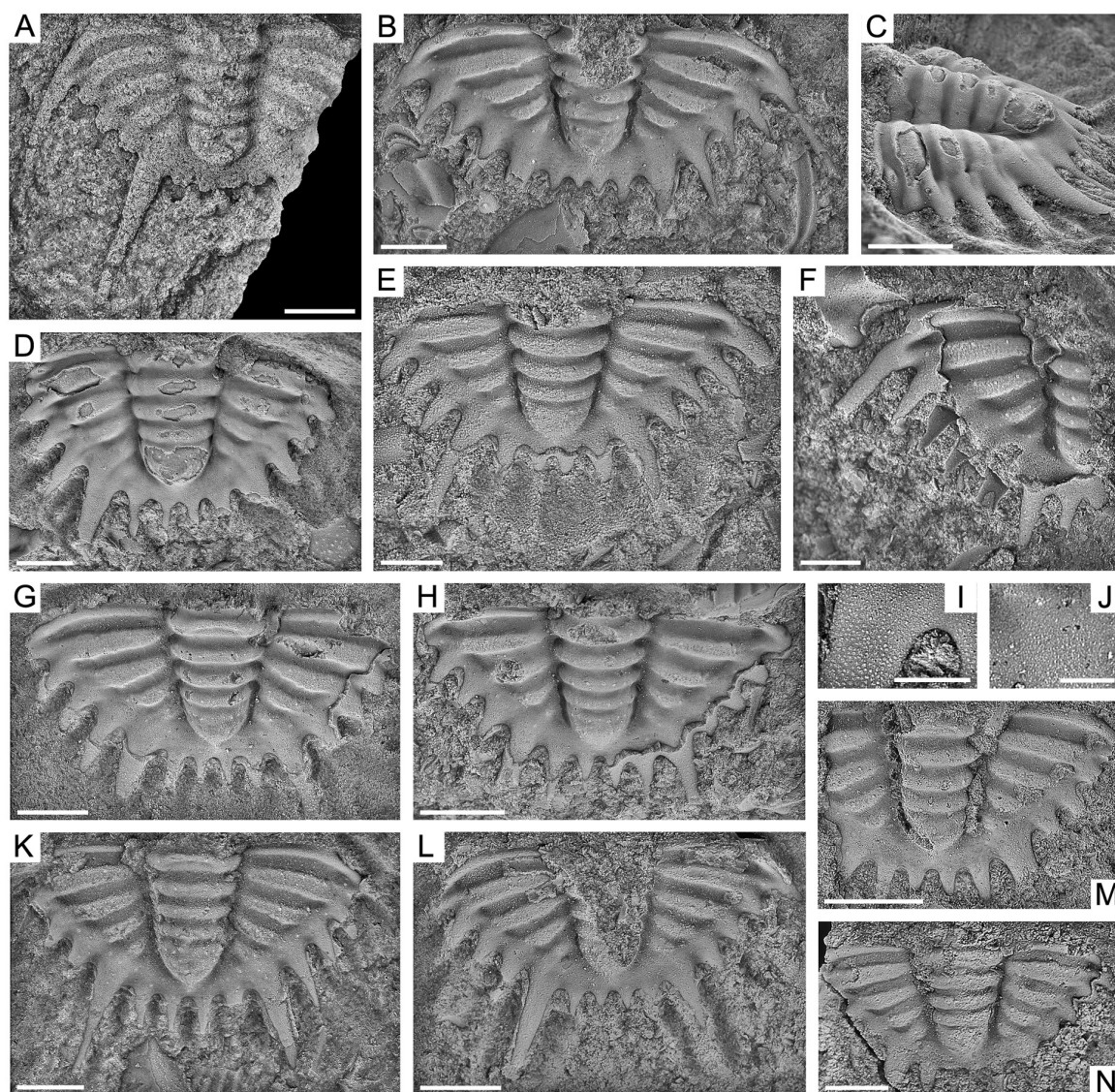


FIGURE 10. *Blackwelderia repanda* Öpik, 1967 from the Mindyallan Goyder Formation. . A comes from spot locality 85-008; and B–N come from GOY/173.6 in the GOY section. A, CPC42258, partial pygidium. B, J, CPC42259, partial pygidium; B, dorsal view; J, close up on pygidium ornament. C, D, I, CPC42260, partial pygidium; C, lateral view; D, dorsal view; I, close up on pygidium spine ornament. E, CPC42261, partial pygidium. F, CPC42262, partial pygidium. G, CPC42263, partial pygidium. H, CPC42264, partial pygidium. K, CPC42265, partial pygidium. L, CPC42266, partial pygidium. M, CPC42267, partial pygidium. N, CPC42268, partial pygidium. All scale bars are 2 mm, except A = 4 mm, E, F, I, N = 1 mm, and J = 0.5 mm.

and a pygidium without interpleural furrows. Both of these features are difficult to discern in Öpik's (1967) figures.

Occurrence. GOY section horizons 73.2, 83.9, 132.7 and 140.7 m (Fig. 3). Also found at 87-008 and GOYWEST.

Distribution. Goyder Formation, Amadeus Basin, Northern Territory; O'Hara Shale, Georgina Basin, Northern Territory and Queensland; Boshy Formation, Koonenberry Belt, New South Wales. Possibly the Skewthorpe Formation, Bonaparte Basin, Western Australia. All occurrences are Cambrian Series 3, Guzhangian (Mindyallan) in age.

***Protaitzeoia* Yang in Yin & Li, 1978**

Type species. *Protaitzeoia yuepingensis* Yang in Yin & Li, 1978.

Discussion. A comprehensive review of this genus, including an exhaustive species list, is given by Peng *et al.* (2004a). The unique morphology of this genus has led to debate about its higher level taxonomic placement. Originally *Protaitzeoia* was assigned to the damesellids (Yang in Yin & Li, 1978), a classification which was accepted by subsequent authors (e.g., Peng 1987; Westrop *et al.* 2008). Recently, Yuan & Yin (2001) transferred the genus to the ordosiids, but Peng *et al.* (2003) disagreed and placed it back in the damesellids. Yuan & Yin (2003) placed *Protaitzeoia* in the cheilocephalids, before Peng *et al.* (2004a) once again returned the genus back to its original assignment. We agree with Peng *et al.* (2004a) and consider *Protaitzeoia* under the family Damesellidae Kobayashi, 1935.

***Protaitzeoia?* sp.**

Fig. 11

Material. Three cranidia figured, CPC42269–CPC42271.

Description. Cranidium trapezoidal in outline, up to 7 mm long (sag.), length:width ratio approximately 55%, maximum width across posterolateral projections of fixigenae, narrowest

point of cranium at the anterior margin; strongly convex (sag., tr.). Anterior margin curved forward (tr.). Posterior margin bowed very slightly anteriorly. Anterior branches of facial suture (γ - β segments) converge very slightly anteriorly at 14° to one another. Glabella long (sag.), truncate, rectangular in outline, highly convex, with maximum convexity across midwidth, lateral slopes gently convex; width:length ratio of 74%, occupying 96% of the cranial length; glabella anterior border defined by anterior border furrow. Axial furrows are very narrow (tr.) and very deep. S1 very well defined, deep and narrow (exsag.), intersecting axial furrow approximately in line with the δ point, directed slightly posteromedially for 31% of the glabellar width, before rapidly shallowing and continuing transversely over the glabella in a shallow furrow until joining with the adjacent side. S2 deep, narrow (exsag.), directed posteromedially and joining with the adjacent side at glabellar mid-point. S3 shallow, narrow (exsag.), short (tr.), directed anteromedially. S4 shallow, narrow (exsag.), very short (tr.), directed anteromedially, more so than S3. Short (sag.) occipital ring above the remaining glabella, becoming very slightly narrower abaxially, posterior margin bowed backwards. SO narrow (sag.), deep abaxially and shallowing slightly medially; bowed slightly backwards abaxially, bowed slightly forward medially. Anterior cranial border of a moderate width (sag., exsag.), becoming narrower in front of glabella; convex, very slightly up-turned, occupying about 5% of sagittal cranial length, occupying about 20% of exsagittal cranial length where the axial furrow contacts the anterior border furrow. Anterior border furrow deep and wide (exsag.), with a narrower (sag.) region where the glabellar anterior intersects the furrow. Preocular field, slightly convex, strongly downsloping toward the anterior border furrow, 8% of sagittal cranial length. Palpebral lobes 24% of total cranial length, width:length ratio of 67%, reniform in outline; defined by a narrow (tr.), very shallow palpebral furrow which depends very slightly posteriorly; anterior tip situated opposite S2, posterior tip half way between the position of S1 and SO. Eye ridge weakly defined, extending posterolaterally from S3 in straight line towards the anterior tip of palpebral lobe. Palpebral area of fixigena very slightly convex, downsloping very slightly towards the axial

furrows, maximum width (tr.) is 46% adjacent glabellar width. Postocular area short (exsag.) downsloping only very slightly towards the posterolateral projections. Posterolateral projections of fixigena long (tr.), narrow (exsag.), strongly downsloping towards lateral corners. Posterior border straight, narrow (exsag.), separated for the most part from fixigenal field by very deep, narrow (exsag.) border furrow.

Prosopon smooth on cranidium.

Hypostome, rostral plate, librigena, thorax and pygidium unknown.

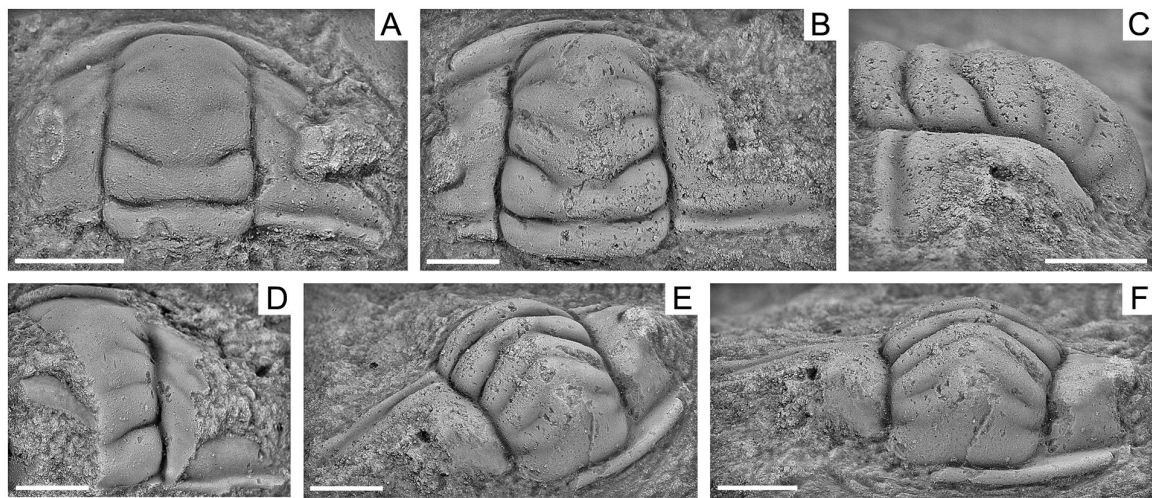


FIGURE 11. *Protaitzehoia?* sp. from the Mindyallan Goyder Formation. All specimens come from spot locality AS168. A, C CPC42269, partial cranidium. B, C, E, F, CPC42270, partial cranidium; B, dorsal view; C, lateral view; E, oblique anterolateral view; F, anterior view. D, CPC42271, partial cranidium. All scale bars are 2 mm.

Discussion. The distinctively long (sag.) subquadrate glabella with four pairs of lateral furrows, relatively small, well developed palpebral lobes located slightly posterior of the cranidial midlength, and an upturned cranidial border that widens abaxially is reminiscent of *Protaitzehoia*. However, the presence of a transglabellar (though medially shallow) S1, an occipital ring without a medial node, a narrow (sag.) SO, a narrow (tr.) palpebral area, posterolateral projections that are directed transversely, and a smooth prosopon differentiates the Goyder Formation specimens from the majority of species currently placed in this genus. The Goyder Formation cranidia resemble those of *Protaitzehoia quadrata* (Resser & Endo in Endo & Resser, 1937) from the Guzhangian Kushan Formation in northeast China, as both have an anterior border of similar dimensions, a subquadrate glabella, and posterolateral

projections that are transverse rather than directed anterolaterally. However, *P. quadrata* differs in possessing a glabella which does not encroach onto the anterior border, shorter glabellar furrows, and wider (tr.) palpebral areas. These differences may warrant separation at the generic level, with the Goyder specimens possibly representing a new genus, but we keep this taxon under open nomenclature until additional specimens, including librigenae and pygidia, are at hand

Occurrence. Only found at AS168 (Fig. 2).

Nomadinis Öpik, 1967

1974 *Fengduia*; Zhu in Lu *et al.*, p. 106.

Type species. *Nomadinis pristinus* Öpik, 1967.

Emended diagnosis. Cranidium outline subquadrate. Glabella truncate, very gently tapered, subquadrate in outline; width:length ratio of 79%, occupying 64% of the cranidial length. S1 well defined, moderately deep and narrow (exsag.). S2 and S3 very faint to completely effaced. Two faint, narrow (tr.), ridges cross preocular field. Faint tropidium extends across cranidium in a broad arc from just behind the midpoint of the γ - β segment, passing in front of the anterior glabellar furrow. Palpebral lobes wide (tr.), long (exsag.), 33% of total cranidial length, sickle-shaped in outline. Palpebral maximum width (tr.) 64% adjacent glabellar width; short (exsag.) baculae, faintly developed in axial furrows. Librigena with narrow (tr.), with faint tropidium extending from behind the midpoint of the γ - β segment to where the posterolateral projection abuts the librigena. . Genal spine flattened, broad-based, blade-like. Pygidium subtriangular in outline, length:width ratio of 50% to 70%. Axis prominent, narrow (tr.), tapered posteriorly, width:length ratio of 60% to 80%, moderately short occupying about

65% to 70% of sagittal length of pygidium. Five faintly defined axial rings present. Pleural regions with five faint, moderately narrow (exsag.), very shallow pleural furrows. Border with seven pairs of broad based spines; first, fifth and seventh pair are slightly longer (exsag.) and wider (tr.).

Discussion. Öpik (1967) originally placed this genus in the Dikelokephalinidae Kobayashi, 1936—now possibly synonymous with the Hungaiidae Raymond, 1924 following Ludvigsen *et al.* 1989, although see Fortey 2011 for an alternative view—based on its similarity to *Dikelocephalus* Owen, 1852 and *Asaphopsis* Mansuy, 1920. Jell & Adrain (2003, p. 412) later placed *Nomadinis* Öpik, 1967 in the Monkaspididae Kobayashi, 1935, but with no supporting evidence. Previous attempts to classify *Nomadinis* have relied on Öpik’s (1967, p. 255, 256) original description, including the associated pygidia that Öpik (1967, pl. 32, figs 6, 7, pl. 33, fig. 3a, b) assigned, since they resembled those of other dikelokephalinids. However, new material from the Goyder Formation demonstrates that Öpik’s (1967) association of sclerites was incorrect. We associate a spiny damesellid-like pygidium with the cranidium of *N. pristinus* based on the similarity in size, equivalent ornamentation, and comparable relative abundance of librigenae and pygidia in the same stratigraphic horizon. This new reconstruction bears a striking resemblance to *Fengduia subcylindrica* Zhu in Lu *et al.*, 1974 from the Guzhangian of China (e.g., Zhu *et al.* 2011, pl. 2, figs 4–20). Both share a poorly defined anterior border, a subquadrate glabella, a well defined S1 furrow that is positioned approximately inline with the δ point, a much fainter S2 furrow, a pair of short (exsag.) bacculae adjacent to L1, a faint pair of facial lines, a faint tropidium, large palpebral lobes with their anterior tips situated adjacent to S2, thick eye ridges, a palpebral area with a width (tr.) approximately 60% the adjacent glabellar width, a pygidium with a subtriangular outline, five axial rings with a short terminal piece, five pleural furrows, and a posterior border with seven pairs of broad based spines, with the first, fifth and seventh pairs longer and wider than

the other spines. Given these close similarities we consider *Fengduia* Zhu in Lu *et al.*, 1974 a junior subjective synonym of *Nomadinis*.

In addition to the type species, *Nomadinis pristinus* Öpik, 1967 from the Mindyallan of both the Amadeus and Georgina basins, and *N. subcylindrica* (Zhu in Lu *et al.*, 1974) and *N. dingzhaiensis* (Sun in Zhou *et al.* 1977) from the Guzhangian of China, another taxon from the Goyder Formation referred to herein as *Nomadinis* cf. *pristinus* (described below) might represent a new species, but coarse preservation in sandstone inhibits a detailed comparison. A species recorded as *Nomadinis*? sp. (figured but not described) from the Guzhangian Kushan (Gushan) Formation of North China (Ng *et al.* 2014) more closely resembles *Geminiclavula* Peng, Babcock & Lin, 2004a in possessing a long (sag.) prelabellar field, a pair of transverse swellings on the preocular areas, and large, wide (tr.) palpebral lobes. Hence, we do not include it in the current species list. The only other potential occurrence of *Nomadinis* is that of a single pygidium reported by Fortey (1994, p. 39, fig. 6A) as *Dipyrgotes* sp. from the Guzhangian Andam Formation of the Sultanate of Oman. This pygidium has the same subtriangular outline, five pleural furrows, and a posterior border with seven pairs of broad based spines, with the first, fifth and seventh pairs being slightly longer (exsag.) and wider (tr.). Yet poor preservation and lack of cranidial material prevents a definitive assignment.

***Nomadinis pristinus* Öpik, 1967**

Figs 12, 13

1967 *Nomadinis pristinus*; Öpik, p. 255–256, text-fig. 87, pl. 32, fig. 5, pl. 33, fig. 2, *non* pl. 32, figs 6, 7, pl. 33, fig. 3.

Holotype. (Original designation) CPC5612, cranidium from the Mindyallan O’Hara Shale, Loc. D29.

Other material. Eight cranidia, two librigenae, two hypostomes and thirteen pygidia figured, CPC42272–CPC42297. Twenty seven cranidia, one-hundred-and-six librigenae, five hypostomes and one-hundred-and-seventy-three pygidia not figured (mostly fragments).

Description. Cephalon semicircular, up to 8 mm long (sag.). Cranidium outline subquadrate, maximum width across posterolateral projections of fixigenae based on librigenal outline, narrowest point at anterior tip of palpebral lobes (γ – γ); moderately convex (sag., tr.). Anterior very slightly rounded. Posterior margin incompletely, appears to have been straight. Anterior branches of facial suture (γ – β segments) diverge strongly from one another at 70°, then curve abruptly towards the midline at the β point before they reach the anterior margin. Glabella truncate, very gently tapered, subquadrate in outline; convex, with maximum convexity across midwidth, lateral slopes convex; width:length ratio of 79%, occupying 64% of the cranidial length; anterior glabellar furrow and axial furrows are narrow (sag., exsag., tr.) and deep. Lateral glabellar furrows abaxial extremities do not intersect axial furrow. S1 well defined, moderately deep and narrow (exsag.); positioned approximately in line with the δ point, directed strongly posteromedially for a short distance, before becoming indistinct. S2 very faint, directed posteromedially for the same distance as S1. S3 very faint to completely effaced, directed anteromedially. Occipital ring short (sag.), above the remaining glabella, becoming slightly wider (exsag.) abaxially; posterior margin slightly bowed backwards; surmounted by a small medial node near the posterior margin. SO deep, narrow (sag.), slightly bowed backwards medially; pair of short (tr.) posterior deflections located approximately inline with the anterior lateral corner of the glabella. Anterior cranidial border not very well defined, lacking an anterior border furrow. Preocular and preglabellar field moderately concave, downsloping toward the anterior border; elongate, approximately 35% of sagittal cranidial length. Two faint, narrow (tr.), facial lines; extending from anterior of the

eye ridges towards the β point before disappearing near tropidium. Faint tropidium extends across cranidium in a broad arc from just behind the midpoint of the γ - β segment, passing in

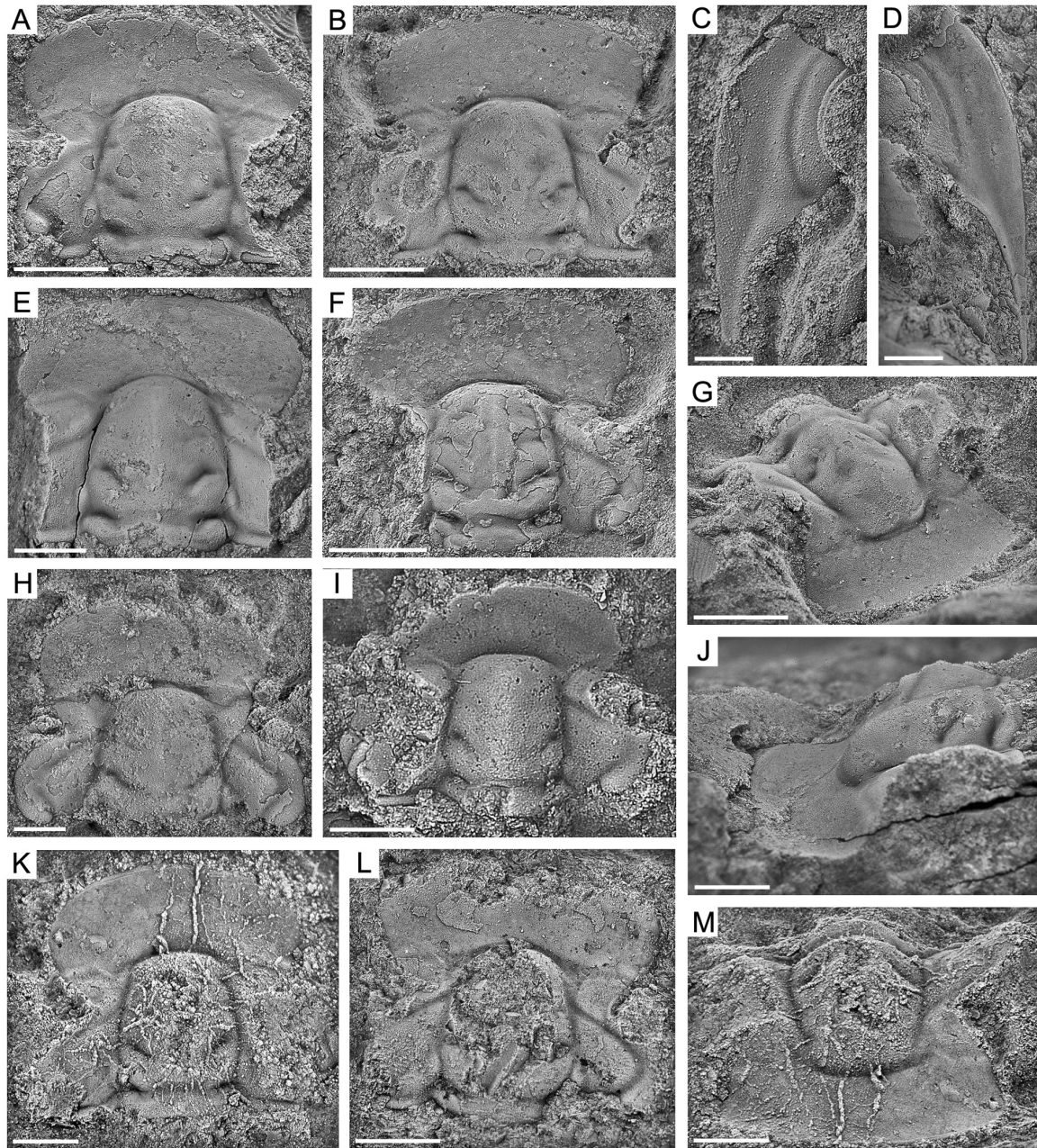


FIGURE 12. *Nomadinis pristinus* Öpik, 1967 from the Mindyallan Goyder Formation. All specimens come from sample GOY/173.6 in the GOY section. A, G, CPC42272, partial cranidium; A, dorsal view; G, oblique anterolateral view. B, CPC42273, partial cranidium. C, CPC42274, partial librigena. D, CPC42275, partial librigena. E, J, CPC42276, partial cranidium; E, dorsal view; J, lateral view. F, CPC42277, partial cranidium. H, CPC42278, partial cranidium. I, CPC42279, partial cranidium. K, M, CPC42280, partial cranidium; K, dorsal view; M, anterior view. L, CPC42281, partial cranidium. All scale bars are 2 mm, except C, D, H, I, K, N = 1 mm

front of the anterior glabellar furrow. Palpebral lobes wide (tr.), long (exsag.), 33% of total cranidial length, sickle-shaped in outline, defined by a narrow (tr.), shallow palpebral furrow;

anterior tip situated approximately in line with S2, posterior tip approximately in line with SO. Eye ridge well defined, extending posterolaterally from the axial furrow just anterior to S2 in a straight line towards the anterior tip of palpebral lobe. Palpebral area of fixigena strongly downsloping towards the axial furrows, maximum width (tr.) is 64% the adjacent glabellar width; short (exsag.) bacculae, faintly developed in axial furrows, anterior tip situated just behind S1, posterior tip opposite anterior of occipital ring. Postocular area very short (exsag.) and roughly horizontal. Posterolateral projections of fixigena incompletely preserved. Posterior border narrow (exsag.), separated for the most part from fixigenal field by deep, very narrow (exsag.) border furrow.

Hypostome small, 3 mm in length (sag.), subtrapezoidal in outline, highly convex (sag., tr.), anterior margin weakly curved forward; lateral margins slightly extended to form wing-like, triangular projections, approximately 1 mm wide (tr.); posterior margin moderately rounded. Length:width ratio of 86%. Middle body with 2 mm, ovale shape anterior lobe and strongly crescentic posterior lobe of moderate width (sag., exsag.); anterior wings short (tr.), subtriangular in outline. Middle furrow narrow (tr.) abaxially, becoming wider medially; shallow, slit-like and directed steeply posteromedially.

Librigena up to 8 mm in length, excluding spine. Lateral margin, including that of genal spine, evenly curved. Posterior margin curved distally. Genal field subtrapeziform, moderately concave. Lateral border poorly defined. Lateral furrow formed where the wide (exsag.), shallow posterior border furrow and maximum concavity of the genal field coalesce, furrow becomes narrower posteriorly and continues onto genal spines for a short distance. Faint tropidium continues from fixigena onto librigena, extending in a broad arc from just behind the midpoint of the γ - β segment to slightly anterior of where the posterolateral projection abuts the librigena. Genal spine flattened, broad-based, blade-like, reaching approximately 91% the length of the librigena.

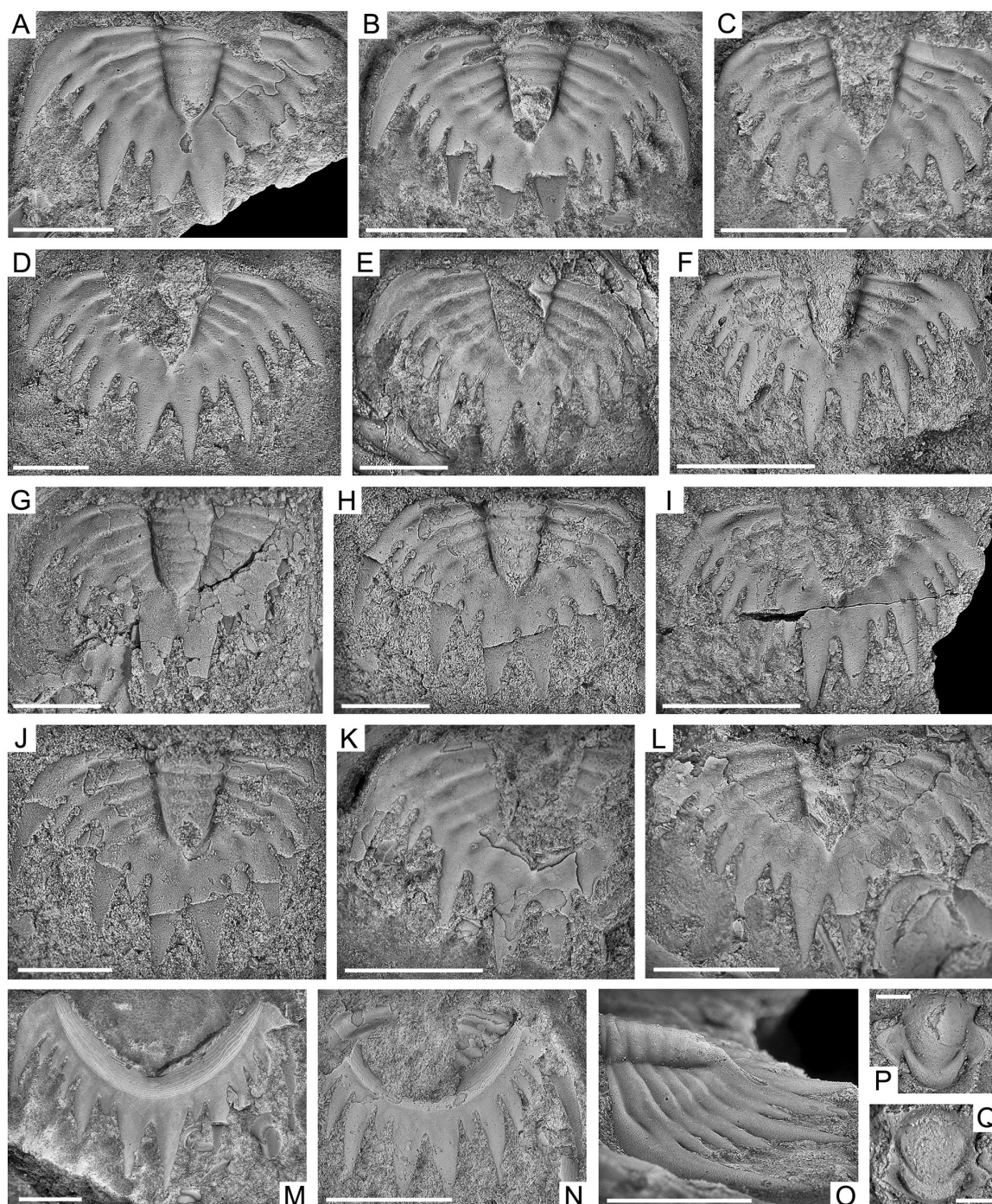


FIGURE 13. *Nomadinis pristinus* Öpik, 1967 from the Mindyallan Goyder Formation. All specimens come from sample GOY/173.6 in the GOY section. A, O, CPC42282, partial pygidium; A, dorsal view; O, lateral view. B, CPC42283, partial pygidium. C, CPC42284, partial pygidium. D, CPC42285, partial pygidium. E, CPC42286, partial pygidium. F, CPC42287, partial pygidium. G, CPC42288, partial pygidium. H, CPC42289, partial pygidium. I, CPC42290, partial pygidium. J, CPC42291, partial pygidium. K, CPC42292, partial pygidium. L, CPC42293, partial pygidium. M, CPC42294, partial pygidium interior showing doublure. N, CPC42295, partial pygidium interior showing doublure. P, CPC42296, partial hypostome. Q, CPC42297, partial hypostome. All scale bars are 4 mm, except D, G, H, J = 2 mm, and P, Q = 1 mm.

Pygidium up to 7 mm long (sag.), subtriangular in outline excluding spines, slightly convex, length:width ratio of 53% to 63% (mean 58%; n = 5). Anterior margin straight.

Posterior margin parabolic. Axis prominent, narrow (tr.), tapered posteriorly, width:length ratio of 72% to 76% (mean 75; n = 4), moderately short occupying about 69% of sagittal length of pygidium. Very narrow (sag.), articulating half-ring, faintly defined by a shallow, narrow (sag.) inter-ring furrow. Five faintly defined axial rings present, separated by very faint, shallow, narrow (sag., exsag.) inter-ring furrows. Terminal piece small, defined posteriorly by abrupt change in slope, small, faint, postaxial ridge present. Axial furrows moderately deep and narrow (tr.), fading out near postaxial ridge. Pleural regions convex; with five faint, moderately narrow (exsag.), very shallow pleural furrows, first furrow roughly transverse, subsequent furrows directed progressively more posterolaterally; furrows terminate at the border after becoming narrower (exsag.) and shallower. Border vague defined by change in slope; with seven pairs of broad based spines; first, fourth, fifth and seventh pair are slightly longer (exsag.) and wider (tr.); first and seventh pair are six and four times longer (exsag.) respectively and three times wider (tr.) than the remaining spines, fourth pair is one and a half times longer (exsag.) and one and a half times wider (tr.) than remaining spines, fifth pair is three times longer (exsag.) and three time wider (tr.) than remaining spines; spines directed posterolaterally, with a slight posterior curve, except for the seventh pair which are directed straight posteriorly. Doublure is approximately 32% the sagittal length of the pygidium, pygidial spines fused at the based extends doublure margin.

Prosopon smooth over most sclerites. Anterior border of cranidium, hypostome lateral margins, lateral borders of librigena and doublure of pygidial border (excluding spines) covered with fine terrace ridges.

Discussion. Cranidia, librigenae and pygidia of this taxon are quite common in the upper sandy limestone beds of the GOY section. The Goyder Formation cranidia are almost identical to those of *Nomadinis pristinus* Öpik, 1967 from the Mindyallan O'Hara Shale of the Georgina Basin in possessing the following: an elongate (sag.), slightly concave frontal area; faint tropidium extending across the cranidium from just behind the midpoint of the γ - β

segment; short (sag.) occipital ring with the posterior margin slightly bowed backwards and surmounted by a small medial node near the posterior margin; deep, narrow (sag.) SO furrow that is slightly bowed backwards medially and with a pair of short (tr.) posterior deflections; wide (tr.), well defined and sickle-shaped palpebral lobes; moderately well defined eye ridges; and wide palpebral areas.

There are a number of small, but significant differences separating *N. pristinus* from *N. subcylindrica*. In *N. pristinus*, these include a longer (sag.) frontal area, shallower axial furrows, a shallower anterior glabellar furrow, less prominent eye ridges, a shorter (sag.) glabella that is more tapered, shallower glabellar furrows, more prominent bacculae, fainter pygidial axial and pleural furrows, as well as a shorter second pair of pygidial spines (compare Figs 12, 13 with Zhu in Lu *et al.* 1974, pl. 42, figs 5–9 and Zhu *et al.* 2011, pl. 2, figs 4–20).

The hypostome associated with the Goyder Formation specimens resembles those originally assigned to *Palaeadotes* by Öpik (1967) from the Mindyallan of the Georgina Basin (compare Fig. 13P, Q with Öpik 1967, pl. 50, fig. 3, pl. 51, fig. 1, 2, 4), which Peng *et al.* (2004a) suggested may actually represent *Paradamesella* Yang in Zhou *et al.*, 1977. Both the Goyder Formation and Georgina Basin material have a similar outline, with large posterior wings. This not only supports a damesellid affinity for *Nomadinis*, but reaffirms the new pygidial association for *N. pristinus*.

Occurrence. GOY section horizons 132.7 and 140.7 m (Fig. 3).

Distribution. Goyder Formation, Amadeus Basin, Northern Territory. Georgina Limestone and O'Hara Shale, Georgina Basin, Northern Territory and Queensland. All occurrences are Cambrian Series 3, Guzhangian (Mindyallan) in age.

Nomadinis cf. *pristinus* Öpik, 1967

Fig. 14

Other material. Seven cranidia figured, CPC42298–CPC42307. Sixteen cranidia not figured (mostly fragments).

Description. Cranidium up to 10 mm long (sag.), outline subrectangular, maximum width across posterolateral projections of fixigenae, narrowest point at anterior tip of palpebral lobes (γ – γ); moderately convex (sag., tr.). Anterior very slightly rounded. Posterior slightly bowed anteriorly. Anterior branches of facial suture (γ – β segments) diverge strongly from one another at 98° , then curve abruptly towards the midline at the β point before they reach the anterior margin. Glabella truncate, very gently tapered, subquadrate in outline; convex, with maximum convexity across midwidth, lateral slopes convex; width:length ratio of 74%, occupying 79% of the cranidial length; anterior glabellar furrow and axial furrows are narrow (sag., exsag., tr.) and deep. Lateral glabellar furrows abaxial extremities do not intersect axial furrow. S1 well defined, moderately deep and narrow (exsag.); abaxially positioned just anterior of the δ point, directed strongly posteromedially for a short distance, before becoming indistinct. S2 very faint, directed transversely for a short distance. S3 very faint to completely effaced. Occipital ring of moderate length (sag.), above the remaining glabella, becoming slightly narrower abaxially, posterior margin strongly bowed backwards. SO of moderate depth, becoming deeper abaxially; narrow (sag.); slightly bowed backwards. Anterior cranidial border not very well defined, lacking an anterior border furrow. Preocular and preglabellar field slightly concave, downsloping toward the anterior border; of modest length, 21% of sagittal cranidial length. Two faint, narrow (tr.), facial lines; extending from anterior of the eye ridges towards the β point before disappearing near tropidium. Very faint tropidium extends across cranidium in a very broad arc from the midpoint of the γ – β segment, passing in front of the anterior glabellar furrow where it becomes almost indistinguishable. Palpebral

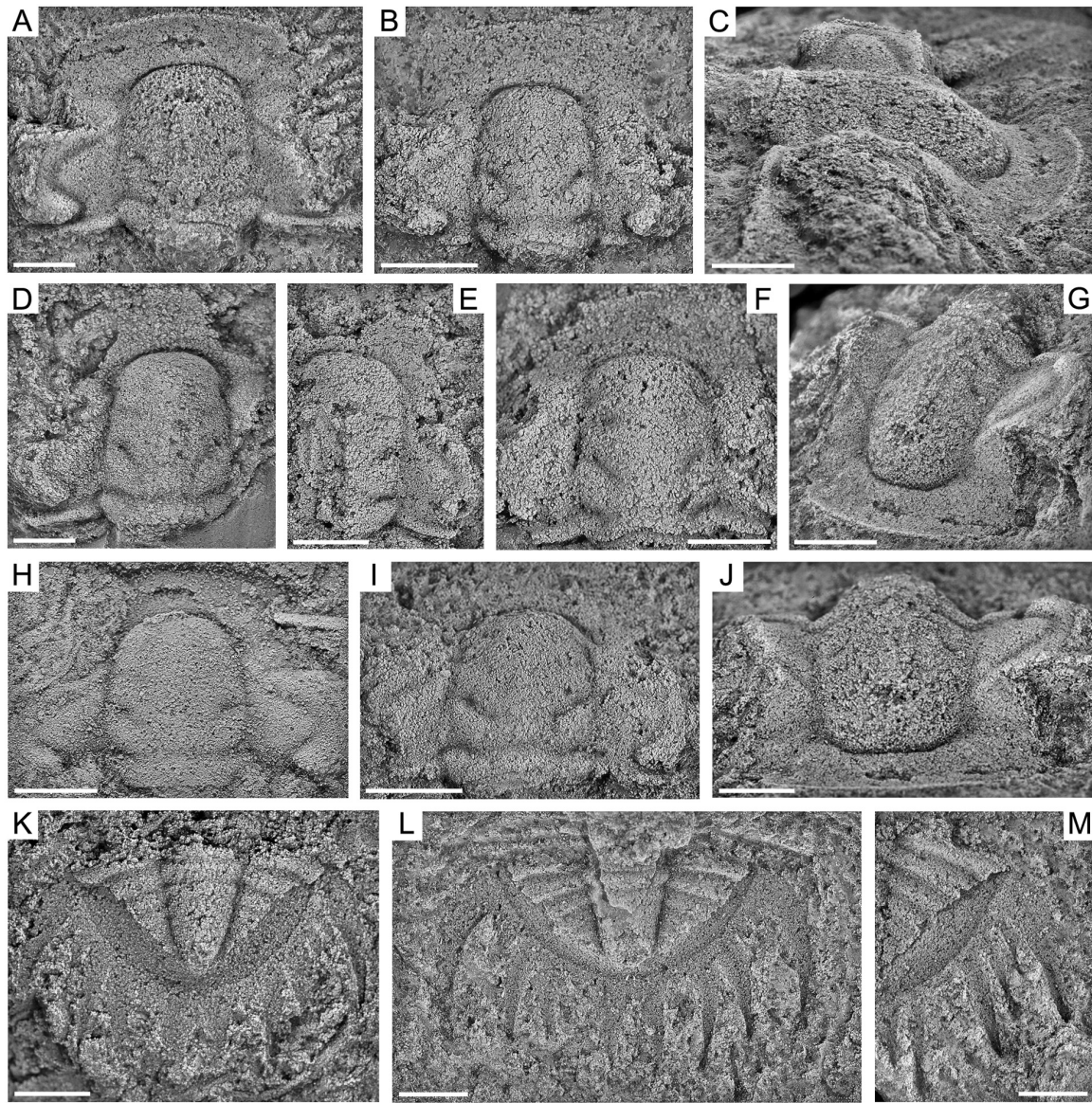


FIGURE 14. *Nomadinis* cf. *pristinus* Öpik, 1967 from the Mindyallan Goyder Formation. All specimens come from spot locality 85-3057. A, C, G, J, CPC42298, partial cranidium; A, dorsal view; C, lateral view; G, oblique anterolateral view; J, anterior view. B, CPC42299, partial cranidium. D, CPC42300, partial cranidium. E, CPC42301, partial cranidium. F, CPC42302, partial cranidium. H, CPC42303, partial cranidium. I, CPC42304, partial cranidium. K, CPC42305, partial pygidium. L, CPC42306, partial pygidium. M, CPC42307, partial pygidium. All scale bars are 2 mm.

lobes wide (tr.), long (exsag.), 38% of total cranidial length, sickle-shaped in outline, defined by a slightly narrow (tr.), shallow palpebral furrow; anterior tip situated approximately in line with S2, posterior tip approximately in line with the lateral posterior margin of the occipital ring. Eye ridge well defined, extending posterolaterally from the axial furrow just anterior to S2 in a straight line towards the anterior tip of palpebral lobe. Palpebral area of fixigena strongly downsloping towards the axial furrows, maximum width (tr.) is 52% the adjacent

glabellar width; short (exsag.) bacculae, faintly developed in axial furrows, anterior tip situated at the midlength between S1 and SO, posterior tip opposite anterior of occipital ring.

Postocular area very short (exsag.) and roughly horizontal. Posterolateral projections of fixigena narrow (exsag.), strongly downsloping towards lateral corners. Posterior border very narrow (exsag.), separated for the most part from fixigenal field by a deep, narrow (exsag.) border furrow.

Pygidium up to 5 mm long (sag.), subtriangular in outline excluding spines, slightly convex, length:width ratio of 55%. Anterior margin straight. Posterior margin parabolic. Axis prominent, narrow (tr.), tapered posteriorly, width:length ratio of 60%, of moderate length, occupying about 80% of sagittal length of pygidium. Very narrow (sag.), articulating half-ring, faintly defined by a shallow, narrow (sag.) inter-ring furrow. Two faintly defined axial rings and a third almost effaced axial ring present, separated by very faint, shallow, narrow (sag., exsag.) inter-ring furrows. Axial furrows moderately deep and narrow (tr.), fading out near posterior. Pleural regions convex; with four, or possibly five in more complete specimens, faint, moderately narrow (exsag.), very shallow pleural furrows, first furrow roughly transverse, subsequent furrows directed progressively more posterolaterally; furrows terminate at the border after becoming narrower (exsag.) and shallower. Border vague defined by change in slope; with seven pairs of broad based spines; first, third, fourth, fifth and seventh pair are slightly longer (exsag.) and wider (tr.); first and seventh pair are three and two times longer (exsag.) respectively and three times wider (tr.) than the remaining spines, fourth pair is two times longer (exsag.) and two times wider (tr.) than remaining spines, fifth pair is two times longer (exsag.) and two times wider (tr.) than remaining spines; spines directed posterolaterally, with a slight posterior curve. Doublure is approximately 28% the sagittal length of the pygidium, pygidial spines fused at the based extends doublure margin.

Hypostome, rostral plate, thorax and librigena unknown.

Discussion. Material of this taxon is preserved as distorted sandstone moulds from the 85-3057 spot locality. In most aspects it resembles *N. pristinus*, in possessing shallow axial furrows, a short (sag.) glabella that is slightly tapered, faint pygidial axial and pleural furrows, as well as a short second and long fourth pair of pygidial spines (compare Figs 12, 13 with Fig. 14). However, specimens from 85-3057 also appear have a shorter (sag.) frontal area, a more deeply incised anterior glabellar furrow, only faintly developed bacculae, and a longer pair of fourth spines on the pygidium. Some of these variations (e.g., development of furrows and bacculae) could simply represent preservational differences between the carbonate samples in the GOY section and the sandstone specimens at 85-3057, but aspects of the frontal area dimensions and pygidial spines appear to be genuine morphological distinctions. Due to the paucity of material, we refrain from making a definitive species assignment.

Occurrence. Only found at 85-3057 (Fig. 3).

Distribution. Goyder Formation, Amadeus Basin, Northern Territory. Cambrian Series 3, Guzhangian (Mindyallan) in age.

***Hebeia* Guo & Duan, 1978**

Type species. *Hebeia conica* Guo & Duan, 1978.

Discussion. Park *et al.* (2013) has recently transferred this genus to the damesellids. This placement is supported by a similarity to *Shantungia* Walcott, 1905, including: a weak median preglabellar ridge (similar to a plectrum), weak facial lines, a strongly tapered glabella, large palpebral lobes that are situated posteriorly, a pygidium with a short (sag.) axis, shallow axial as well as pleural furrows on the pygidium, and a spinose pygidial margin that

exhibits a long anteriormost pair of spines. They also suggested a pair of long broad-based posteriormost pygidial spines might also be shared, but at least two species of *Hebeia* Guo & Duan, 1978 lack this feature (see *Hebeia stewarti* sp. nov., Fig 16A–G and *Hebeia huainanensis* Qiu in Qiu *et al.*, 1983, pl. 48, fig. 11). Given the close similarities between *Hebeia* and other damesellids, we follow the classification of Park *et al.* (2013) herein.

Currently, we consider the genus to contain only four valid species. These include: the type species *Hebeia conica* Guo and Duan, 1978, *H. huainanensis* Qiu in Qiu *et al.*, 1983, *Hebeia pingquanensis* Guo and Duan, 1978, and *H. stewarti* sp. nov. (see below), all from the Guzhangian. Material described as *Hebeia pulchera* Zhang & Wang, 1986 shows a remarkable similarity to *H. huainanensis*, with both possessing a moderately convex preglabellar field that appears to lack the median ridge, and in having an almost identical pygidia (compare Qiu in Qiu *et al.*, 1983, pl. 48, fig. 8–11 to Zhang & Wang 1986, pl. 3, fig. 7–11). Therefore, we consider the two synonymous. Zhang & Wang (1986) also described *Hebeia hutoushanensis*, but the holotype pygidium is far too fragmentary for a detailed species comparison (see Zhang & Wang 1986, pl. 3, fig. 12) and whether it is even a representative of *Hebeia* is doubtful. Hence this taxon has been removed from the current species list. Specimens identified as *Hebeia* sp. 1 by Park *et al.* (2013, fig. 4.27–4.32) appear to lack the typical elongated (sag.) preglabellar field seen in all other species of the genus. In this regard, they more closely resemble species assigned to *Teinistion* Monke, 1903 or *Metashantungia* Zhang, 1957. For this reason, we also exclude this species and suggest it be transferred to another genus.

***Hebeia stewarti* sp. nov.**

Fig. 15 & 16

Etymology. In honour of A. J. Stewart, for his work on the geology of the Amadeus Basin.

Holotype. CPC42308, cranidium from the Goyder Formation at sample GOY/97, 73.2 m above the base of the formation (Fig. 15A).

Paratypes. One cranidium: CPC42317 (Fig. 15J), from sample GOY/86, 64.9 m above the base of the formation. Nine cranidia: CPC42309 (Fig. 15B); CPC42310 (Fig. 15C); CPC42311 (Fig. 15D); CPC42312 (Fig. 15E); CPC42313 (Fig. 15F); CPC42314 (Fig. 15G, N, O); CPC42316 (Fig. 15I); CPC42318 (Fig. 15K); and CPC42320 (Fig. 15M); two librigena: CPC42315 (Fig. 15H); CPC42319 (Fig. 15L); and seven pygidia: CPC42321 (Fig. 16A, H); CPC42322 (Fig. 16B); CPC42323 (Fig. 16C); CPC42324 (Fig. 16D); CPC42325 (Fig. 16E); CPC42326 (Fig. 16F); and CPC42327 (Fig. 16G), from sample GOY/97.0, 73.2 m above the base of the formation.

Material. Eleven cranidia, two librigenae, and seven pygidia figured, CPC42308–CPC42326. Fifty-one cranidia, thirteen librigenae, and sixteen pygidia not figured (mostly fragments).

Diagnosis. Glabella truncate, very strongly tapered at 24° to 30°, elongate trapezoid to subtriangular in outline; width:length ratio of 81%, occupying 56% of the cranidial length. All lateral glabellar furrows except SO effaced. Very shallow, wide (exsag.), faint SO. Anterior border furrow very wide (sag., exsag.) and very shallow. Preocular field slightly convex. Preglabellar field concave forming a wide (tr.) moderately deep preglabellar furrow. Preocular field and preglabellar field elongate, 33% of sagittal cranidial length. Two faint, narrow (tr.), facial lines cross preocular field and one faint, narrow (tr.), median ridge crosses preglabellar field. Palpebral lobes wide (tr.), 29% of total cranidial length. Eye ridge weakly defined. Elongate (exsag.) bacculae, width:length of 50%, moderately developed near axial furrows. Librigena genal field 77% of librigenal width (tr.). Genal spine flattened, blade-like. Pygidium subtrapezoidal in outline, length:width ratio of 59%. Axis moderately narrow (tr.),

width:length ratio of 87%, short occupying about 63% of sagittal length of pygidium. Three faintly defined and a fourth indistinct axial ring present. Pleural regions with three to four faint, wide (exsag.), very shallow pleural furrows. Border with seven pairs of broad based spines, first and sixth pair are slightly longer (exsag.) and wider (tr.), first pair is much longer than the others; seventh pair of spines short (exsag.). Prosopon very minutely granulose.

Description. Cephalon semicircular, up to 8 mm long (sag.). Cranidium outline transversely subelliptical, maximum width across posterolateral projections of fixigenae based on librigena outline, narrowest point at anterior tip of palpebral lobes (γ - γ); very slightly convex (sag., tr.). Anterior margin strongly rounded. Posterior margin incompletely preserved. Anterior branches of facial suture (γ - β segments) diverge strongly from one another at 60° , then curve abruptly towards the midline at the β point before they reach the anterior margin. Glabella truncate, elongate, very strongly tapered at 24° to 30° (mean 26° ; $n = 4$), elongate trapezoid to subtriangular in outline; width (tr.) across anterior 29% maximum width; slightly convex; maximum convexity across midwidth, lateral slopes gently convex; width:length ratio of 81%, occupying 56% of the cranidial length; anterior glabellar furrow and axial furrows are moderately narrow (sag., exsag., tr.) and only slightly deep. All lateral glabellar furrows except SO effaced. Occipital ring of moderate length (sag.), above the remaining glabella, becoming slightly wider abaxially, posterior margin slightly bowed backwards. Very shallow, wide (exsag.), faint SO; bowed backwards medially. Anterior cranidial border moderately narrow (sag., exsag.) and very slightly convex, occupying about 5% of sagittal cranidial length, narrowing abaxially. Anterior border furrow very wide (sag., exsag.) and very shallow. Preocular field slightly convex, moderately downsloping toward the anterior border furrow. Preglabellar field concave, forming a wide (tr.) moderately deep prelabellar furrow. Preocular field and prelabellar field elongate, 33% of sagittal cranidial length. Two faint, narrow (tr.), facial lines cross preocular field and one faint, narrow (tr.), median ridge crosses

preglabellar field; facial lines extend from anterior of the eye ridges to just posterior of the β point medial; median prelabellar ridge traces the sagittal line between the glabellar anterior and anterior border furrow, nested within the prelabellar furrow. Palpebral lobes wide (tr.), 29% of total cranial length, reniform in outline, defined by a wide (tr.), shallow palpebral furrow; anterior tip situated 60% of cranial length from the anterior border, posterior tip just posterior of SO. Eye ridge weakly defined, extending posterolaterally from the axial furrow just anterior of the γ point in a straight line towards the anterior tip of palpebral lobe.

Palpebral area of fixigena horizontal, maximum width (tr.) is 100% the adjacent glabellar width; very elongate (exsag.) baculae, width:length of 50%, moderately developed near axial furrows, anterior tip situated opposite midlength of palpebral lobe, posterior tip opposite anterior of SO. Postocular area short (exsag.) and strongly downsloping toward the posterior border furrow. Posterolateral projections of fixigena incompletely preserved. Posterior border narrow (exsag.), separated for the most part from fixigenal field by very shallow, moderately narrow (exsag.) border furrow.

Librigena up to 8 mm in length excluding spine. Lateral margin, including that of genal spine, evenly curved. Posterior margin curved distally. Genal field subtrapeziform, 77% of librigenal width (tr.), slightly convex. Lateral border very well defined. Lateral and posterior border furrows wide (exsag.) and shallow, furrows coalesce in an even curve, lateral furrow becomes wider (tr.) posteriorly and continues onto genal spines for a short distance. Facial lines continue from fixigena onto librigena field, extending anterolaterally from just posterior to the β point to the lateral border furrow. Genal spine flattened, blade-like, reaching approximately 50% the length of the librigena.

Pygidium up to 5 mm long (sag.), subtrapezoidal in outline excluding spines, slightly convex, length:width ratio of 59%. Anterior margin straight. Posterior margin a broad parabolic curve. Axis prominent, moderately narrow (tr.), tapered posteriorly, width:length ratio of 87%, short occupying about 63% of sagittal length of pygidium. Narrow (sag.)

articulating half-ring, faintly defined by a shallow, narrow (sag.) inter-ring furrow. Three faintly defined and a fourth indistinct axial ring present, separated by faint, shallow, narrow (sag., exsag.) inter-ring furrow. Terminal piece small, up to 33% of axial length (sag.), defined posteriorly by abrupt change in slope, small, faint, postaxial ridge present. Axial furrows moderately deep and narrow (tr.), becoming shallower and broader posteriorly until fading out completely. Pleural regions only very slightly convex, with three to four faint, wide (exsag.), very shallow pleural furrows. Furrows roughly transverse, directed slightly more backwards and becoming fainter posteriorly, terminate slight before reaching margins. Border with seven pairs of broad based spines (on largest specimen), first and sixth respective pair are slightly longer (exsag.) and wider (tr.), first pair is much longer than the others; seventh pair of spines short (exsag.); all spines directed posteriorly.

Prosopon over cephalon, librigena and pygidium is very minutely granulose. Anterior border of cranidium and lateral borders of librigena covered by terrace ridges.

Discussion. Cranidia from the Goyder Formation are very similar to the type species, *H. conica* from the Guzhangian of northeastern China (compare Fig. 16A–G, I–K, M with Guo and Duan 1978, pl. 2, figs 17–19). Only a slightly wider (tr.) γ – γ section of the cranidium, less distinct eye ridges, a wider (tr.) palpebral area of the fixigena and more prominent bacculae separate the Goyder Formation material. *Hebeia pingquanensis* and *H. huainanensis*, both from the Guzhangian of East China, are more distinctive in having short glabellar furrows, a narrower γ – γ section of the cranidium and either a wider (tr.) or absent preglabellar ridge. A shorter preglabellar field in *H. pingquanensis* can also be used to separate it from the Goyder Formation taxon.

Of the two Chinese species that have associated pygidia, the material described here is comparable to *H. huainanensis* (compare Fig. 16A–G with Qiu in Qiu *et al.*, 1983, pl. 48, fig. 11; and Zhang & Wang 1986, pl. 3, fig. 8, 9, 11 = *H. pulchra*). These pygidia appear to have

the same subtrapezoidal outline, shallow pleural furrows, no defined border and a longer first pair of spines. Slight differences separate the Goyder Formation material, including a slightly

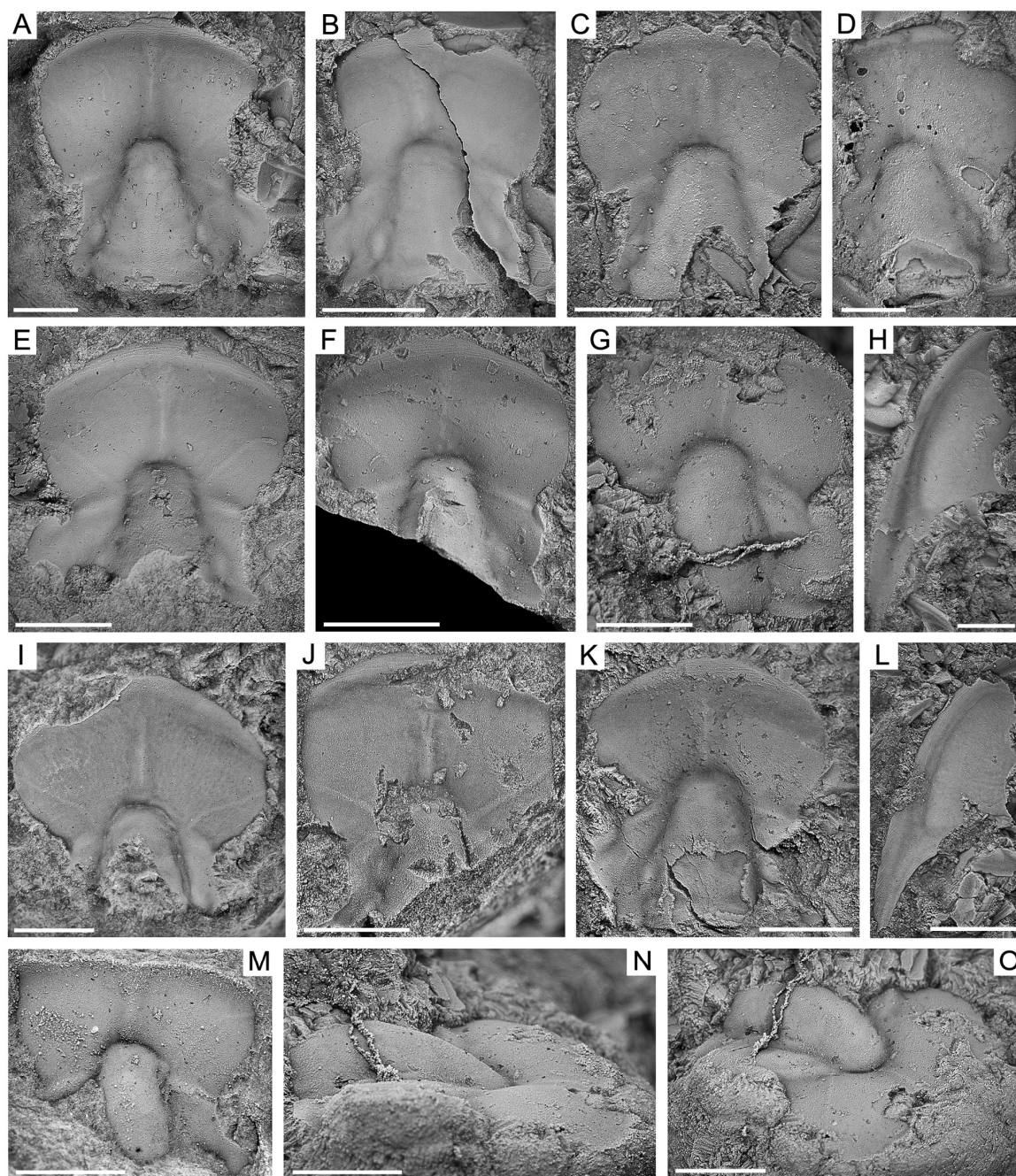


FIGURE 15. *Hebeia stewarti* sp. nov. from the Mindyallan Goyder Formation. A–I, K–O come from sample GOY/97 in the GOY section; and J comes from sample GOY/86 in the GOY section. A, holotype, CPC42308, partial cranidium. B, paratype, CPC42309, partial cranidium. C, paratype, CPC42310, partial cranidium. D, paratype, CPC42311, partial cranidium, latex cast. E, paratype, CPC42312, partial cranidium. F, paratype, CPC42313, partial cranidium. G, N, O, paratype, CPC42314, partial cranidium, latex cast; G, dorsal view; J, lateral view; K oblique anterolateral view. H, paratype, CPC42315, partial librigena. I, paratype, CPC42316, partial cranidium. J, paratype, CPC42317, partial cranidium. K, paratype, CPC42318, partial cranidium. L, paratype, CPC42319, partial librigena. M, paratype, CPC42320, partial cranidium, latex cast. All scale bars are 2 mm.

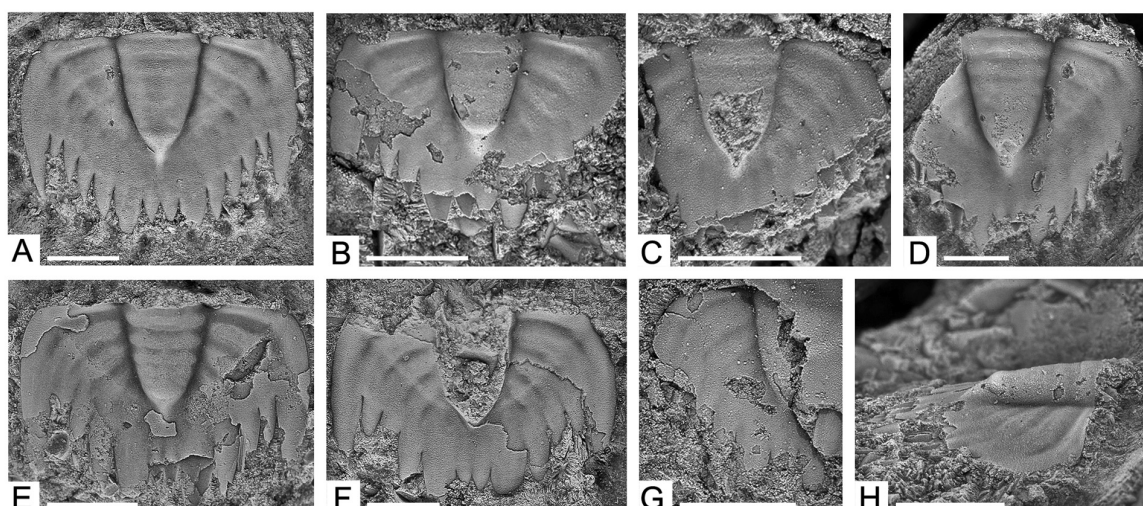


FIGURE 16. *Hebeia stewarti* sp. nov. from the Mindyallan Goyder Formation. All specimens come from sample GOY/97 in the GOY section. A, CPC42321, partial pygidium. B, H, CPC42322, partial pygidium; B, dorsal view; H, lateral view. C, CPC42323, partial pygidium. D, CPC42324, partial pygidium. E, CPC42325, partial pygidium. F, CPC42326, partial pygidium. G, CPC42327, partial pygidium. All scale bars are 2 mm.

longer (sag.) axis and a more prominent seventh pair of spines (in larger specimens) at the posterior margin. The associated pygidia of *H. pingquanensis* (Zhang & Wang 1986, pl. 3, fig. 4–5) are quite different, especially in possessing two broad-based spines at the posterior margin, and appear to have more in common with those of *Shantungia*. Hence, it is possible that the pygidia of *H. pingquanensis* have been misidentified and we therefore refrain from making further comparisons here.

The Goyder Formation pygidia have a varying number of pygidial spines, with the largest specimen having seven (Fig. 16A) and smaller specimens having six (Fig. 16B, C–G). Given the size difference between the pygidia we consider this variation to likely represent an ontogenetic trend,

Occurrence. GOY section horizons 64.9, and 73.2 m (Fig. 3). Also found at GOYWEST.

Distribution. Goyder Formation, Amadeus Basin, Northern Territory. Cambrian Series 3, Guzhangian (Mindyallan) in age.

***Polycyrtaspis* Öpik, 1967**

Type species. *Polycyrtaspis flexuosa* Öpik, 1967.

Discussion. Öpik (1967, p. 383) initially assigned this monotypic genus to its own family, the Polycyrtaspididae Öpik, 1967, as he found no close comparison to any other ptychoparioid genera. *Hebeia* was later assigned to this same family (Guo & Duan 1978; Qiu *et al.* 1983; Duan *et al.* 2005) based on similarities that include a weak median preglabellar ridge (similar to a plectrum), a strongly tapered glabella, large palpebral lobes that are situated posteriorly, and a differentiated preglabellar field and anterior border with a distinct border furrow. In particular, *Hebeia pingquanensis* Guo & Duan, 1978 is very similar to *Polycyrtaspis flexuosa* Öpik, 1967, with both possessing a deep anterior border furrow, a preglabellar field of comparable length (sag.), and almost identical glabellar furrows (compare Fig. 17A, B and Öpik 1967, pl. 9, figs 1, 2 to Guo & Duan 1978, pl. 2, figs 9–10).

Park *et al.* (2013, p. 997), in transferring *Hebeia* to the damesellids, suggested that the Polycyrtaspididae may also be part of, or derived from, the damesellids. Difficulties in assessing the validity of the Polycyrtaspididae as a separate family lie with the paucity of type material and the sclerite associations of *Polycyrtaspis flexuosa*, comprising only two cranidia, in addition to a tentatively assigned pygidium and hypostome (Öpik 1967, pl. 9, figs 1–4). The cranidia and hypostome come from the same locality (D29), but Öpik (1967, p. 384) attributed the pygidium from locality D6 to *P. flexuosa* based on the assumption that “an ‘unusual’ pygidium should correspond to an ‘unusual’ cranidium.”, thus making the association highly questionable. More definitive pygidial material of *Polycyrtaspis* is needed to help resolve the placement of this genus.

The long (sag.) preglabellar field of *Polycyrtaspis* differs from most damesellids,

which typically have the anterior border furrow abut with the front of the glabella. Those few damesellids which supposedly possess a preglabellar field (e.g. *Nomadinis*) normally have a simplified frontal area lacking an anterior border with a distinct furrow. Only *Hebeia* shares this feature with *Polycyrtaspis*, and given the strong similarity of the former to the damesellids (discussed above) we tentatively place *Polycyrtaspis* in the same family.

***Polycyrtaspis* cf. *flexuosa* Öpik, 1967**

Fig. 17

Material. Two partial crania figured, CPC42328, CPC42329.

Description. Cranium up to 7 mm long (sag.) outline incompletely preserved; strongly convex (sag., tr.). Anterior margin a slight rounded obtuse angle. Posterior margin incompletely preserved. Anterior branches of facial suture (γ - β segments) diverge moderately from one another at 36° , then curve abruptly towards the midline at the β point before they reach the anterior margin. Glabella slightly truncate, very strongly tapered at 47° , pyriform in outline; width (tr.) across anterior 29% maximum width; moderately convex; maximum convexity across midwidth, lateral slopes gently convex; width:length ratio of 96%, occupying 72% of the cranial length; anterior glabellar furrow wide (sag., exsag.) and shallow, disappearing around median preglabellar ridge; axial furrows are narrow (tr.) and moderately deep. S1 well defined, deep and narrow (exsag.), intersecting axial furrow approximately inline with the anterior of the palpebral lobe, directed posteromedially. S2 and S3 much fainter; S2 in line with the ϵ point and directed posteromedially. S3 reduced to a slight indentation in glabella margin, positioned slightly anterior to the ϵ point. Occipital ring short (sag.), above the remaining glabella, posterior margin incompletely preserved; surmounted by a small occipital node medially. SO moderately deep and seems to be widest

(sag.) medially, with the lateral corners being slightly narrower and deeper; bowed backwards laterally and strongly forward medially. Anterior cranial border moderately narrow (sag., exsag.), occupying about 10% of sagittal cranial length, narrowing abaxially; outline a wide (tr.) based, broadly triangular shape; very slightly convex. Anterior border furrow narrow (sag., exsag.) and deep, disappears in front of median preglabellar ridge. Preocular field slightly convex, moderately down sloping toward the anterior border furrow. Preglabellar field with narrow (tr.) ridge crossing sagittally the preglabellar field, ridge traces the sagittal line between the glabellar anterior and anterior border furrow, nested within a preglabellar furrow. Preocular field and preglabellar field elongate (sag., exsag.), 18% of sagittal cranial length. Palpebral lobes long and of moderate width (tr.), 30% of total cranial length, reniform in outline; anterior tip opposite S1, posterior tip just posterior of SO. Eye ridge incompletely preserved. Palpebral area of fixigena slightly downsloping towards the axial furrows, maximum width (tr.) is 44% the adjacent glabellar width; a pair of thin ridges run along the palpebral area from opposite S2 to opposite the ϵ point. Postocular area, posterolateral projections and posterior border all incompletely preserved.

Prosopon over cranidium smooth. Anterior border covered by fine terrace ridges.

Hypostome, rostral plate, librigena, thorax and pygidium unknown.

Discussion. This taxon is represented by two fragmentary cranidia from the upper sandy limestone beds of the GOY section. These specimens can be very closely compared with cranidia of *Polycyrtaspis flexuosa* Öpik, 1967 from the Mindyallan O'Hara Shale in the Georgina Basin. In the Goyder Formation cranidia, the broadly triangular anterior cranial border, preglabellar field with weak median preglabellar ridge, pyriform glabella with well defined furrows, and long palpebral lobes, and a pair of thin ridges running across the palpebral area all agree with features seen in the holotype (cf. Öpik 1967, pl. 9, fig. 1). The Goyder cranidia do appear to be marginally wider (tr.) with a more strongly tapered glabella,

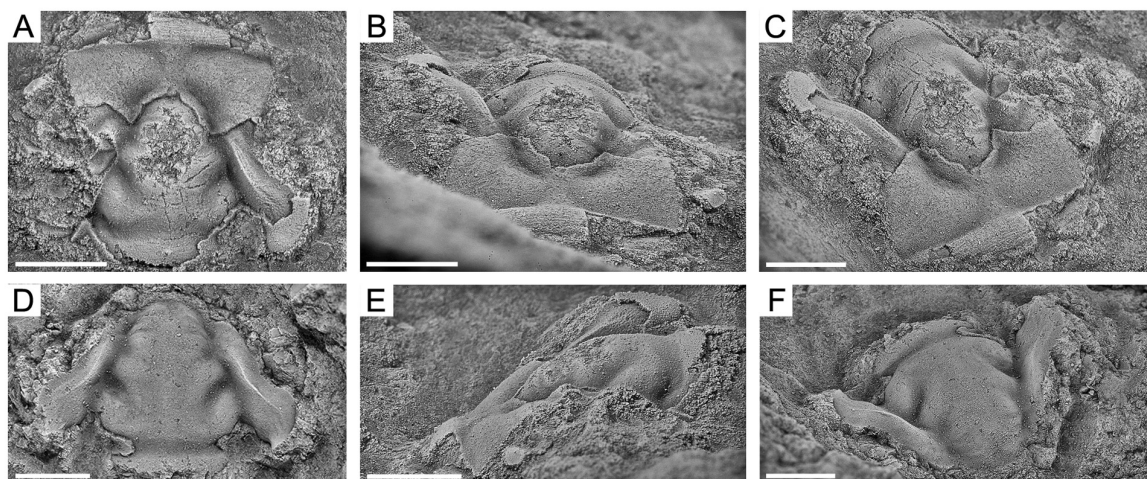


FIGURE 17. *Polycyrtaspis* cf. *flexuosa* Öpik, 1967 from the Mindyallan Goyder Formation. A, B, C, E come from sample GOY/173.6 in the GOY section; and D, F come from sample GOY/168.9 in the GOY section. A, C, E, F, CPC42328, partial cranidium; A, dorsal view; B, anterior view; C, oblique anterolateral view; E, lateral view. D, F, CPC42329, partial cranidium; D, dorsal view; F, oblique anterolateral view. All scale bars are 2 mm.

but without more specimens it is difficult to assess if these differences are just taphonomic or ontogenetic features, or genuine taxonomic distinctions. The second, much smaller cranidium of *P. flexuosa* illustrated by Öpik (1967, pl. 9, fig. 2) varies slightly compared to the holotype, displaying a less tapered glabella and broader (tr.), more strongly curved palpebral lobes. The size and morphology of the Goyder Formation specimens do not appear to contradict these ontogenetic trends, so it is possible that they may represent the same species.

Occurrence. GOY section horizon 132.7 m (Fig. 3).

Family Eoacidaspidae Poletaeva, 1957

***Paraacidaspis* Poletaeva, 1960**

Type species. *Paraacidaspis hunanica* Egorova in Poletaeva, 1960.

Discussion. For a review of the tumultuous taxonomic history of the genus and a comprehensive species list, see Zhang (1990), Shergold *et al.* (2000) and Peng *et al.* (2004a).

***Paraacidaspis priscilla* (Öpik, 1967)**

Fig. 18

1967 *Saukia?* *priscilla*; Öpik, p. 250–251, pl. 30, figs 5–7.

Material. Six pygidia figured, CPC42330–CPC42335. Four pygidia not figured (mostly fragments).

Description. Pygidium up to 5 mm long (sag.), transversely semicircular, only slightly convex, length:width ratio of 65%. Anterior margin slightly arched forward. Posterior margin broadly rounded, very slight anterior inflection in margin medially near the postaxial ridge. Axis prominent, moderately narrow (tr.), tapering posteriorly, width:length ratio of 71%; small, occupying about 60% of sagittal length of pygidium. Articulating half-ring very narrow (sag.), defined by narrow (sag.), shallow articulating furrow. Five moderately well developed to faint axial rings present, separated by shallow, narrow (sag.) inter-ring furrows. Terminal piece small. Long (sag.), postaxial ridge continues from the terminal piece until just before the posterior border, ridge the same width (tr.) as the terminal piece. Axial furrows very deep and narrow (tr.), fading around postaxial ridge. Pleural regions slight convex, with five narrow (exsag.), shallow pleural furrows that terminate just before reaching margin; pleural furrows directed posterolaterally; five very distinct, shallow, narrow (exsag.) interpleural furrows present, following the same course as pleural furrows, dividing the pleura into a slightly narrower (exsag.) anterior band and a wider (exsag.) posterior band. Border not well defined.

Prosopon over pygidium of very fine pustules.

Cephalon, hypostome, rostral plate and thorax unknown.

Discussion. The pygidia from the Goyder Formation are almost identical to those reported as *Saukia? priscilla* by Öpik (1967) from the Mindyallan O'Hara Shale and Georgina Limestone in the Georgina Basin. Both possess a transversely semicircular outline, a short axis, five axial rings (see Öpik 1967, pl. 30, fig. 7), a long (sag.) postaxial ridge, five narrow (exsag.) pleural and interpleural furrows, pleurae divided into a narrow anterior and wide posterior bands, no pygidial border, and a very fine pustulose ornament. The only apparent difference in the Georgina Basin pygidia appears to be the lack of a subtle indentation in the posteromedial margin, immediately behind the postaxial ridge. These slight variations, however, are more likely to be a preservation artefact, as two of the three Georgina Basin specimens do not have a complete posterior margin.

Öpik (1967) questionably assigned the material from the Georgina Basin to *Saukia* Walcott, 1914. This was based on the presence of five axial rings and five pleural furrows,

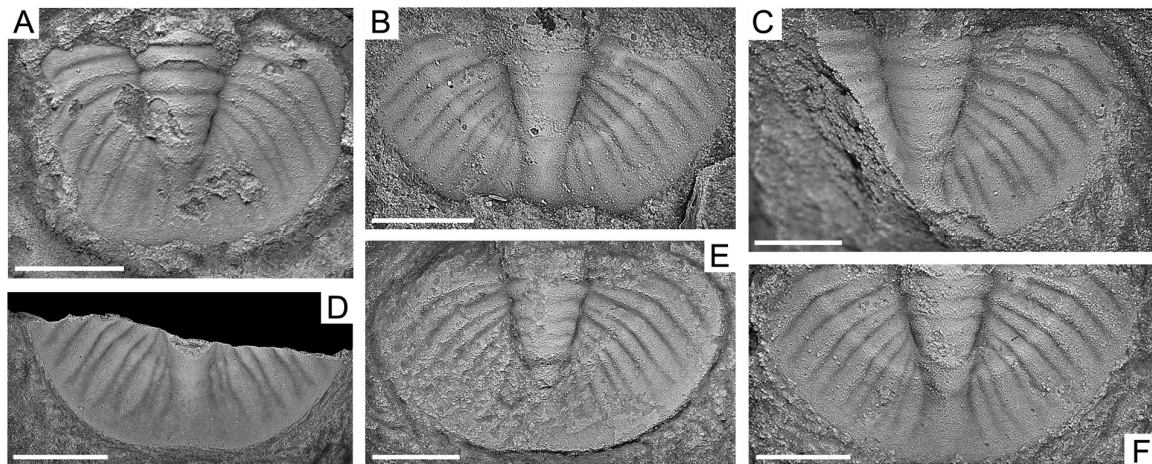


FIGURE 18. *Paraacidaspis priscilla* (Öpik, 1967) from the Mindyallan Goyder Formation. A comes from sample GOY/109.2 in the GOY section; and B–F come from spot locality AS168. A, CPC42330, partial pygidium. B, CPC42331, partial pygidium, latex cast. C, CPC42332, partial pygidium. D, CPC42333, partial pygidium. E, CPC42334, partial pygidium, latex cast. F, CPC42335, partial pygidium. All scale bars are 2 mm, except C = 1 mm.

which Öpik (1967) suggested was similar to both *Saukia* and *Tellerina* Ulrich & Resser, 1933. The pygidia illustrated herein and by Öpik (1967) seem unlikely to belong to either of these genera as *Saukia* and *Tellerina* typically have a more subtriangular pygidial outline, a relatively wider (tr.) axis, a shorter postaxial ridge, and wider pleural and interpleural furrows. A better comparison can be made with *Paraacidaspis*, namely *P. hunanica* Egorova in Poletaeva, 1960 and *Paraacidaspis* sp. (Peng *et al.* 2004a) from Guzhangian of China, and *P. ultima* Shergold, Feist & Vizcaino, 2000 from the Guzhangian–Paibian of southern France. *Paraacidaspis hunanica* and *P. ultima* have essentially identical pygidia that are very similar to those from the Goyder Formation and Öpik’s (1967) Georgina Basin material. *Paraacidaspis* sp. described by Peng *et al.* (2004a) also has a similar pygidium, although it has a more coarsely granulose prosopon making it immediately distinguishable from the material reported herein. The Goyder Formation and Georgina Basin material differs from these previously described species in possessing: a slightly longer (sag.) axis, narrower anterior pleural bands, and wider posterior pleural bands. These minor differences are likely of only specific significance, hence, we reassign *Saukia? priscilla* Öpik, 1967 to *Paraacidaspis*.

Similar pygidia have also been described from the Boomerangian to Idamean Spurs Formation in Antarctica. The pygidium assigned to *Nganasanella?* sp. by Cooper *et al.* (1996, fig. 5U) is small and incomplete, but does show an overall similarity to the Goyder Formation material. The minor differences include a shorter (sag.) axis and a relatively wider anterior pleural band. *Coosia?* sp. 2 of Jago & Cooper (2005, fig. 6S) seems to have a similar outline to the Goyder Formation species, however, it possesses more pleural and interpleural furrows than the Goyder pygidia. *Coosia?* sp. 1 of Jago & Cooper (2005, fig. 6R) differ from the Goyder specimens in that it has a more subcircular outline, a narrow (tr.) axis, a wider (exsag.) anterior pleural band, and a longer (sag.) terminal area. Material described by Bentley *et al.* (2009, figs 7K, L, 8U) as *Coosia?* sp. also differs in having wider anterior pleural bands

and a longer (sag.) terminal area. Given these differences it is possible that the Antarctic taxon—following the synonymy of Bentley *et al.* (2009, p. 183) in considering all of the above-mentioned specimens as being conspecific—represents a novel species of *Paraacidaspis*.

Another similar pygidium, identified as ?*Paraacidaspis* sp., has been described from the Guzhangian of Sweden (Żylińska *et al.* 2015). This specimen differs from previously described taxa, including *Paraacidaspis priscilla* (Öpik, 1967), in possessing a subrectangular outline, only four pleural furrows and a narrower (tr.) postaxial ridge.

Occurrence. GOY section horizons 73.2 and 83.9 m (Fig. 3). Also found at AS168.

Distribution. Goyder Formation, Amadeus Basin, Northern Territory. O’Hara Shale and Georgina Limestone, Georgina Basin, Northern Territory and Queensland. All occurrences are Cambrian Series 3, Guzhangian (Mindyallan) in age.

Family Liostracinidae Raymond, 1937

***Liostracina* Monke, 1903**

Type species. *Liostracina krausei* Monke, 1903.

Discussion. Extensive discussion of *Liostracina* Monke, 1903 was given by Öpik (1967). More recently, Park *et al.* (2014) provided an up-to-date commentary on the genus, a complete species list, as well as remarks on the phylogenetic position of the trinucleoids. Species of *Liostracina* are typically differentiated by variations in the anterior border furrow, depth of the median preglabellar furrow, development of the ocular ridges, bacculae and ornament (Shergold *et al.* 2007).

***Liostracina joyceae* sp. nov.**

Fig. 19

Etymology. In honour of Miss Joyce Gilbert-Tomlinson, for her work on the Cambrian fossils of the Amadeus Basin.

Holotype. CPC42336, cranidium from the Goyder Formation sample GOY/97.0, 73.2 m above the base of the formation (Fig. 19A).

Paratypes. Eleven cranidia; CPC42337 (Fig. 19B); CPC42338 (Fig. 19C, H); CPC42340 (Fig. 19E, L, P, T); CPC42341 (Fig. 19F); CPC42342 (Fig. 19G); CPC42343 (Fig. 19I); CPC42344 (Fig. 19J); CPC42345 (Fig. 19K); CPC42346 (Fig. 19M); CPC42347 (Fig. 19N); and CPC42348 (Fig. 19O); one librigena, CPC42339 (Fig. 19D); and three pygidium; CPC42349 (Fig. 19Q); CPC42350 (Fig. 19R); CPC42351 (Fig. 19S); from sample GOY/97.0, 73.2 m above the base of the formation.

Material. Twelve cranidia, one librigena, and three pygidia figured, CPC42336–CPC42351. Forty-three cranidia, fifteen librigenae and one pygidium not figured (mostly fragments).

Diagnosis. Cranidium outline transversely subelliptical. Glabella truncate, oblong in outline, width:length ratio of 58% to 63%, occupying 62% to 71% of the cranidial length. S1 very short (tr.). S2 very short (tr.), slightly less deeper than S1. S3 very short (tr.), shallow to almost completely effaced. Occipital ring of moderate length. Moderately deep, narrow (sag.) SO. Anterior cranial border 6% to 9% of sagittal cranidial length. Preglabellar field 26% to 29% of sagittal cranidial length, with faint preglabellar furrow. Palpebral lobes 20% of total cranidial length, reniform in outline. Eye ridge very well defined. Ovate bacculae, moderately

developed. Genal spine elongate, approximately 1.4 times the length of the librigena. Pygidium small subtriangular, length:width ratio 33%. Axis prominent, width:length ratio 83%, occupying about 93% of sagittal length of pygidium. Four well defined axial rings and a small terminal piece. Pleural regions with three narrow (exsag.), shallow pleural and two very shallow, narrow (exsag.) interplueral furrows. Frontal area evenly covered in small granules and network of genal caeca, except in preglabellar furrow. Glabella, occipital ring, eye ridges, palpebral lobes, palpebral, postocular areas and posterolateral projections of fixigena all densely covered in small granules. Librigenal field covered in faint small granules and a network of genal caeca. Pygidium prosopon faint small granules.

Description. Cephalon semicircular, up to 4 mm long (sag.). Cranidium outline transversely subelliptical, maximum width across posterolateral projections of fixigenae, narrowest point at anterior tip of palpebral lobes (γ - γ); slightly convex (sag., tr.). Anterior margin strongly rounded. Posterior margin slightly bowed forward. Anterior branches of facial suture (γ - β segments) diverge strongly from one another at 75° , then curve abruptly towards the midline at the β point, slightly after the border furrow before they reach the anterior margin. Glabella truncate, parallel-sided, oblong in outline; moderately convex, with maximum convexity across midwidth; width:length ratio of 58% to 63% (mean 61%; $n = 5$), occupying 62% to 71% (mean 66%; $n = 4$) of the cranidial length. Anterior glabellar furrow and axial furrows are narrow (sag., exsag., tr.) and deep. S1 very short (tr.), deep and narrow (exsag.), intersecting axial furrow slightly anterior to the ε point, directed transversely. S2 very short (tr.), slightly less deep than S1, narrow (exsag.), intersecting axial furrow at the γ point, directed transversely. S3 very short (tr.), shallow to almost completely effaced, intersecting axial furrow slightly anterior of where the eye ridges intersect the glabella, directed anteromedially. Occipital ring of moderate length (sag.), below the remaining glabella, becoming distinctly narrower abaxially, posterior margin bowed strongly backwards, faint medial node surmounting the posterior of occipital ring. Moderately deep, narrow (sag.) SO,

directed transversely. Anterior cranial border moderately narrow (sag., exsag.), occupying about 6% to 9% (mean 8%; $n = 3$) of sagittal cranial length, narrowing abaxially. Anterior border furrow slightly wide (sag., exsag.) and deep. Preocular field moderately convex, strongly down sloping toward the anterior border furrow. Preglabellar field is slightly concave forming a narrow (tr.) moderately shallow prelabellar furrow. Preglabellar field 26% to 29% (mean 28%; $n = 4$) of sagittal cranial length. Palpebral lobes (tr.), 20% of total cranial length, reniform in outline, defined by a narrow (tr.), deep palpebral furrow; anterior tip situated in line with S2, posterior tip in line with the point between the midlength of S1 and SO. Eye ridge very well defined and prominent, extending posterolaterally from the axial furrow opposite S3 in a straight line towards the anterior tip of palpebral lobe. Palpebral area of fixigena horizontal, maximum width (tr.) is 100% to slightly greater than the adjacent glabellar width. Postocular area short (exsag.), and slightly downsloping toward the posterolateral projections; ovate bacculae, moderately developed near axial furrows, anterior tip situated slightly posterior S1, posterior tip opposite SO. Posterolateral projections of fixigena narrow (exsag.), strongly downsloping towards lateral corners. Posterior border very narrow (exsag.), separated for the most part from fixigenal field by deep, moderately narrow (exsag.) border furrow.

Librigena up to 2 mm in length excluding spine. Lateral margin, including that of genal spine, evenly curved. Posterior margin curved distally. Genal field subtrapeziform, 53% of librigenal width (tr.), slightly convex. Lateral border very well defined. Lateral border furrow wide (tr.) and deep, lateral furrow becomes wider posteriorly and continues onto genal spines for a short distance. Genal spine flattened, elongate, blade-like, reaching approximately 1.4 times the length of the librigena.

Pygidium small, up to 2 mm long (sag.), subtriangular, slightly convex, wide (tr.), length:width ratio of 33%. Anterior margin straight. Posterior margin rounded. Axis prominent, narrow (tr.), tapered posteriorly, width:length ratio of 83%, occupying about 93% of sagittal length of pygidium. Articulating half-ring very narrow (sag.), defined by narrow

(sag.), moderately deep articulating furrow. Four well defined axial rings present, separated by moderately deep to shallow, narrow (sag.) inter-ring furrows, becoming fainter posteriorly. Terminal piece small. Axial furrows shallow and wide (tr.), fading around terminal piece. Pleural regions only very slightly convex, with three narrow (exsag.), shallow pleural furrows that terminate before reaching margin, becoming shorter and fainter posteriorly. Very shallow, narrow (exsag.) interplueral furrows on first and second plural ribs, extending the entire length, dividing pleural rib in two equal parts. Border narrow (sag., exsag.), defined by change in convexity from the pleural region.

Prosopon consists of granules varying in size. Frontal area evenly covered in small granules and network of genal caeca, except in preglabellar furrow. Glabella, occipital ring, eye ridges, palpebral lobes, palpebral, postocular areas and posterolateral projections of fixigena all densely covered in small granules. Librigenal field covered in faint small granules and an anastomosing network of genal caeca. Anterior and lateral borders covered in terrace ridges. Pygidium prosopon faint small granules.

Hypostome, rostral plate and thorax unknown.

Discussion. Specimens from the Goyder Formation are similar to at least three other species of *Liostracina* Monke, 1903, which all share a prosopon covered in granules of varying sizes. The most comparable of these is *Liostracina bella* Lin & Zhou in Lin *et al.*, 1983, from the eponymous zone (late Guzhangian–early Paibian) of China. The type specimens of *L. bella* include three poorly preserved cranidia with an associated librigena from drillcore material in the Tuanshan Formation (Lin *et al.*, 1983). However, more well preserved specimens of *L. bella* were figured by Peng *et al.* (2004a, pl. 61, figs 1–14, pl. 62, figs 1–13) from the Huaqiao Formation. Both taxa share not just an identical prosopon, but also a cranidium with a transversely subelliptical outline, very short (tr.) S1, S2 and S3 glabellar furrows (with S3 almost effaced), prominent eye ridges, moderately developed ovate (exsag.) bacculae, a pygidium with a length:width ratio of approximately 33%, and posterior margin which is

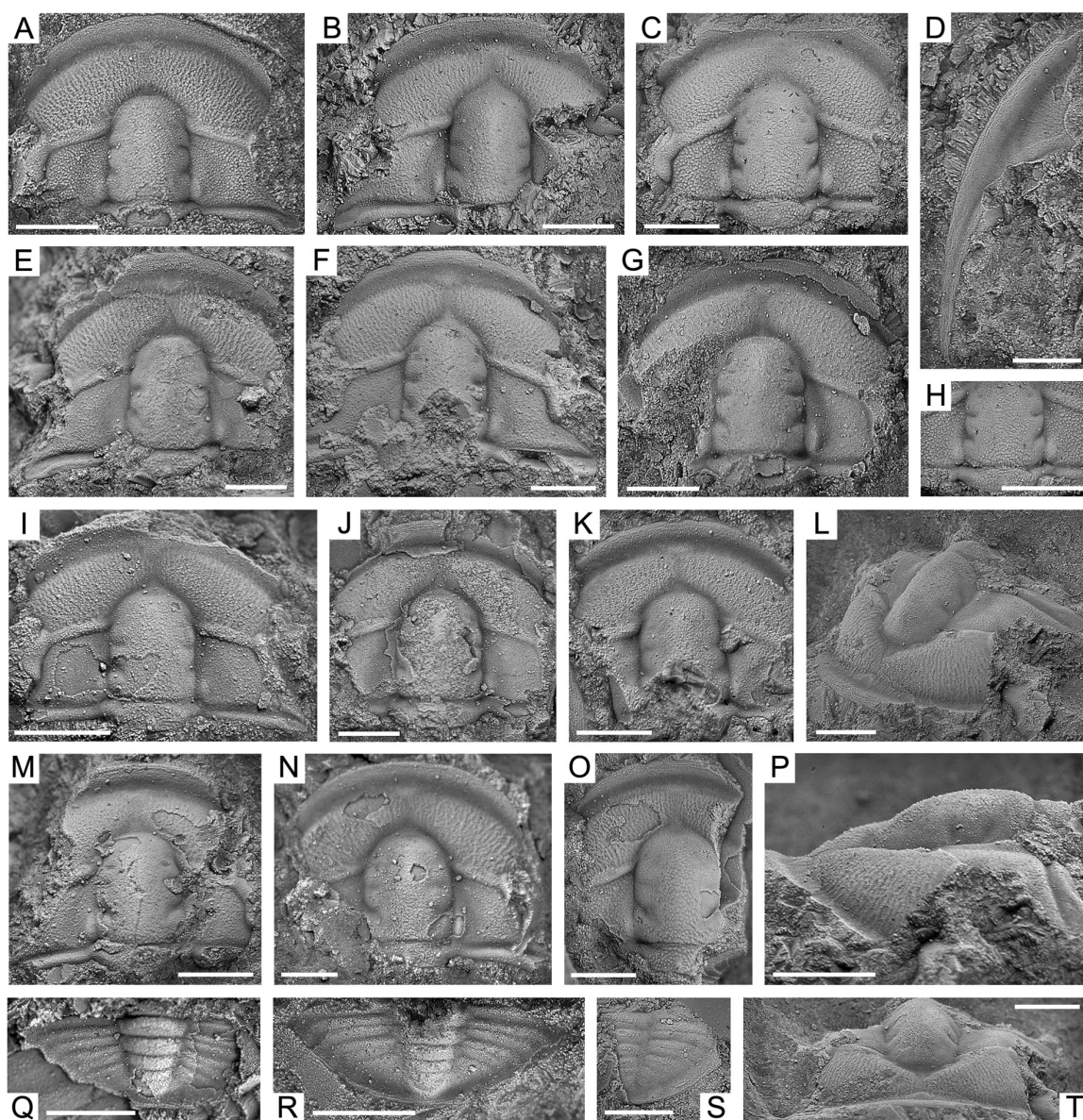


FIGURE 19. *Liostracina joyceae* sp. nov. from the Mindyallan Goyder Formation. All specimens come from sample GOY/97 in the GOY section. A, holotype, CPC42336, partial cranidium. B, paratype, CPC42337, partial cranidium. C, H, paratype, CPC42338, partial cranidium; C, dorsal view; H, close up on ornament. D, paratype, CPC42339, partial librigena. E, L, P, T, paratype, CPC42340, partial cranidium; E, dorsal view; L, oblique anterolateral view; P, lateral view; T, anterior view. F, paratype, CPC42341, partial cranidium. G, paratype, CPC42342, partial cranidium. I, paratype, CPC42343, partial cranidium. J, paratype, CPC42344, partial cranidium. K, paratype, CPC42345, partial cranidium. M, paratype, CPC42346, partial cranidium. N, paratype, CPC42347, partial cranidium. O, paratype, CPC42348, partial cranidium. Q, paratype, CPC42349, partial pygidium. R, paratype, CPC42350, partial pygidium. S, paratype, CPC42351, partial pygidium, latex cast. All scale bars are 1 mm.

moderately rounded. The Goyder Formation specimens differ in having a much wider (tr.) and slightly longer (sag.) glabella, a more transverse occipital ring, a somewhat less upturned anterior border, shorter (tr.), thicker eye ridges, longer (exsag.) palpebral lobes, and more distinct pleural and interpleural furrows on the pygidium. The librigenae of *L. bella* are very

similar to those from the Goyder Formation, except for a narrower (tr.) and more prominent lateral border.

Liostracina joyceae is also similar to *L. nolens* Öpik, 1967 from the Mindyallan Georgina Limestone in the Georgina Basin. The latter species effectively shares the same features as *L. bella*, with which it is likely synonymous (compare Öpik 1967, pl. 35, fig. 6, 7 to Peng *et al.* 2004a, pl. 61, figs 1–5, 7, 8, 12, pl. 62, fig. 1–5, 8, 12).

The only other species with a granulose prosopon is *Liostracina simesi* Jago & Cooper, 2005 from the Mindyallan of Antarctica. The Goyder Formation specimens differ quite distinctly from this taxon, having a much wider (tr.) glabella with more distinct S1–S3 furrows, a more transverse occipital ring, shorter (tr.), thicker and more prominent eye ridges, less distinct bacculae, and a more densely granulose prosopon with genal caeca on the frontal area.

All other taxa currently recognised in the genus, particularly the better known species such as *Liostracina bilimbata* Zhang in Qui *et al.*, 1983 (= *L. suixiensis* Bi in Qui *et al.*, 1983, see Park *et al.* 2014), *L. kaulbacki* Shergold, Laurie & Shergold, 2007, *L. krausei* Monke, 1903, *L. qingyangensis* Qian in Qui *et al.*, 1983, *L. tangwangzhaiensis* Park, Kihm, Kang & Choi, 2014, and *L. volens* Öpik, 1967 lack the granulose prosopon, at least in the available illustrations. These other taxa also have more effaced glabellar furrows and eye ridges, as well as a glabella that is distinctly narrower (tr.), with the exception of *L. kaulbacki* which may be slightly wider (tr.).

There are at least five other taxa which are assigned to *Liostracina* (in some cases tentatively), including: *L. bifurcata* Zhang in Qui *et al.*, 1983, *L.(?) pauper* Resser & Endo in Endo & Resser, 1937, *L.(?) paupiforme* Endo, 1944, and two described below (see *L. cf. kaulbacki* and *L. sp.*). These species are only based on a single specimen or a small collection of poorly preserved cranidia, making further comparison difficult.

Occurrence. GOY section horizons 49.4, 73.2 and 83.9 m (Fig. 3). Also found at GOYWEST.

Distribution. Goyder Formation, Amadeus Basin, Northern Territory. Cambrian Series 3, Guzhangian (Mindyallan) in age.

***Liostracina cf. kaulbacki* Shergold, Laurie & Shergold, 2007**

Fig. 20

Material. Four cranidia figured, CPC42352–CPC42355. One hundred and thirty-eight very poorly preserved cranidia not figured (mostly fragments).

Description. Cranidium up to 4 mm long (sag.), outline transversely subelliptical, maximum width across posterolateral projections of fixigenae, narrowest point at anterior tip of palpebral lobes (γ – γ); slightly convex (sag., tr.). Anterior margin strongly rounded. Posterior margin very slightly bowed forward. Anterior branches of facial suture (γ – β segments) appear to diverge from one another, then curve abruptly towards the midline at the β point. Glabella truncate, parallel-sided, oblong in outline; moderately convex, with maximum convexity across midwidth, lateral slopes gently very convex; width:length ratio of 70%, occupying approximately 70% of the cranidial length; anterior glabellar furrow and axial furrows are narrow (sag., exsag., tr.) and deep; All lateral glabellar furrow except SO effaced. Occipital ring short (sag.), below the remaining glabella, becoming slightly narrower abaxially, posterior margin bowed strongly backwards. Shallow, narrow (sag.) SO, directed transversely. Anterior cranidial border incompletely known. Anterior border furrow slightly wide (sag., exsag.) and shallow. Preocular field moderately convex, strongly downsloping toward the anterior border furrow. Preglabellar field with a very shallow, almost effaced preglabellar furrow. Preglabellar field approximately 19% of sagittal cranidial length.

Palpebral lobes (tr.) incompletely preserved. Eye ridge very faint to almost completely effaced. Palpebral area of fixigena horizontal, maximum width (tr.) is 93% the adjacent glabellar width. Postocular area short (exsag.), and slightly downsloping toward the posterolateral projections; bacculae completely effaced. Posterolateral projections of fixigena narrow (exsag.), strongly downsloping towards lateral corners. Posterior border very narrow (exsag.), separated for the most part from fixigenal field by deep, moderately narrow (exsag.) border furrow.

Hypostome, rostral plate, librigena, thorax and pygidium unknown.

Discussion. Cranidia of this taxon are found in large numbers, often distorted, at the 85-3057 spot locality. Specimens are only coarsely preserved as sandstone moulds with limited fine detail. They are remarkably similar to *Liostracina kaulbacki* Shergold, Laurie & Shergold, 2007 from the Mindyallan Skewthorpe Formation of WA, possessing effaced median preglabellar and glabellar furrows, a shallow anterior border furrow, and lacking bacculae (cf. Shergold *et al.* 2007 fig. 13A–G). *Liostracina kaulbacki* also occurs in a sandy lithofacies and given that limited detail can be preserved in coarse moulds, these features (or lack of) may be taphonomic artefacts rather than representing true morphology. Lack of pygidial or other material from the Goyder Formation and poor preservation make precise taxonomic assignment very difficult.

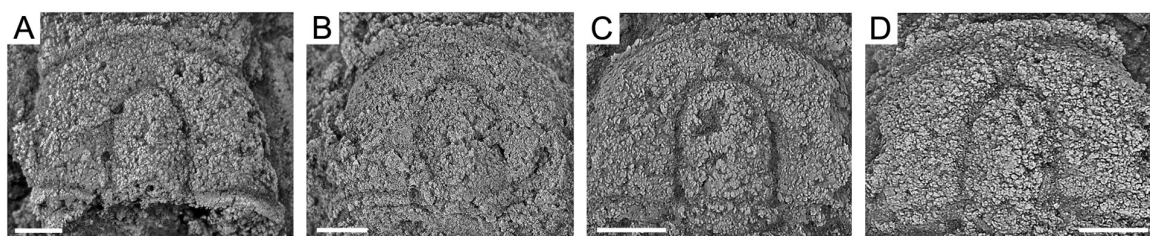


FIGURE 20. *Liostracina* cf. *kaulbacki* Shergold, Laurie & Shergold, 2007 from the Mindyallan Goyder Formation. All specimens come from spot locality 85-3057. A, CPC42352, partial cranidium. B, CPC42353, partial cranidium. C, CPC42354, partial cranidium. D, CPC42355, partial cranidium. All scale bars are 1 mm.

Occurrence. Only found at 85-3057 (Fig. 3).

***Liostracina* sp.**

Fig. 21

Material. One cranidium figured, CPC42356. Nine cranidia not figured (mostly fragments).

Description. Cranidium up to 5 mm long (sag.), outline transversely subelliptical, maximum width across posterolateral projections of fixigenae, narrowest point at anterior tip of palpebral lobes (γ - γ); very slightly convex (sag., tr.). Anterior margin strongly rounded. Posterior margin straight. Anterior branches of facial suture (γ - β segments) diverge moderately from one another at 35° , then curve abruptly towards the midline at the β point inline with the border furrow. Glabella truncate, parallel-sided, oblong in outline; moderately convex, with maximum convexity across midwidth, lateral slopes gently very convex; width:length ratio of 58%, occupying 61% of the cranidial length. Anterior glabellar furrow and axial furrows are narrow (sag., exsag., tr.) and deep. S1 very short (tr.), deep and narrow (exsag.), intersecting axial furrow slightly anterior to the ϵ point, directed posteromedially for a short distance before fading. S2 faint, very short (tr.), shallow, intersecting axial furrow at the δ point, directed transversely. S3 faint, very short (tr.), shallow to almost completely effaced, intersecting axial furrow slightly anterior of the γ point, directed slightly anteromedially. Occipital ring of moderate length (sag.), below the remaining glabella, posterior margin bowed slightly backwards, lacking axial node. Moderately shallow, narrow (sag.) SO slightly bowed toward the anterior medially. Anterior cranidial border of moderate length (sag., exsag.), occupying about 12% of sagittal cranidial length, narrowing strongly abaxially. Anterior border furrow slightly narrow (sag., exsag.) and shallow. Preocular field

moderately convex, gently downsloping toward the anterior border furrow. Preglabellar field with a narrow (tr.) very faint and shallow preglabellar furrow, small pit at junction between the median preglabellar furrow and the anterior border furrow. Preglabellar field 24% of sagittal cranial length. Palpebral lobes (tr.), 16% of total cranial length, reniform in outline, defined by a wide (tr.), shallow palpebral furrow; anterior tip situated slightly anterior of S2, posterior tip in line with the point between the midlength of S1 and SO. Eye ridge very faint to almost completely. Palpebral area of fixigena horizontal, maximum width (tr.) is slightly greater than the adjacent glabellar width. Postocular area short (exsag.), and slightly downsloping toward the posterolateral projections; faint, very elongate (exsag.) bacculae, near axial furrows, anterior tip situated opposite S1, posterior tip opposite anterior of SO. Posterolateral projections of fixigena narrow (exsag.), strongly downsloping towards lateral corners. Posterior border very narrow (exsag.), separated for the most part from fixigenal field by deep, moderately narrow (exsag.) border furrow.

Prosopon over cranidium smooth.

Hypostome, rostral plate, librigena, thorax and pygidium unknown.

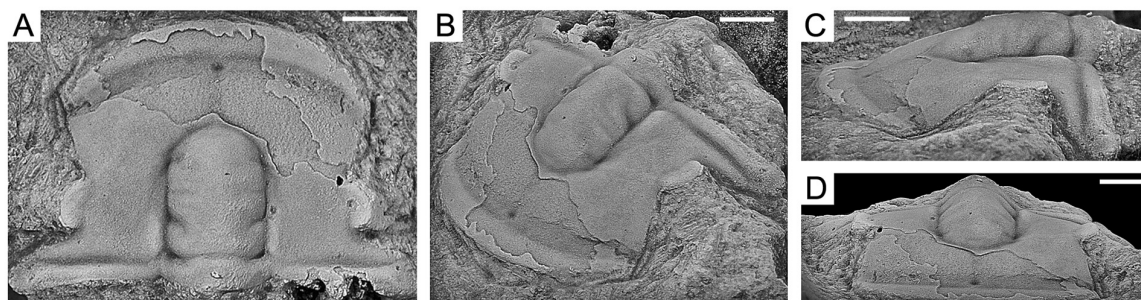


FIGURE 21. *Liostracina* sp. from the Mindyallan Goyder Formation. All specimens come from spot locality AS178. A, B, C, D, CPC42356, partial cranidium; A, dorsal view; B, oblique anterolateral view; C, lateral view; D, anterior view. All scale bars are 1 mm.

Discussion. This species is represented largely by fragments. Only a single nearly complete cranidium from the AS178 spot locality provides detailed morphology. This taxon was originally reported as *Liostracina* cf. *volens* by Öpik (1967) from the Ross River Gorge at locality NT187; however, it was neither figured nor described.

The best specimen from the Goyder Formation (Fig. 21) resembles *Liostracina volens* Öpik, 1967 from the Mindyallan O'Hara Shale in the Georgina Basin, having a glabella of similar width and length, faint eye ridges, short (exsag.) palpebral lobes, and a smooth prosopon (cf. Öpik 1967, pl. 35, fig. 1–3). The Goyder taxon differs in having a longer anterior cranial border, more deeply incised glabellar furrows, a pit at the junction between the median preglabellar furrow and the anterior border furrow, an occipital ring that is not strongly arched backwards, no occipital node, and a narrower posterior border furrow.

Occurrence. Only found at AS178 (Fig. 3).

Family Monkaspidae Kobayashi, 1935

***Monkaspis* Kobayashi, 1935**

1967 *Metopotropis*; Öpik, p. 224.

1987 *Monkaspis* Kobayashi, 1935; Zhang & Jell, pp. 191, 192.

2004a *Monkaspis* Kobayashi, 1935; Peng, Babcock, Lin, pp. 181, 182 (*cum. syn.*).

Type species. *Anomocare? daulis* Walcott, 1905.

Discussion. This genus has been discussed extensively by Zhang & Jell (1987, p. 190, 191) and Peng *et al.* (2004a, p.181, 182) and has been synonymised with *Liaoningaspis* Zhu, 1959, *Kushanopyge* Zhu, 1959 and *Paraliaoningaspis* Zhu in Lu *et al.*, 1965. An emended diagnosis was also provided by Peng *et al.* (2004a), expanding the range of morphological variability encompassed by the addition of the above-mentioned junior synonyms. The character states

used in this emended diagnosis can also be seen in *Metopotropis* Öpik, 1967. Given the type species, *Metopotropis travesi* Öpik, 1967, possesses a cranidium with a rounded anterior margin, a long (sag.) prelabellar field that is slightly concave, a short anterior border with a shallow border furrow, a tropidium situated slightly anterior to the glabella, a parallel-sided to slightly tapered glabella with a rounded anterior, faint bacculae, and posteriorly-located palpebral lobes, it seems reasonable to suggest placement within the current concept of *Monkaspis* Kobayashi, 1935.

Metopotropis was thought to differ from *Monkaspis* in possessing a distinctive tropidium. However, this feature is variably developed in *Monkaspis*, not just between species but intraspecifically, e.g., compare specimens of *Monkaspis quadrata* Yang in Zhou *et al.*, 1977 illustrated by Peng *et al.* (2004a, pl. 63, figs 1–7). In undistorted material, the tropidium of *Metopotropis travesi* from the Georgina Limestone (see Öpik 1967, pl. 16, fig. 9b) and *Metopotropis sinensis* Peng, Babcock & Lin, 2004a from the Guzhangian of China (see Peng *et al.* 2004a, pl. 51, figs 1–4) is remarkably similar to some species of *Monkaspis* (e.g., Peng *et al.* 2004a, pl. 63, figs 3–5, 7; Zhang & Jell 1987, pl. 84, fig. 11). Hence, we consider the distinctiveness of the tropidium as a non-diagnostic character. The only other feature that may distinguish *Metopotropis* is a slight posterior curve in the eye ridge and a slight bulge in the proximal portion of the eye ridge. This feature is difficult to observe in *Metopotropis travesi* (Öpik 1967, pl. 16, fig. 9b), as the single cranidium figured appears to be missing the majority of the eye ridge on both sides. *Metopotropis sinensis* more clearly displays this feature (Peng *et al.* 2004a, pl. 51, figs 1, 2), but the figured specimen is slightly compressed, so the anterior bulge may be the result of distortion. The material from the Goyder Formation displays only faint eye ridges, with no clear evidence of an anterior bulge. Interestingly, eye ridges seem to be highly variable in *Monkaspis*, with some having distinct ridges that are almost transverse (e.g. Zhang & Jell 1987, pl. 85, figs 1, 2) or directed posteriorly (e.g., Zhang & Jell 1987, pl.

84, fig. 11, pl. 85, fig. 6), while in others they are almost effaced (Peng *et al.* 2004a, pl. 63, figs 2–4, 7). Therefore, given the range of morphological variation and overlap seen in species of *Monkaspis* and *Metopotropis*, we consider the latter a junior subjective synonym.

***Monkaspis cf. travesi* (Öpik, 1967)**

Fig. 22 & 23

Material. Twelve cranidia, and eight pygidia figured, CPC42357–CPC42375. Thirteen cranidia and thirteen pygidia not figured (mostly fragments).

Description. Cranidium up to 12 mm long (sag.), outline transversely subelliptical, maximum width across posterolateral projections of fixigenae and the β – β section of the cranidium, narrowest point at anterior tip of palpebral lobes (γ – γ); moderately convex (sag., tr.). Anterior margin strongly rounded. Posterior margin bowed slightly backwards. Anterior branches of facial suture (γ – β segments) diverge strongly from one another at 130° , then curve very abruptly towards the midline at the β point before they reach the anterior margin. Glabella truncate, parallel-sided, oblong in outline; moderately convex, with maximum convexity across midwidth, lateral slopes gently very convex; width:length ratio of 71%, occupying 57% to 63% (mean 61%; $n = 3$) of the cranidial length; anterior glabellar furrow and axial furrows are moderately narrow (sag., exsag., tr.) and only slightly deep; All lateral glabellar furrow except SO effaced. Occipital ring short (sag.), above the remaining glabella, posterior margin very slightly bowed backwards. Slightly deep, narrow (sag.) SO; bowed backwards medially. Anterior cranidial border not very well defined, lacking an anterior border furrow. Preocular and preglabellar fields moderately concave, downsloping toward field midlength (sag.). Preocular field and preglabellar field elongate, 33% to 40% (mean 37%; $n = 3$) of sagittal cranidial length. Faint tropidium extends across cranidium in a strong arc from just

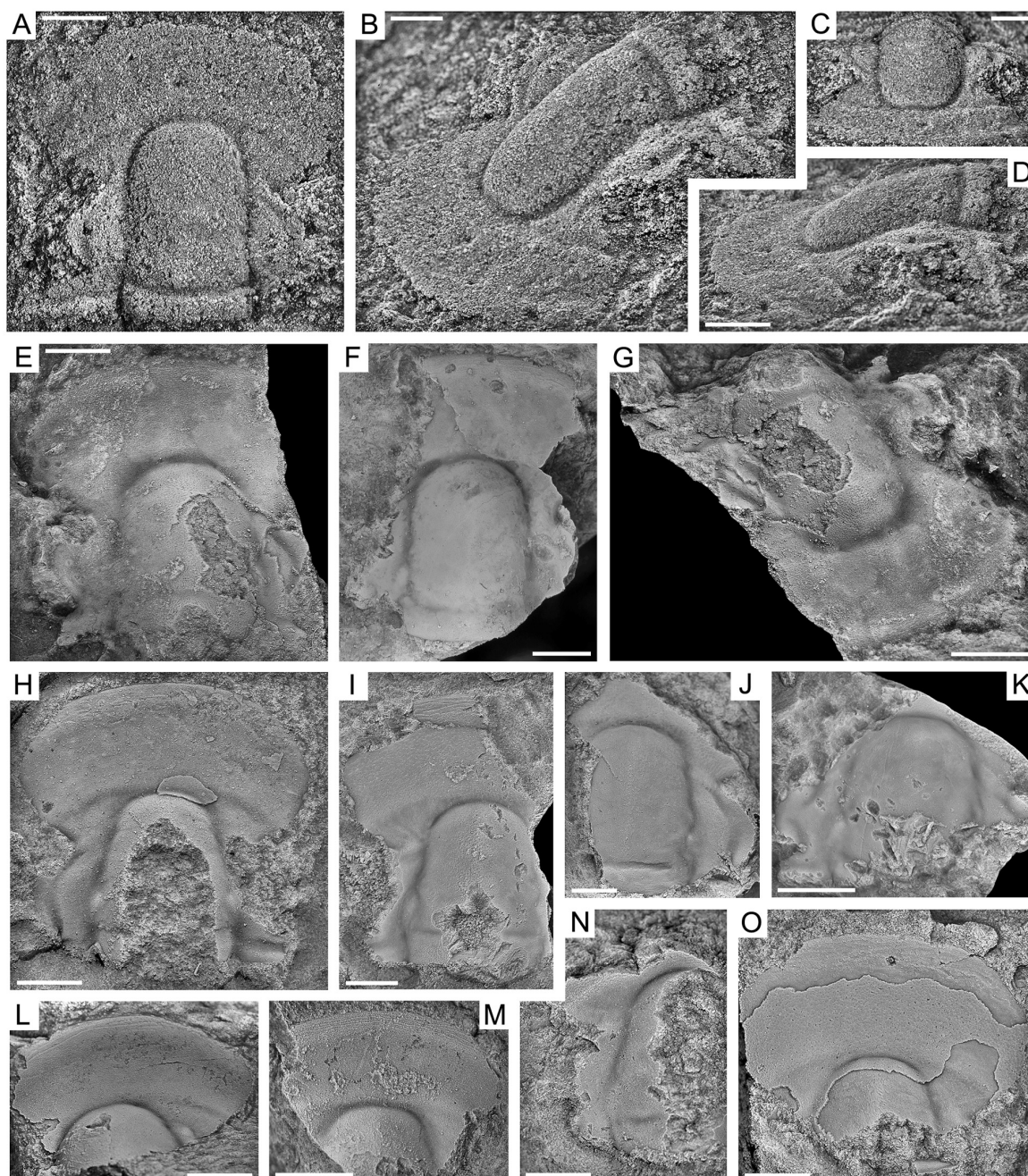


FIGURE 22. *Monkaspis* cf. *travesi* (Öpik, 1967) from the Mindyallan Goyder Formation. A–D come from spot locality 87-008; E–G, M come from sample GOY/109.2 in the GOY section; H–J, N, O come from spot locality GOYWEST; K comes from sample GOY/97 in the GOY section; and L comes from spot locality AS168. A, B, C, D, CPC42357, partial cranidium; A, dorsal view; B, oblique anterolateral view; C, anterior view; D, lateral view. E, G, CPC42358, partial cranidium; E, dorsal view; G, oblique anterolateral view. F, CPC42359, partial cranidium. H, CPC42360, partial cranidium. I, CPC42361, partial cranidium. J, CPC42362, partial cranidium. K, CPC42363, partial cranidium. L, CPC42364, partial cranidium. M, CPC42365, partial cranidium. N, CPC42366, partial cranidium. O, CPC42367, partial cranidium. All scale bars are 2 mm, except K = 4 mm.

behind the midpoint of the γ - β segment, passing in front of the anterior glabellar furrow.

Palpebral lobes narrow (tr.), 28% of total cranidial length, sickle shaped in outline, defined by a narrow (tr.), shallow palpebral furrow; anterior tip situated 54% of cranidial length from the

anterior border, posterior tip just anterior of SO. Eye ridge very weakly defined. Palpebral area of fixigena horizontal to slightly downsloping towards preocular field, very narrow (tr.) with maximum width 48% the adjacent glabellar width; very elongate (exsag.). Postocular area short (exsag.) and downsloping toward the posterior lateral projections. Very small, faint bacculae present, appears nested within the glabellar axial furrow at the base of the SO furrow. Posterolateral projections of fixigena narrow (exsag.), strongly downsloping towards lateral corners. Posterior border very narrow (exsag.), separated for the most part from fixigenal field by deep, moderately narrow (exsag.) border furrow.

Pygidium up to 5 mm long (sag.), transversely elliptical, strongly convex, length:width ratio of 52%. Anterior margin slightly arched forward. Posterior margin broadly rounded. . Axis prominent, narrow (tr.), tapered posteriorly, width:length ratio of 65%, of moderate length, occupying about 77% of sagittal length of pygidium. Very narrow (sag.), articulating half-ring, faintly defined by a moderately shallow, narrow (sag.) inter-ring furrow. Six faintly defined axial rings present, separated by very faint, moderately shallow, narrow (sag., exsag.) inter-ring furrows. Terminal piece small, defined posteriorly by abrupt change in slope, small, faint, postaxial ridge present. Axial furrows moderately deep and narrow (tr.), fading out near posterior. Pleural regions strongly convex, with four narrow (exsag.), moderately deep pleural furrows and a shorter, much fainter fifth furrow; all furrows directed posterolaterally, terminating before reaching margin, becoming shorter and fainter posteriorly. Border vague defined by change in slope; with six pairs of broad based spines and much shorter posterior axial spine; spines progressively shorten posteriorly, directed backwards, with a gentle curve.

Prosopon over cephalon, librigena and pygidium is smooth. Anterior of cranidium covered by terrace ridges.

Hypostome, rostral plate, librigena and thorax unknown.

Discussion. This material was originally reported by Öpik (1967, appendix 2, p. 16) as “*Metopotropis* sp. nov.” in the Ross River Gorge at the NT187 locality. Specimens from AS167, AS168, AS178, GOYWEST, the GOY section and 87-008 show a great deal of similarity, particularly in the outline of the anterior cranial margin, the shape and dimensions of the glabella, frontal area and palpebral lobe, position of the tropidium, the outline of the pygidium, dimensions of the axial lobe, positioning of the pleural furrows, and shape of the pygidial spines. The only differences between specimens would be the slightly deeper lateral glabellar furrows and SO in cranidia from the 87-008 locality. These differences, however, are likely to be taphanomic, due to their preservation in different lithofacies. Therefore, we consider it reasonable that all of these specimens belong to the same taxon.

The single figured cranidium of *Monkaspis travesi* (Öpik, 1967) is almost identical to the specimens described here (Öpik 1967, pl. 16, fig. 9). The Goyder Formation material only differ slightly in having a somewhat narrower (tr.) palpebral area, a more shallow, and a tropidium that is situated more posteriorly at the anterior of the glabella. However, given the small size of the holotype cranidium of *M. travesi*, it is likely that these differences are ontogenetic (e.g. see ontogenetic variation in *M. quadrata* in Peng *et al.* 2004a, by comparing pl. 63, fig. 1 with pl. 63 fig. 7). Since there are no larger specimens of *M. travesi* or associated pygidia currently known, we only tentatively compare the Goyder Formation material.

The cranidia from the Goyder Formation also resemble material assigned to *Monkaspis sichuanensis* (Zhu in Lu *et al.* 1974) from the Guzhangian of China in having a rounded anterior margin, parallel-sided to slightly tapered glabella with a rounded anterior, faint bacculae, a long (sag.) preglabellar area, and development of tropidium extending as a strong arc across the cranidium just behind the midpoint of the γ - β segment (see Lu *et al.* 1974, pl. 42, fig. 1, 2). Unfortunately, the cranidia of *M. sichuanensis* are too fragmentary to allow further comparison. Pygidia from the Goyder Formation resemble those belonging to

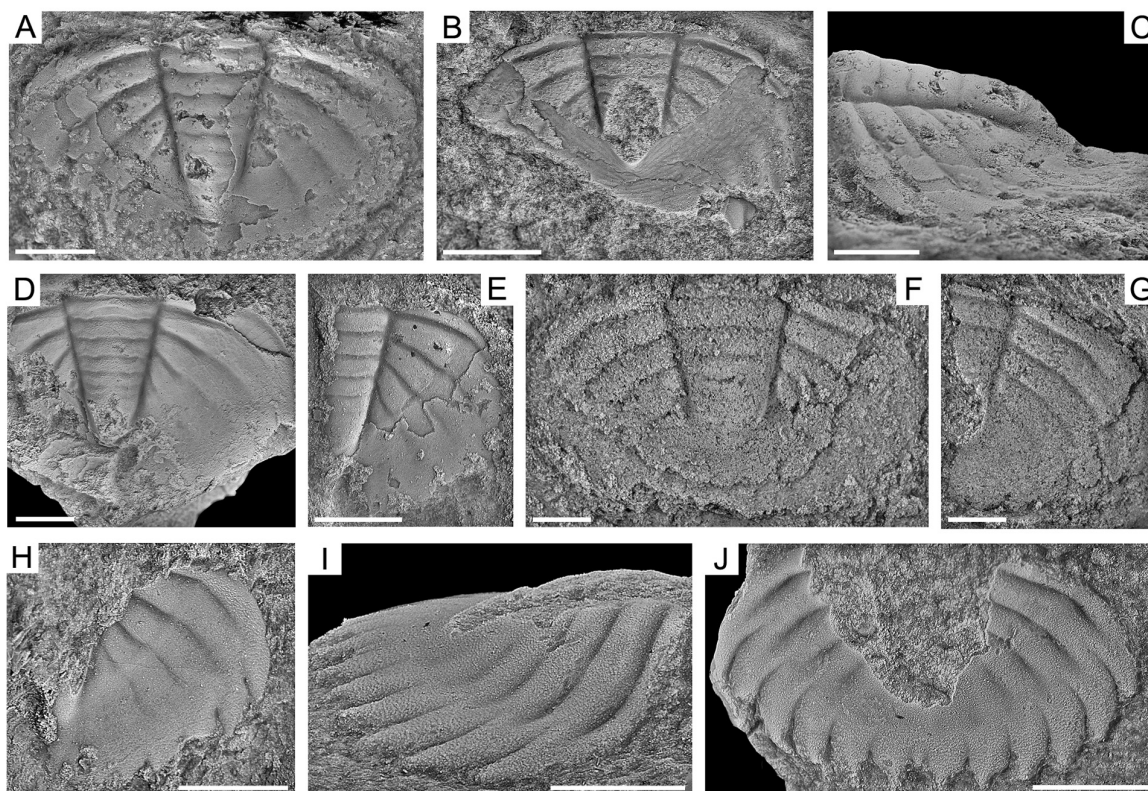


FIGURE 23. *Monkaspis* cf. *travesi* (Öpik, 1967) from the Mindyallan Goyder Formation. A, C come from spot locality AS167; B, D, E come from spot locality GOYWEST; F, G, come from spot locality 87-008; H comes from sample GOY/86 in the GOY section; and I, J, come from spot locality AS168. A, C, CPC42368, partial pygidium; A, dorsal view; C, lateral view. B, CPC42369, partial pygidium. D, CPC42370, partial pygidium. E, CPC42371, partial pygidium. F, CPC42372, partial pygidium. G, CPC42373, partial pygidium. H, CPC42374, partial pygidium. I, J, CPC42375, partial pygidium; I, lateral view; J, dorsal view. All scale bars are 2 mm, except B = 4 mm.

M. sichuanensis, particularly those figured by Zhou *et al.* (1977 pl. 46, figs 24, 25), with both sharing a transversely elliptical outline (width:length approximately 45% to 55%), five pleural furrows which become fainter posteriorly, six pairs of short, broad-based spines and a much shorter posterior axial spine. In this way, both the Goyder Formation material and *M. sichuanensis* differ from most other species of *Monkaspis* which often have a longer pygidium (sag.) that lacks the posteromedial axial spine. However the Goyder Formation material differs from *M. sichuanensis* in possessing six, rather than five, axial rings on the pygidium.

Occurrence. GOY section horizons 64.9, 73.2, 83.9 m (Fig. 3). Also found at 87-008, AS167, AS168, AS178 and GOYWEST.

Family Ceratopygidae Linnarsson, 1869

Proceratopyge Wallerius, 1895

Type species. *Proceratopyge conifrons* Wallerius, 1895.

Discussion. There has been immense discussion on the generic concept of *Proceratopyge* Wallerius, 1895 (see Choi *et al.* 2008 and references therein). Some authors favour Rushton (1983) and Pratt's (1992) view of a single genus, whilst others follow Lu & Lin (1989) and Peng's (1992) concept of three subgenera: *Proceratopyge* Wallerius, 1895, *Sinoproceratopyge* Lu & Lin, 1989 and *Lopnorites* Troedsson, 1937. Peng (1992) suggested that the three subgenera appeared in stratigraphic order (the same as given above, from oldest to youngest), noting that older species have more transverse pygidia with shorter (sag.), less segmented axes. However, the three subgenera are known to overlap in Sweden (Shergold *et al.* 2000). Given that over 70 species are currently described (Rushton 1983; Lee & Choi 1995; Yuan & Yin 1999), it appears this genus is in desperate need of a comprehensive taxonomic revision. We, therefore, refrain from using the subgeneric classification until more detail is known about *Proceratopyge*.

Proceratopyge sp.

Fig. 24

Material. Eleven pygidia figured, CPC42376–CPC42386. Thirty-nine pygidia not figured (mostly fragments).

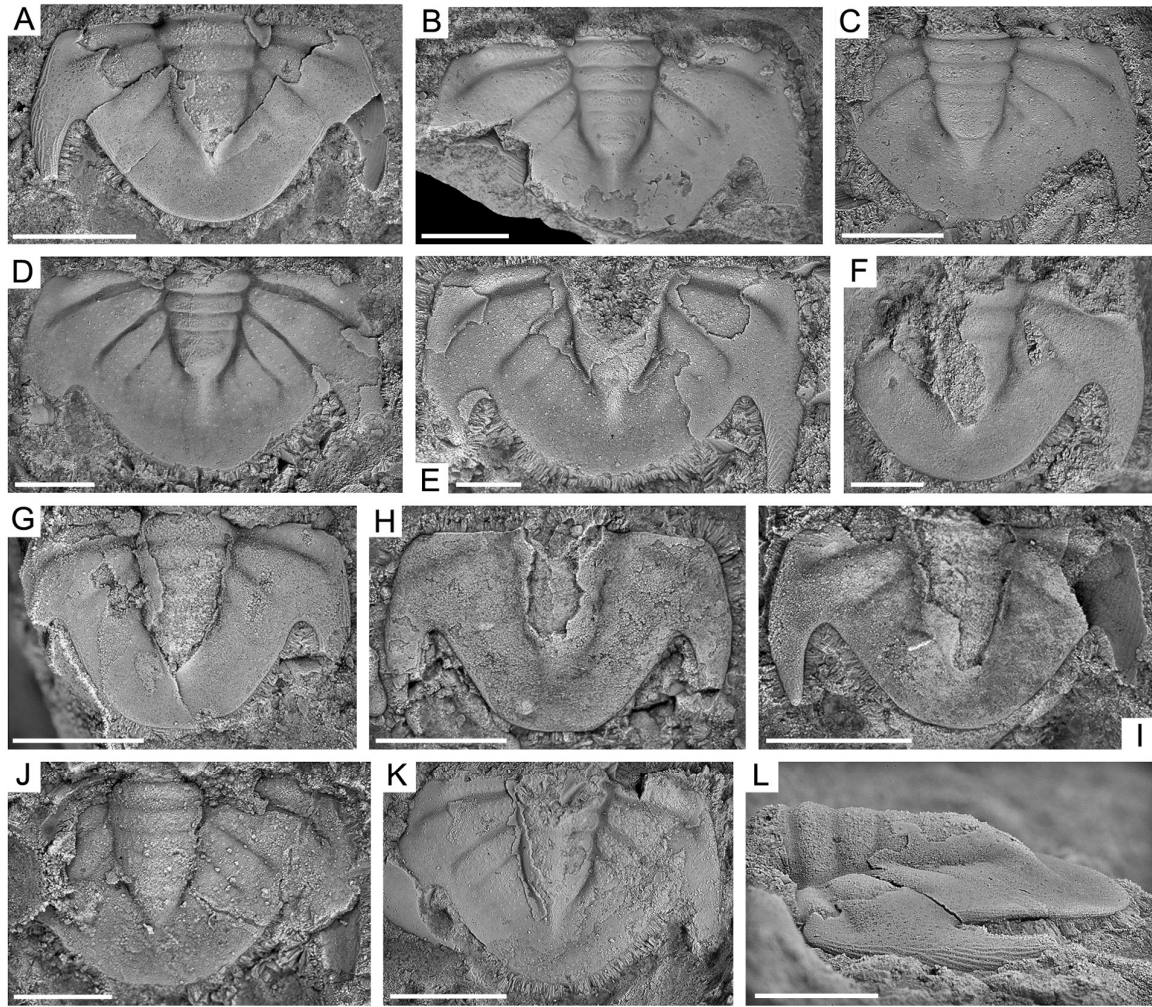


FIGURE 24. *Proceratopyge* sp. from the Mindyallan Goyder Formation. A–E, F–L come from sample GOY/97 in the GOY section; E comes from sample GOY/67 in the GOY section. A, L, CPC42376, partial pygidium; A, dorsal view; L, lateral view. B, CPC42377, partial pygidium. C, CPC42378, partial pygidium, latex cast. D, CPC42379, partial pygidium. E, CPC42380, partial pygidium. F, CPC42381, partial pygidium. G, CPC42382, partial pygidium. H, CPC42383, partial pygidium. I, CPC42384, partial pygidium. J, CPC42385, partial pygidium. K, CPC42386, partial pygidium. All scale bars are 2 mm, except A, B, H, K = 4 mm, and E, F = 1 mm.

Description. Complete pygidia up to 8 mm long, fragments up to 11 mm (sag.); subtriangular in outline excluding spines, slightly convex, length:width ratio of 64% to 69% (mean 67%; $n = 6$). Anterior margin straight. Posterior margin a strong parabolic curve. Axis prominent, moderately narrow (tr.), modestly tapered posteriorly, width:length ratio of 75% to 81% (mean 78%; $n = 3$), short, occupying about 65% of sagittal length of pygidium. Very narrow (sag.) articulating half-ring, faintly defined by a shallow, narrow (sag.) inter-ring furrow. Three well defined axial ring and a faint fourth present, separated by shallow, narrow (sag., exsag.) inter-ring furrows. Terminal piece small, defined posteriorly by abrupt change in

slope; short (sag.), faint, postaxial ridge present. Axial furrows moderately deep and narrow (exsag.), becoming shallower and broader posteriorly until fading out completely around postaxial ridge. Pleural regions only very slightly convex, with three narrow (exsag.), moderately deep pleural furrows and a fourth much shorter (exsag.), shallower furrow. First pleural furrow encroaches slightly onto pygidial spine. The first three pleural furrows directed posterolaterally, terminate about halfway to the margins; fourth pleural furrow directed posteriorly and terminates shortly after axial furrows. Border not well defined, only distinguishable by slight change in convexity. Pairs of very broad based spines attached to pygidial anterior lateral corners, spines are broad (tr.) and blade-like, directed posteriorly.

Prosopon smooth over pygidial axis. Pleural field with minute granules on pleural ribs. Spines and posterior margin covered with very fine terrace lines and evenly spaced pits near the spine bases.

Cephalon, hypostome, rostral plate and thorax unknown.

Discussion. Originally, this taxon was reported by Öpik (1967, appendix 2, p. 16) as ‘*Plectrifer* ? sp. nov. (pygidia)’, despite the fact these pygidia show little similarity with this genus. *Plectrifer* Öpik, 1967 differs mainly in having a long axis that extends more than 90% the length of the pygidium, a distinct pygidial border furrow, and a pair of pygidial spines that extend from the border and appear to be independent of pleural segmentation. The Goyder Formation pygidia have greater similarity with *Proceratopyge* in exhibiting a subtrapezoidal to subtriangular outline, a small postaxial ridge, a very poorly defined pygidial border furrow, and spines developed from the first pleural segment. It differs from most species in the genus having a distinctly subtriangular outline and relatively short (sag.) pygidial axis. In these respects, the Goyder Formation material is similar to Australian species placed in the *Proceratopyge* (*Sinoproceratopyge*) subgenus by Yuan & Yin (1999). In particular, these specimens are comparable to *Proceratopyge gordonensis* Jago, 1987 and *Proceratopyge* sp.

from the Idamean Singing Creek Formation of Tasmania (Jago 1987. The Goyder Formation material differs, however, in having narrower pleural furrows and a slightly more curved posterior margin. Given the paucity of cranidial material, this taxon is left under open nomenclature.

Occurrence. GOY section horizons 49.4 and 73.2 m (Fig. 3).

Family Nepeidae Whitehouse, 1939

***Biaverta* Öpik, 1967**

Type species. *Biaverta biaverta* Öpik, 1967.

Discussion. Öpik (1967) originally placed *Biaverta* Öpik, 1967 in the Menomoniidae Walcott, 1916, based on its concave preglabellar field, large, highly convex palpebral and posterior areas, deep glabellar furrows which widen (exsag.) slightly adaxially, and anteriorly-situated palpebral lobes. Bentley *et al.* (2009) suggested that *Biaverta* was better placed in the Nepeidae Whitehouse, 1939 rather than the Menomoniidae (Öpik 1967; Wang, *et al.* 1989). The characteristics used by Paterson (2005) to define the Nepeidae exclude *Biaverta* as it lacks a number of features including: distinctive palpebral lobes, prominent bifurcating eye ridges, and a preglabellar boss. However, Westrop & Adrain (2009) conducted a cladistic analysis, which placed *Biaverta* as an ingroup member of the Nepeidae. This result was largely based on the shared deep lateral glabellar furrows, large, convex palpebral and posterior areas, and a posterior border furrow which is deep abaxially, but shallows at the steep downturn near the extremities of the posterolateral projections. We follow Bentley *et al.* (2009) and Westrop & Adrain (2009) in placing *Biaverta* within the Nepeidae.

***Biaverta reineri* Öpik, 1967**

Fig. 25

1967 *Biaverta reineri*; Öpik, p. 371–372, pl. 39, figs 1–5.

?1989 *Biaverta* sp. indet.; Wang, Mills, Webby, Shergold, p. 113, fig. 4Q.

Holotype. (Original designation) CPC5660, cranidium from the Mindyallan Mungerebar Limestone, Loc. G119.

Other material. Twelve cranidia figured, CPC42387–CPC42398. Twenty-four cranidia not figured (mostly fragments).

Description. Largest cranidium 5 mm long (sag.). Cranidium subtrapeziform, length:width ratio 65%, maximum width across posterolateral projections of fixigena; narrowest point of cranidium at the γ – γ section, where it is about 60% of maximum cranidial width (tr.). Anterior margin strongly rounded; elevated medially being retroverted. Posterior margin strongly bowed forward (exsag.), moderately expanding abaxially. Anterior branches of facial suture (γ – α) converge anteriorly in a broad arc. Posterior branches of facial suture strongly curve towards posterolateral corners of cranidium. Axial furrows broad and indistinct. Glabella narrow (tr.) and moderately convex, with maximum convexity at about midwidth, width:length ratio of 81% to 82% (mean 81%; n = 3), occupying about 68% cranidial length; slightly tapering forward, width (tr.) across anterior 52% maximum width of glabella. Lateral glabellar furrows narrow (tr.) and deep. S1 short (tr.), directed transversely, becoming slightly wider (exsag.) adaxially before terminating. S2 parallel to and shorter (tr.) than S1; S3 effaced. Occipital ring moderately wide (sag.), narrowing abaxially; SO moderately narrow (sag.), bowed forward medially, deep and deepening abaxially. Very faint circular bacculae,

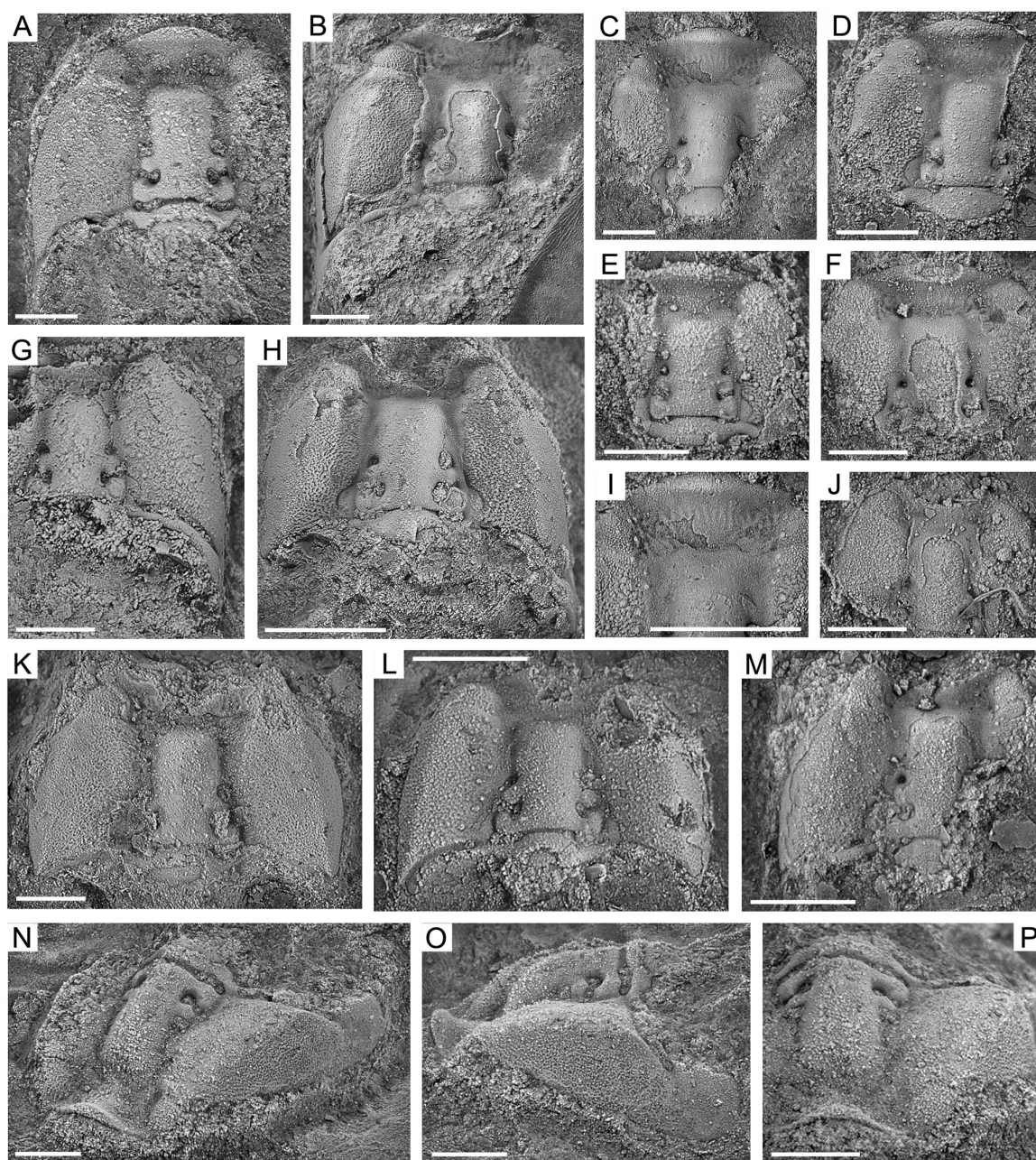


FIGURE 25. *Biaverta reineri* Öpik, 1967 from the Mindyallan Goyder Formation. All specimens come from sample GOY/173.6 in the GOY section. A, N, O, P, CPC42387, partial cranidium; A, dorsal view; N, oblique anterolateral view; O, lateral view; P, anterior view. B, CPC42388, partial cranidium. C, I, CPC42389, partial cranidium; C, dorsal view; I, close up on ornament. D, CPC42390, partial cranidium. E, CPC42391, partial cranidium. F, CPC42392, partial cranidium. G, CPC42393, partial cranidium. H, CPC42394, partial cranidium. J, CPC42395, partial cranidium. K, CPC42396, partial cranidium. L, CPC42397, partial cranidium. M, CPC42398, partial cranidium. All scale bars are 1 mm.

positioned opposite and behind L1. Anterior border strongly upturned medially; poorly defined, lacking anterior border furrow. Preglabellar field of moderate length, making up 26% of total sagittal length; strongly concave Preocular field highly convex and strongly downsloping adaxially towards preglabellar field. Palpebral lobes absent. Eye ridges faintly

defined on exterior surface, more visible of exfoliated cranidia; extending from the anterolateral corners of the axial furrows in a slight anterior curve towards the γ points; eye ridges appear faintly bifurcated. Palpebral area situated very forward on the cranidium, slightly forward of the glabella anterior; very short (exsag.); convex, downsloping towards axial furrows and preglabellar field. Postocular field long (exsag.), 68% of sagittal cranidial length; wide (tr.), 72% of the maximum cranidial width; slightly downsloping medially towards the axial furrows and posteriorly near the posterior border furrow. Posterolateral projections of fixigena are flat with a steep downturn at the lateral extremities. Posterior border very narrow (exsag.) and slightly wider abaxially. Posterior border furrow deep, very narrow (exsag.), disappearing abaxially at the steep downturn near lateral extremities.

Prosopon consists of minute granules interconnected to form a dense reticulated pattern covering the palpebral area. Small, dense granules cover the anterior border, glabella, preocular field, eye ridges and posterolateral projections. Preglabellar field with faint caecal veins all directed anteriorly. Axial furrows smooth.

Hypostome, rostral plate, librigena, thorax and pygidium unknown.

Discussion. These distinctive cranidia are commonly found in the upper sandy limestone facies of the GOY section. The Goyder Formation material shows a remarkable resemblance to *Biaverta reineri* Öpik, 1967 described from Mindyallan Mungerebar Limestone in the Georgina Basin (Öpik 1967). Specimens from both localities have the characteristic slightly upturned anterior border, preglabellar field of moderate length that is laterally strongly concave and medially slightly convex, as well as a prosopon of dense minute granules (compare Fig. 25A–M with Öpik 1967, pl. 39, fig. 1–5). The taxon described here only varies marginally from those from the Mungerebar Limestone specimen, particularly the holotype, in possessing better developed lateral glabellar furrows and eye ridges, although this may be attributed to preservational quality, as the Mungerebar material is rather poorly preserved, especially the coarsely silicified specimens (e.g., Öpik 1967, pl. 39, fig. 3–5). *Biaverta reineri*

is easily distinguished from the only other named species, *B. biaverta* Öpik, 1967, by its less upturned anterior border and longer preglabellar field.

Specimens from the Goyder Formation also resemble a single, poorly preserved cranidium described by Wang *et al.* (1989) as *Biaverta* sp. from the Mindyallan Boshy Formation, NSW. Both the Goyder Formation material and NSW specimen share the slightly upturned anterior border and longer (sag.) preglabellar field that is typical of *B. reineri*. Given that the NSW cranidium has been distorted and is coarsely preserved in sandstone, we have only questionably synonymised it with the Goyder Formation material.

Occurrence. GOY section horizon 132.7 m (Fig. 3).

Distribution. Goyder Formation, Amadeus Basin, Northern Territory. Mungerebar Limestone, Georgina Basin, Northern Territory and Queensland. Possibly the Boshy Formation, Koonenberry Belt, New South Wales. All occurrences are Cambrian Series 3, Guzhangian (Mindyallan) in age.

***Biaverta?* sp.**

Fig. 26A–C

Material. A single partial cranidium figured, CPC42399.

Description. Incomplete cranidium 3 mm long (sag.). Cranidium subtrapeziform, maximum width appears to have been across posterolateral projections of fixigena; narrowest point of cranidium at the γ – γ section. Anterior margin strongly rounded; slightly elevated medially being only moderately retroverted. Posterior margin unknown. Anterior branches of facial suture (γ – α) converge anteriorly in a broad arc. Axial furrows broad and indistinct. Glabella narrow (tr.) and moderately convex, with maximum convexity at about midwidth; slightly

tapering forward, anterior glabellar margin truncate. Lateral glabellar furrows narrow (exsag.) and shallow. S1 short (tr.), directed posteromedially. S2 unknown; S3 effaced. Anterior border very slightly upturned medially; poorly defined, lacking anterior border furrow. Preglabellar field short; slightly concave. Preocular field highly convex and strongly downsloping adaxially towards preglabellar field. Palpebral lobes absent. Eye ridges moderately well defined extending from the anterolateral corners of the axial furrows in a slight anterior curve towards the γ points; eye ridges wide (exsag.). Palpebral area situated very forward on the cranidium, slightly forward of the glabellar anterior; very short (exsag.); convex, downsloping towards axial furrows and preglabellar field. Postocular field long (exsag.), wide (tr.) and slightly downsloping medially towards the axial furrows. Posterolateral projections unknown.

Prosopon incompletely known from exfoliated specimen.

Hypostome, rostral plate, librigena, thorax and pygidium unknown.

Discussion. This taxon is represented by a single cranidium from the lower limestone beds of the GOY section. The slightly upturned anterior border, concave preglabellar field, an apparent lack of palpebral lobes, and a long (exsag.) and inflated postocular area support possible placement of this taxon in *Biaverta*. It bears a modest resemblance to small cranidia of *B. reineri* (e.g., Öpik 1967, pl. 39, fig. 4). However, given the larger size of the cranidium in this taxon (3 mm incomplete, estimated to be roughly 4 to 4.5 mm complete), it seems unlikely that this specimen belongs to *B. reineri*. Due to the incomplete preservation of the only available cranidium, we questionably assign it to *Biaverta*.

Occurrence. GOY section horizon 73.2 m (Fig. 3).

Nepeidae gen. et sp. indet.

Fig. 26D–F

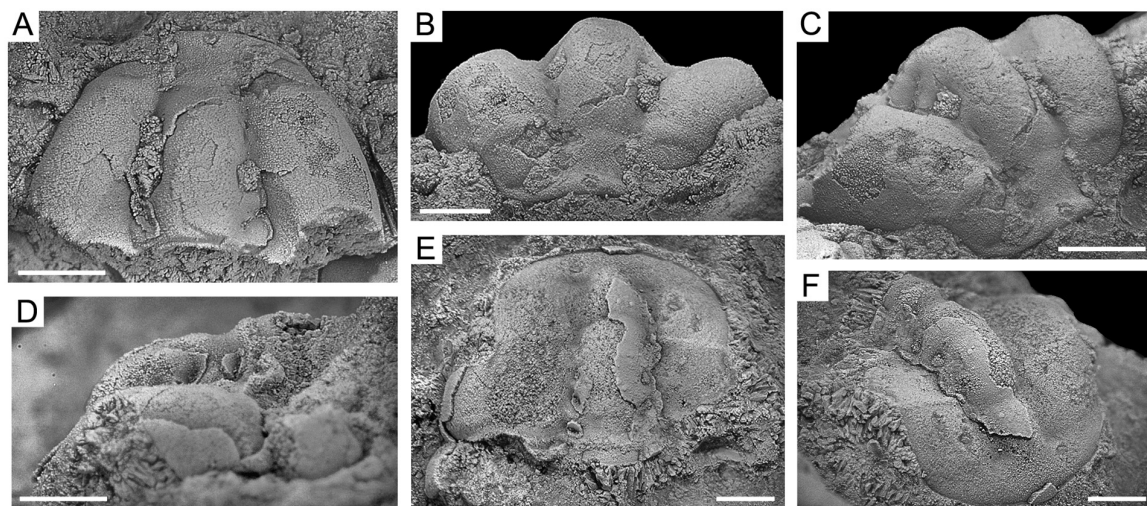


FIGURE 26. *Biaverta?* sp. from the Mindyallan Goyder Formation. Specimen comes from sample GOY/97 in the GOY section. A–C, CPC42399, partial cranidium; A, dorsal view; B, anterior view; C, oblique anterolateral view. Nepeidae gen. et sp. indet. from the Mindyallan Goyder Formation. Specimen comes from sample GOY/67 in the GOY section. D–F, CPC42400, partial cranidium; D, lateral view; E, dorsal view; F, oblique anterolateral view. All scale bars are 1 mm.

Material. A single partial cranidium figured, CPC42400.

Description. Largest cranidium 4 mm long (sag.). Cranidium trapeziform, length:width ratio 70%, maximum width across posterolateral projections of fixigena; narrowest point of cranidium forward of the palpebral lobes (γ – γ), where it is about 64% of maximum cranidial width (tr.). Anterior margin strongly rounded; posterior margin incompletely preserved. Anterior branches of facial suture subparallel, then convergent to anterior margin; posterior branches strongly divergent, curved to distal end of posterolateral projection. Glabella narrow (tr.) and moderately convex, with maximum convexity at about midwidth, width:length ratio of 67%, occupying about 58% cranidial length; slightly tapering forward, width (tr.) across anterior 60% maximum width of glabella; anterior glabellar margin truncate. Axial furrows broad and indistinct. Baculae poorly developed. Lateral glabellar furrows narrow (exsag.) and deep. S1 directed posteromedially; S2 shorter (tr.) than S1, only being a small indent in the lateral glabella surface; S3 poorly developed or absent. Occipital ring of moderate width;

SO moderately wide (sag.), bowed very slightly forward medially, shallow medially and deepening abaxially. Anterior border downsloping to anterior margin; length (sag.) 7% total cranidial length. Anterior border furrow very shallow and poorly defined. Preglabellar field possesses an inflated prelabellar boss, triangular in outline, with the anterior border furrow bowed around its anterior margin, maximum width (tr.) of boss approximately equal to anterior glabellar width. Preocular field highly convex and strongly downsloping adaxially towards prelabellar boss. Palpebral lobe small, less than 4% of total cranidial length (sag.), not very clearly defined. Eye ridges very faint, thin (exsag.), extending from the anterolateral corners of the axial furrows in a straight line towards the anterior tip of palpebral lobes. Palpebral area of fixigena flat to slightly convex, very gently downsloping towards axial furrows. Postocular field flat anteriorly and downsloping near the posterior border furrow. Posterolateral projections of fixigena with a steep downturn at the lateral extremities, directed posterolaterally and widening (exsag.) posteriorly. Posterior border incompletely preserved. Posterior border furrow shallow, wide (exsag.), widening (exsag.) strongly near posterolateral extremities.

Prosopon incompletely known from exfoliated specimen.

Hypostome, rostral plate, librigena, thorax and pygidium unknown.

Discussion. This taxon is known from one poorly preserved cranidium found in the lowest bed of the GOY section. Presence of a cranidium with a trapeziform outline, a moderately tapered glabella with two pairs of lateral glabellar furrows, a glabella with a length (sag.) around 58% of cranidial length, prelabellar boss with a triangular outline, and posterolateral projections that are strongly downsloping all suggest an assignment to the nepeids. The presence of a triangular prelabellar boss would advocate placement in the genus *Penarosa* Öpik, 1970. However the Goyder Formation material has small palpebral lobes and lacks the S3 lateral glabellar furrow, placing it outside generic concept (Paterson 2005). The

combination of small palpebral lobes and a faint anterior border in Goyder Formation material give it the resembles to *Ascionepea janitrix* Öpik, 1967, a taxon which was later interpreted as a juvenile specimen of *Ferenepea hispida* Öpik, 1967 (Paterson 2005, pl. 7, fig. 11). Yet the larger size of the Goyder Formation specimen makes it unlikely that this material represents a juvenile. Given the indifferent nature of preservation and only a single cranidium a more detailed comparison is impossible. Hence, the material described here is placed under open nomenclature.

Occurrence. GOY section horizon 49.4 m (Fig. 3).

Family Catillicephalidae Raymond 1937

***Paradistazeris* Zhu in Zhang *et al.*, 1980**

Type species. *Distazeris* (*Paradistazeris*) *sichuanensis* Zhu in Zhang *et al.*, 1980.

Discussion. For a comprehensive discussion of the genus, see Peng *et al.* (2004b, p. 57, 58).

***Paradistazeris* sp.**

Fig. 27A–C

Material. A single partial cranidium figured, CPC42401.

Description. Cranidium outline semicircular, incomplete specimen 2 mm long (sag.), maximum width across posterolateral projections of fixigenae, narrowest point approximately at anterior tip of palpebral lobes (γ – γ); highly convex (sag., tr.). Anterior and posterior margin

incompletely preserved. Glabellar anterior strongly rounded, parallel sided, oblong in outline; strongly convex (sag., tr.), with maximum convexity across posterior; width:length ratio of 68%; anterior glabellar furrow and axial furrows are narrow (sag., exsag., tr.) and deep. Lateral glabellar furrows abaxial extremities do not intersect axial furrow. S1 well defined, deep and narrow (exsag.), directed transversely for a short distance before bifurcating; posterior branch continues backwards for a short distance, anterior branch transverse and abruptly ends shortly after bifurcation. S2 well developed, narrow (exsag.) and deep, directed transversely for the same distance as S1. S3 completely effaced. Occipital ring of moderate length (sag.), above the remaining glabella, becoming slightly narrower abaxially; posterior margin bowed backwards strongly; surmounted by a thin (tr.) spine near the posterior margin, spine is incompletely preserved. SO deep, narrow (sag.), slightly bowed backwards. Anterior cranidium incompletely preserved. Preocular and preglabellar field moderately convex, downsloping toward the anterior border. Palpebral lobes incompletely preserved. Eye ridge well developed, extending posterolaterally from the axial furrow, just posterior of the anterior glabellar furrow, in a forwardly bowed line towards the anterior tip of palpebral lobe. Palpebral area of fixigena slightly downsloping abaxially, maximum width (tr.) is 50% the adjacent glabellar width. Postocular area short (exsag.) and downsloping towards the posterolateral projections. Posterolateral projections of fixigena incompletely preserved.

Prosopon over entire cranidium unknown from exfoliated specimen.

Hypostome, rostral plate, librigena, thorax and pygidium unknown.

Discussion. The sole specimen from the upper beds of the GOY section is preserved as a sandy internal mould. The strongly convex, oblong glabella, bifurcated S1 furrows, glabellar furrows that do not reach the axial furrows, well developed eye ridges, and an occipital spine in the Goyder Formation specimen is closely comparable to that of *Paradistazeris hubeiensis* Zhu in Zhang *et al.*, 1980 from the lower Furongian of South China (cf. Zhang *et al.*, 1980, pl.

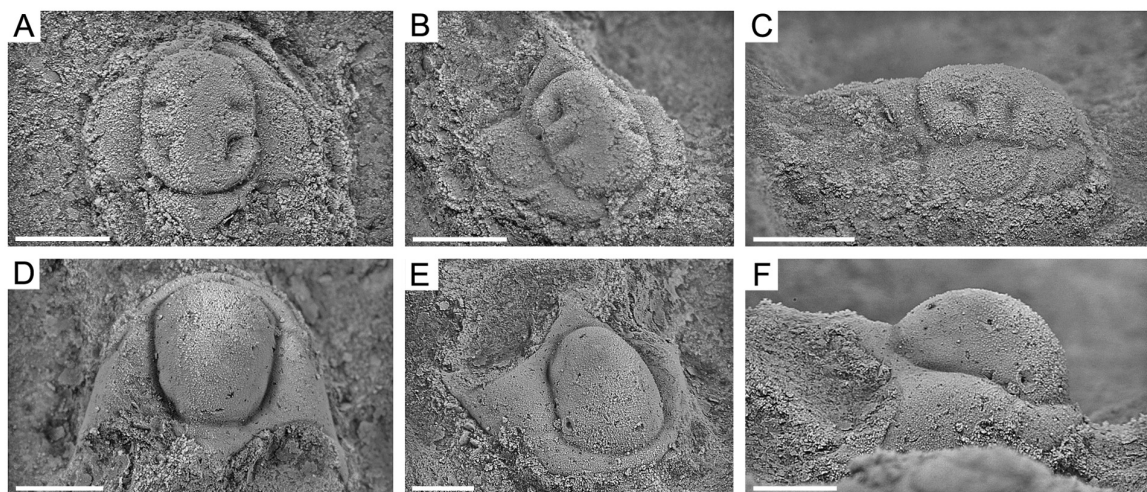


FIGURE 27. *Paradistazeris* sp. from the Mindyallan Goyder Formation. All specimens come from sample GOY/173.6 in the GOY section. A–C, CPC42401, partial cranidium; A, dorsal view; B, oblique anterolateral view; C, lateral view. Catillicephalidae gen. et sp. indet. from the Mindyallan Goyder Formation. Specimen comes from sample GOY/173.6 in the GOY section. D–F, CPC42402, partial cranidium; D, dorsal view; E, oblique anterolateral view; F lateral view. All scale bars are 1 mm.

132, figs 13–15; Peng *et al.* 2004b, pl. 21, fig. 7–10, 13–15). The only difference in the Goyder cranidium is a discernable preglabellar field. However, smaller, similar-sized specimens of *P. hubeiensis* also appear to show this same feature (e.g., Peng *et al.* 2004b, pl. 21, fig. 8), with the preglabellar field becoming shorter (sag.) throughout ontogeny. Unfortunately, the limited material of the Goyder taxon inhibits a specific assignment.

Occurrence. GOY section horizon 132.7 m (Fig. 3).

Catillicephalidae gen. et sp. indet.

Fig. 27D–F

Material. A single partial cranidium figured, CPC42402.

Description. Cranidium outline semicircular, incomplete specimen 3 mm long (sag.), maximum width across posterolateral projections of fixigenae, narrowest point at anterior tip

of palpebral lobes ($\gamma-\gamma$); highly convex (sag., tr.). Anterior strongly rounded. Posterior margin incompletely preserved, appears to have been bowed forward strongly. Anterior branches of facial suture ($\gamma-\alpha$) converge anteriorly in a broad arc. Glabellar anterior strongly rounded, gently expanding anteriorly, obpyriform in outline; strongly convex (sag., tr.), with maximum convexity across midwidth, lateral slopes convex; width:length ratio of 75%, occupying 96% of the cranial length; anterior glabellar furrow and axial furrows narrow (sag., exsag., tr.) and deep. All lateral glabellar furrow except SO effaced. Occipital ring of moderate length (sag.), below the remaining glabella, becoming slightly narrower abaxially; posterior margin bowed backwards strongly; surmounted by a thin (tr.) spine near the posterior margin, spine is incompletely preserved. SO shallow, narrow (sag.), directed transversely. Anterior cranial border not very well defined, lacking an anterior border furrow. Preocular and preglabellar field moderately convex, downsloping toward the anterior border; very short (sag.), 4% of sagittal cranial length. Palpebral lobes small (exsag.), incompletely preserved. Eye ridge very faint, extending posterolaterally from the axial furrow, just posterior of the anterior glabellar furrow, in a straight line towards the anterior tip of palpebral lobe. Palpebral area of fixigena slightly downsloping towards the lateral borders, maximum width (tr.) is 31% the adjacent glabellar width. Postocular area long (exsag.) and downsloping towards the posterolateral projections. Posterolateral projections of fixigena are slightly downsloping towards the lateral corners, with a steep downturn at the lateral extremities. Posterolateral corners with a small (exsag.) broad-based spine. Posterior border incompletely preserved.

Prosopon over entire cranium is smooth.

Hypostome, rostral plate, thorax and pygidium unknown.

Discussion. This isolated cranium closely resembles material described as “*Catillicephalidae*, gen. nov. et sp. nov.” by Öpik (1967, p. 207, pl. 9, fig. 5) from the Mindyallan Georgina Limestone, later reassigned to *Catillicephalina glasgowensis* (Jago &

Cooper, 2005) by Bentley *et al.* (2009). The Goyder Formation and Georgina Limestone material both possess an effaced obpyriform glabella, faintly developed eye ridges, anteriorly situated palpebral lobes, and posterolateral projections of fixigena that steeply downturn at the lateral extremities (cf. Öpik 1967, pl. 9, fig. 5). However, the presence of a preglabellar field and occipital spine excludes the Goyder specimen being assigned to *C. glasgowensis*. The Goyder cranidium also has a vague resemblance to the poorly preserved specimen identified as *Avonina* sp. nov., also from the Mindyallan Georgina Limestone (Öpik 1967, p. 211, pl. 9, fig. 6); however, the lack of detail on the cranidium prevents further comparison.

While the Goyder cranidium possesses the typical morphology of a catillicephalid, it also closely resembles *Interalia serena* Öpik, 1967 from the Mungerebar Limestone of the Georgina Basin – a monotypic genus that Öpik (1967) assigned to the Lonchocephalidae Hupé, 1953. The only obvious features that separate the Goyder specimen (Fig. 27D–F) from *I. serena* (Öpik 1967, pl. 10, figs 6, 7) are that the latter has a parallel-sided glabella with faint furrows. It is possible that *Interalia* belongs to the Catillicephalidae, but without an associated pygidium, this remains an open question. Given the paucity of sclerites from the Goyder Formation, this species should not be assigned to any catillicephalid genus.

Occurrence. GOY section horizon 132.7 m (Fig. 3).

Family Proasaphiscidae Zhang, 1963

***Adelogonus* Öpik, 1967**

Type species. *Adelogonus solus* Öpik, 1967.

Discussion. This genus was discussed by Peng *et al.* (2004b, p. 25, 26) and was considered a

senior synonym of *Sinocoosella* Yuan & Yin, 1998 and *Plesiocilia* Yuan & Yin, 1998, which are both monospecific genera. The holotype of *Sinocoosella typica* Yuan and Yin, 1998 (pl. 1, fig. 15a, b; GPIN127898), more closely resembles *Henadoparia* Öpik, 1967, exhibiting fused facial sutures, faint eye ridges, a rounded glabellar anterior, deeply incised glabellar furrows that intersect the axial furrows, bifurcated S1 furrows, and a short (sag.) prelabellar field. Given these similarities in the type species, we consider *Sinocoosella* a junior synonym of *Henadoparia*. The only other figured cranidium is the paratype for *Sinocoosella* (GPIN127899, Yuan & Yin 1998, pl. 1, fig. 16), which more closely resembles *Adelogonus* in having unfused facial sutures, a more transverse glabellar anterior, and faintly defined S1 furrows that do not intersect the axial furrows. Whereas the larger size of the paratype cranidium (3.6 mm) compared to the holotype (2.3 mm) of *Sinocoosella* suggests that these discernable differences varied ontogenetically, the specimens from the Goyder Formation demonstrate that *Adelogonus* does not undergo such a dramatic morphogenesis, even at sizes comparable to *Henadoparia* (compare Fig. 28I, J to Fig. 29F, I–K). Therefore, we consider the paratype cranidium of *Sinocoosella typica* to belong in a currently unnamed species of *Adelogonus*.

Peng et al. (2004b, p. 25) also considered *Plesiocilia* Yuan & Yin, 1998 to be a junior synonym of *Adelogonus* based on the morphology being “identical in all respects” to *Sinocoosella typica* Yuan & Yin, 1998. We assume this is made in reference to the paratype specimen of *S. typica*, as the figured cephalic material of *Plesiocilia* (Yuan & Yin 1998, pl. 3, figs 11–13) lacks the fused facial sutures, as in the holotype of *S. typica*. They also noted that the smaller size clearly meant that these specimens represented juveniles. The narrow (tr.) tapered glabella of *Plesiocilia* with S1 furrows situated more in line with the palpebral lobe posterior is very different from juvenile specimens of *Adelogonus*, as seen in the Goyder Formation, which appear to have a relatively wide (tr.), strongly tapered glabella with the S1 furrows situated forward between the γ – ε midpoints (compare Fig. 28I with Yuan & Yin

1998, pl. 3, figs 11, 12). Therefore, we do not place *Plesiocilia* in synonymy with *Adelogonus*.

***Adelogonus prichardi* sp. nov.**

Fig. 28

Etymology. In honour of C. E. Prichard, for his work on the Goyder Formation, including coining its name.

Holotype. CPC42403, cranidium from the Goyder Formation at spot locality AS273 (Fig. 28A–D).

Paratypes. Seven cranidia; CPC42404 (Fig. 28E, F); CPC42405 (Fig. 28G, P); CPC42406 (Fig. 28H); CPC42407 (Fig. 28I, J); CPC42409 (Fig. 28L); CPC42410 (Fig. 28M); and CPC42413 (Fig. 28P); one librigena, CPC42408 (Fig. 28K); and two pygidium; CPC42412 (Fig. 28O); and CPC42414 (Fig. 28R) from sample GOY/97.0, 73.2 m above the base of the formation. One librigena, CPC42411 (Fig. 28N) from sample GOY/109, 83.9 m above the base of the formation.

Material. Eight cranidia, two librigena, and two pygidia figured, CPC42403–CPC42414. Seven cranidia, one librigenae and nine pygidia not figured (mostly fragments).

Diagnosis. Cranidium up to 19 mm long sagittally. Anterior branches of facial suture diverge strongly at 136° – 156° (mean 148° ; $n = 4$). Glabella truncate, pyriform in outline; width:length ratio of 91% to 93%, occupying 77% to 81% of the cephalon length. S1 faintly defined, moderately deep and broad (exsag.), approximately in line with the midpoint between γ – ε , not

intersecting axial furrows. S2 fainter, not intersecting axial furrow; S3 either effected or very faint. SO moderately shallow, narrow, slightly bowed backwards medially; lateral extremities bifurcate in line (exsag.) with anterolateral corners of glabella. Anterior cranidial border moderately broad (sag.), occupying 12% to 13% sagittal cranidial length. Preocular and preglabellar short, 8% to 13% of sagittal cranidial length. Very faint tropidium extends across cranidium in a very broad arc from slightly behind the β point. Palpebral lobe about 24% to 27% (of total cranidial length, reniform in shape. Palpebral area maximum width (tr.) 30% to 34% adjacent glabellar width. Prosopon varies over cephalon. Glabella, occipital lobe, eye ridges, palpebral lobes and palpebral areas with minute granules. Preocular, preglabellar and genal field with an anastomosing network of genal caeca. Anterior board covered with terrace ridges approaching Bertillon pattern.

Description. Cranidium up to 19 mm long (sag.) in complete specimens and potentially over 25 mm long (sag.) in incomplete fragments. Maximum width possibly across posterolateral projections of fixigenae, narrowest point of cranidium forward of the palpebral lobes ($\gamma-\gamma$); moderately convex (sag., tr.). Anterior margin strongly rounded. Posterior margin incompletely preserved. Anterior branches diverge strongly at 136° – 156° (mean 148° ; $n = 4$), then curve abruptly towards the midline at the β point, approximately level with the border furrow before they reach the anterior margin. Glabella truncate, pyriform in outline, moderately convex, with maximum convexity across midwidth, lateral slopes gently convex; width:length ratio of 91% to 93% (mean 92%; $n = 3$), occupying 77% to 81% of the cephalon length; anterior glabellar furrow and axial furrows very narrow (sag., exsag., tr.) and moderately deep. S1 faintly defined, moderately deep and broad (exsag.), approximately in line with the midpoint between $\gamma-\epsilon$, not intersecting axial furrows, directed slightly posteromedially for a short (tr.) distance, before becoming indistinct. S2 and S3 fainter, not intersecting axial furrow; S2 is directed slightly more transversely than S1, whilst S3 is either

effected or very faint and directed slightly anteromedially. Occipital ring of moderate length (sag.), below the remaining glabella, posterior margin slightly bowed backwards. SO moderately shallow, narrow, slightly bowed backwards medially; lateral extremities bifurcate in line (exsag.) with anterolateral corners of glabella; not intersecting axial furrows. Anterior cranial border moderately broad (sag.) and slightly convex, occupying about 12% to 13% (mean 13%; n = 3) of sagittal cranial length, narrowing abaxially; defined by a moderately deep and broad anterior border furrow. Preocular and preglabellar field slightly concave, downsloping toward the anterior border; short, 8% to 13% (mean 10%; n = 3) of sagittal cranial length. Very faint tropidium extends across cranidium in a very broad arc from slightly behind the β point, passing in front of the anterior glabellar furrow. Palpebral lobe about 24% to 27% (mean 26%; n = 3) of total cranial length, reniform in shape, defined by shallow palpebral, anterior tip situated slightly anterior to S3, posterior tip opposite posterior portion of L1. Eye ridge strongly defined, extending posterolaterally from L2 in a straight line diagonally towards the anterior tip of palpebral lobe. Palpebral area of fixigena flat, gently downsloping anteriorly towards eye ridge, maximum width (tr.) is 30% to 34% (n=2) adjacent glabellar width. Postocular area moderately short (exsag.) and sloping slightly posteriorly. Posterolateral projections of fixigena incompletely preserved. Posterior border narrow (exsag.), separated from fixigenal field by shallow, broad (exsag.) border furrow.

Librigena up to 7 mm in length in incomplete specimen. Lateral margin and posterior margins not preserved. Genal field subtrapeziform, moderately convex.

Pygidium large, up to 17 mm long in incomplete specimen (sag.), moderately convex, shape incompletely preserved. Axis, anterior margin and posterior margin incompletely preserved. Pleural regions gently convex, with broad (exsag.), very shallow pleural furrows and narrower interpleural furrows dividing the field into a border (exsag.) anterior and a narrower (exsag.) posterior band. Border not clearly differentiated.

Prosopon varies over entire cephalon. Glabella, occipital lobe, eye ridges, palpebral

lobes and palpebral areas covered with minute granules. Preocular, preglabellar and genal field with an anastomosing network of genal caeca. Anterior board covered with terrace ridges approaching Bertillon pattern. Pygidium prosopone smooth.

Hypostome, rostral plate and thorax unknown.

Discussion. This species is the largest taxon in the Goyder Formation, making fragments easily identifiable. The large truncate glabella with a pyriform outline, bifurcated SO furrow that is not connected to the axial furrows, the narrow (tr.) palpebral area, moderately long (exsag.) palpebral lobes, presence of a faint tropidium (“preocular ridge” of Peng *et al.* 2004b), and minutely granular prosopon all support assignment of these specimens to *Adelogonus* Öpik, 1967. The Goyder material somewhat resembles two Chinese taxa, *Adelogonus oblongus* Lin, Peng Zhou & Yang, 2013 and a currently unnamed taxon described originally as the paratype (GPIN127899) for *Sinocoosella typica* Yuan & Yin, 1998. These three species shares a short preglabellar field which is convex rather than concave (cf. Yuan & Yin 1998, pl. 1, fig. 16), as seen in the other species of *Adelogonus* discussed below. The Goyder Formation material differs, however, from these comparable species in having a more distinct bifurcation in the SO furrow, a slightly more anteriorly situated S1, a longer (sag.) anterior border and more strongly divergent anterior branches of the facial sutures. The presence of a faint tropidium (“preocular ridge” of Peng *et al.* 2004b) in a number of Goyder specimens near the anterior border furrow (Fig. 28E–G, L, P) is remarkably similar to *Adelogonus hunanensis* Peng, Babcock & Lin, 2004b from the Guzhangian Huaqiao Formation in South China (Peng *et al.* 2004b, pl. 9, figs 1–3). The tropidium of the Goyder species, however, is slightly more posteriorly situated and is not effaced near the anterior glabellar furrow, continuing in a broad arc across the entire frontal area. The cranidia of *Adelogonus hunanensis* and the type species, *Adelogonus solus* Öpik, 1967 from the Mindyallan O’Hara Shale in the Georgina Basin, differ from the Goyder Formation

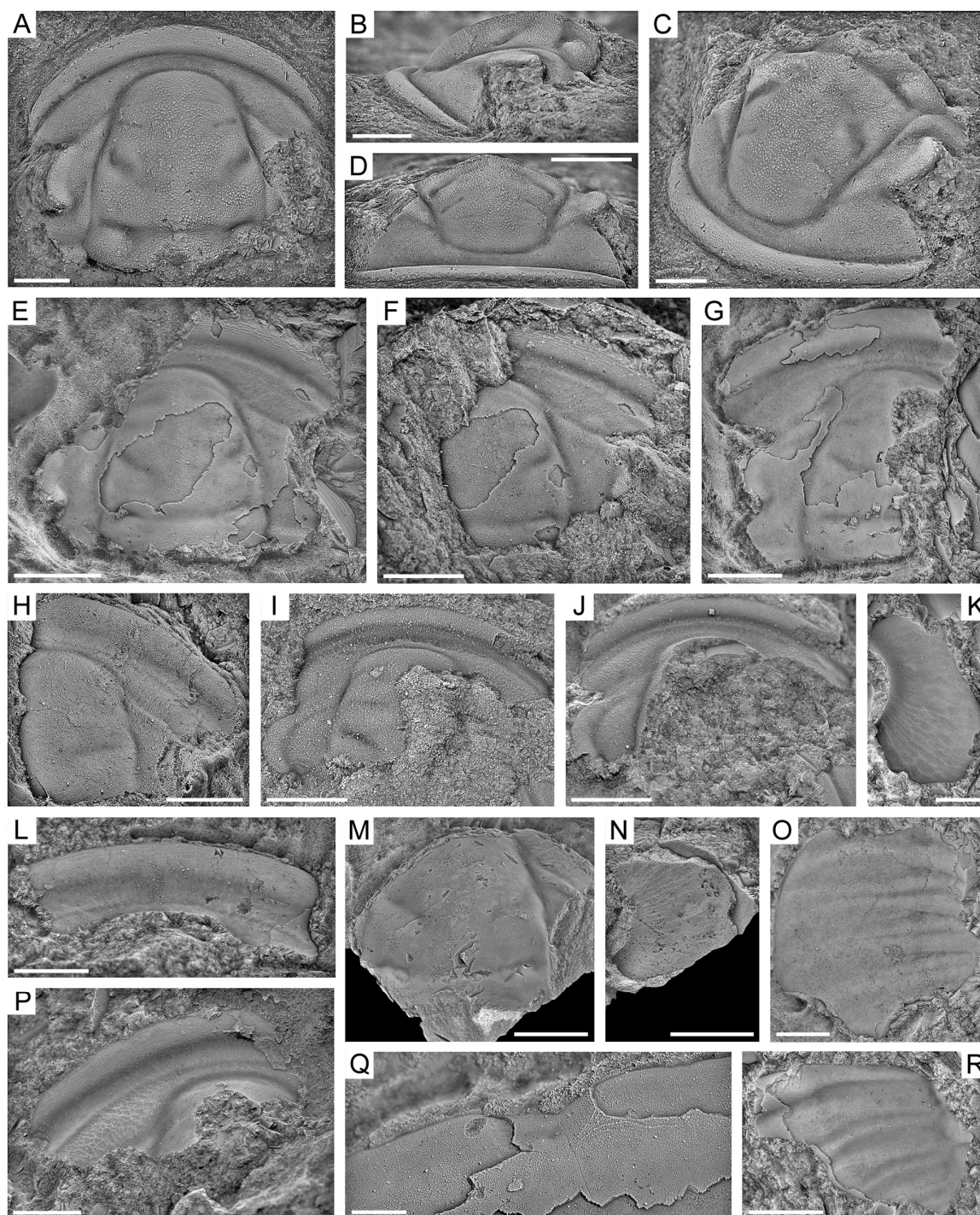


FIGURE 28. *Adelogonus prichardi* sp. nov. from the Mindyallan Goyder Formation. A–D come from from spot locality AS273; E–M, O–R from sample GOY/97 in the GOY section; and N comes from sample GOY/109 in the GOY section. A–D, holotype, CPC42403, partial cranidium; A, dorsal view; B, lateral view; C, anterior view; D, oblique anterolateral view. E, F, paratype, CPC42404, partial cranidium; dorsal view; F, dorsal view of latex cast. G, Q, paratype, CPC42405, partial cranidium; G, dorsal view; Q, close up on healed region of anterior boarder. H, paratype, CPC42406, partial cranidium latex cast. I, J paratype, CPC42407, partial cranidium; I, dorsal view of latex cast; J, dorsal view. K, paratype, CPC42408, partial librigena. L, paratype, CPC42409, partial cranidium. M, paratype, CPC42410, partial cranidium. N, paratype, CPC42411, partial librigena. O, paratype, CPC42412, partial pygidium. P, paratype, CPC42413, partial cranidium. R, paratype, CPC42414, partial pygidium. All scale bars are 4 mm, except A, D, I, Q = 1 mm, B, C, J, P = 2 mm, K = 0.5 mm, and M = 5 mm.

material in having much more convergent anterior branches of the facial suture and poorly defined S1 furrows. The only other material currently assigned to the genus is *Adelogonus?* sp., a pygidium from the Huaqiao Formation (Peng *et al.* 2004b, pl. 35, figs 15, 16). It is likely that this pygidium does not belong to *Adelogonus* (see Peng *et al.* 2004b, p. 27, 28) and given the scarcity of pygidial material from the Goyder Formation, this limits meaningful comparison.

Occurrence. GOY section horizon 73.2 m (Fig. 3). Also found at AS273.

Distribution. Goyder Formation, Amadeus Basin, Northern Territory. Cambrian Series 3, Guzhangian (Mindyallan) in age.

***Henadoparia* Öpik, 1967**

1967 *Henadoparia*; Öpik, p. 348.

1998 *Sinocoosella*; Yuan & Yin, p. 143, 144, pl. 1, fig. 15a, b, *non* pl. 1, figs 14, 16.

2005 *Henadoparia* Öpik; Jago & Cooper, p. 671.

2009 *Henadoparia* Öpik; Bentley, Jago & Cooper, p. 185.

Type species. *Henadoparia integra* Öpik, 1967.

Discussion. Öpik (1967) originally assigned *Henadoparia* to the cedariids based on comparisons with "*Cedaria*" *woosteri* (Whitfield, 1882) from the upper Marjuman Eau Claire Formation of the USA. Adrain *et al.* (2009) has recently disagreed with this comparison, based on the later restudy of "*C.*" *woosteri* by Hughes *et al.* (1997), suggesting rather that

Henadoparia integra Öpik, 1967 belongs to the Proasaphiscidae Zhang, 1963. This seems reasonable given *Henadoparia* shares similarities with other genera in the family, such as *Adelogonus* and *Grandiocus* Cossmann, 1908, which all possess a relatively flat, well defined anterior border, a very short (sag.) preglabellar field, a tapered glabella, and moderately sized palpebral lobes situated midway on the cranidium.

Independently of *Sinocoosella* being included within *Adelogonus* by Peng *et al.* (2004b), *Sinocoosella* was also synonymised with *Henadoparia* by Jago & Cooper (2005) based on “no significant difference” between the two genera. As already discussed under *Adelogonus* above, the type specimen of *Sinocoosella typica* is very similar to *Henadoparia*. The apparently fused facial sutures is a highly diagnostic feature of *Henadoparia* and separates it from all other proasaphiscids (see Fig. 29; Öpik 1967, pl. 37, fig. 1–3; Jago & Cooper 2005, fig. 4M–O; Bentley *et al.* 2009, fig. 8O–S). As the type specimen of *Sinocoosella* (GPIN127898) shows these distinctive fused facial sutures, as well as all the other characteristics typical of the genus, we agree with Jago & Cooper (2005) in synonymising *Sinocoosella* under *Henadoparia*.

***Henadoparia integra* Öpik, 1967**

Fig. 29

1967 *Henadoparia integra*; Öpik, p. 348–350, text-fig. 134, pl. 37, figs 1–5.

2005 *Henadoparia integra* Öpik; Jago & Cooper, p. 671, fig. 4M–O, Q, *non* fig. 4J, P.

?2009 *Henadoparia cf. integra* Öpik; Bentley, Jago & Cooper, p. 185, fig. 8O–S.

Holotype. (Original designation) CPC5642, cephalon from the Mindyallan O’Hara Shale, Loc. D6.

Other material. Ten cranidia figured, CPC42415–CPC42424. Fifteen cranidia not figured (mostly fragments).

Description. Cephalon semicircular, up to 4 mm long (sag.) in complete specimens and 6 mm long (sag.) in incomplete fragments. Length:width ratio approximately 53%; moderately convex (sag., tr.). Anterior margin strongly rounded (tr.). Posterior margin bowed moderately anteriorly. Facial suture appear absent. Glabella truncate, trapezoidal in outline, highly convex, with maximum convexity across midwidth, lateral slopes gently convex; width:length ratio of 84%, occupying 81% of the cephalon length; anterior glabellar furrow and axial furrows very narrow (sag., exsag., tr.) and deep. S1 well defined, deep and narrow (exsag.), intersecting axial furrow approximately in line with the ϵ point, directed slightly posteromedially for a short distance, before bifurcating with the anterior branch traversing a small distance anteromedially before becoming indistinct and the posterior branch continuing posteromedially. S2 and S3 fainter; S2 is directed transversely, whilst S3 is directed slightly anteromedially. Occipital ring of moderate length (sag.), below the remaining glabella, becoming slightly narrower abaxially, posterior margin strongly bowed backwards. SO narrow, strongly bowed backwards medially, deep and deepening abaxially before intersecting the axial furrows, lateral extremities bifurcate in line (exsag.) with anterolateral corners of glabella. Anterior cranial border narrow (sag., exsag.), slightly convex, occupying about 8% of sagittal cranial length. Anterior border furrow shallow and wide (sag., exsag.). Preglabellar field very short (sag., exsag.); slightly concave, almost forming a prelabellar furrow. Preocular field, slightly convex, strongly downsloping toward the anterior border furrow. Palpebral lobes large, 29% of total cranial length, reniform in outline, defined by narrow (tr.), very shallow palpebral furrow, anterior tip situated slightly forward of S2, posterior tip just behind the position of S1. Eye ridge moderately defined, extending slightly posterolaterally from S3 in a straight line towards the anterior tip of

palpebral lobe. Palpebral area slightly convex, downsloping towards the axial furrows, maximum width (tr.) is 39% adjacent glabellar width. Postocular area moderately long (exsag.) and slightly downsloping toward the posterior border furrow. Posterolateral corners strongly downsloping in a similar manner towards the lateral corners and onto the genal spine. Posterior border narrow (exsag.), separated for the most part from the rest of the cephalon by moderately deep, wide (exsag.) border furrow. Lateral margins of cephalon, including that of genal spine, evenly curved. Lateral border moderately well defined by slightly wide (tr.), moderately deep lateral and posterior border furrows; furrows coalesce in an even curve; furrow continues onto genal spine. Genal spine broad based, blade-like, reaching approximately 45% the total cephalon sagittal length.

Prosopon on the borders, palpebral area and palpebral lobes all smooth. Lateral, subocular surfaces of cephalon as well as the glabella and occipital ring covered in very minute granules. Genal field with an anastomosing network of genal caeca.

Rostral plate, thorax unknown. See Öpik (1967) for a description of the pygidium from the type locality.

Discussion. The specimens described here bear a strong resemblance to *Henadoparia integra* Öpik, 1967 from the Mindyallan O'Hara Shale and Georgina Limestone in the Georgina Basin. The Goyder Formation material has the same cephalic outline, short (sag.) preglabellar field, fused facial sutures, glabellar shape and furrows, as well as the same palpebral lobe, eye ridge morphology and presence of genal caeca (Fig. 29H). The Goyder Formation specimens also closely resemble those described by Jago & Cooper (2005) and Bentley *et al.* (2009), as *H. integra* and *Henadoparia cf. integra*, respectively, from the Mindyallan Spurs Formation in Antarctica. While the Goyder specimens are almost identical to those described by Öpik (1967) and Jago & Cooper (2005), the more incomplete specimens illustrated by Bentley *et al.* (2009) leave some doubt as to whether they are conspecific.

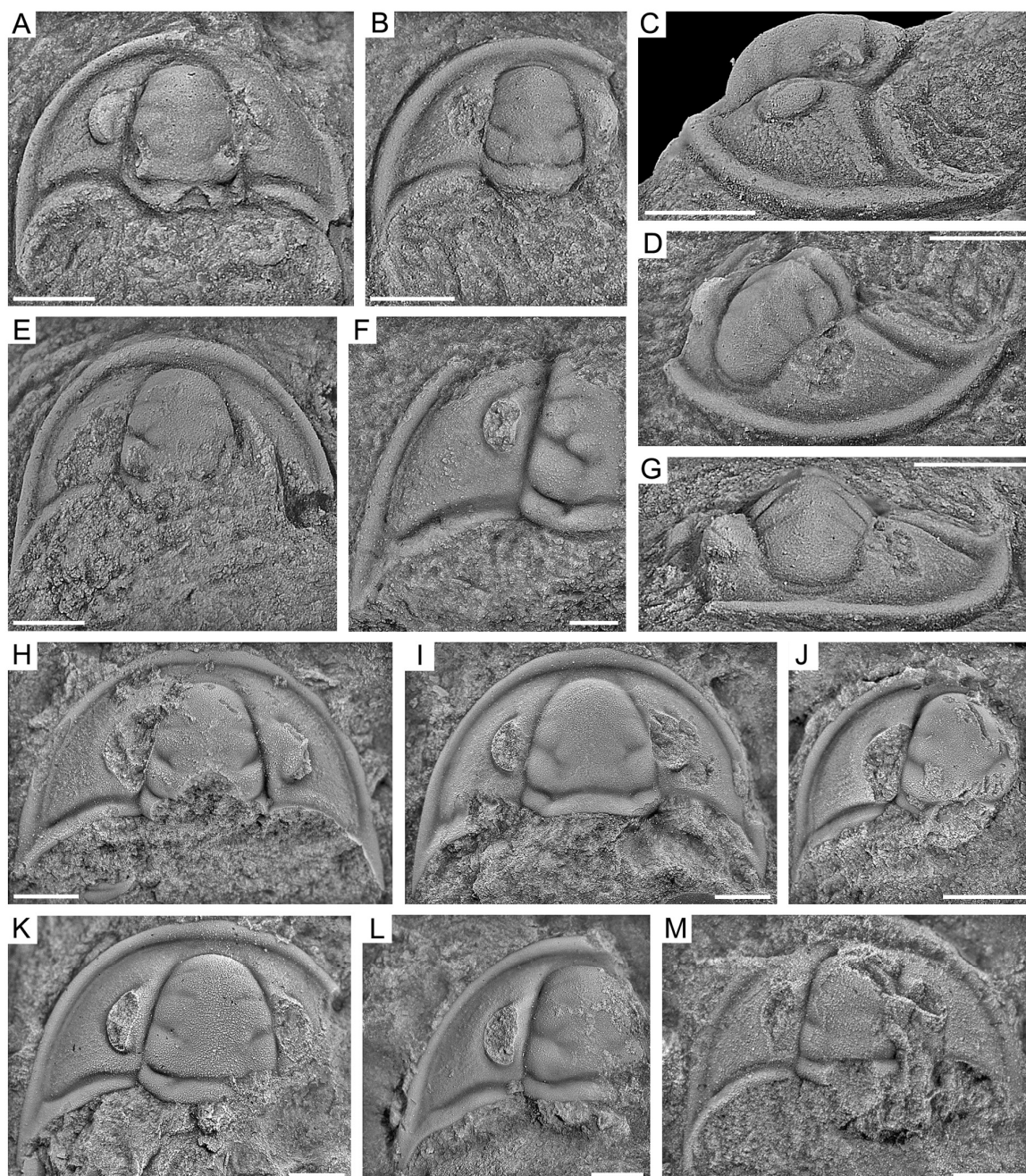


FIGURE 29. *Henadoparia integra* Öpik, 1967 from the Mindyallan Goyder Formation. A–G come from spot locality AS168; and H–M come from sample GOY/97 in the GOY section. A, C, CPC42415, partial cranidium; A, dorsal view; C, lateral view. B, D, G, CPC42416, partial cranidium; B, dorsal view; D, oblique anterolateral view; G, anterior view. E, CPC42417, partial cranidium. F, CPC42418, partial cranidium. H, CPC42419, partial cranidium. I, CPC42420, partial cranidium. J, CPC42421, partial cranidium. K, CPC42422, partial cranidium. L, CPC42423, partial cranidium. M, CPC42424, partial cranidium. All scale bars are 1 mm, except J = 2 mm.

Occurrence. GOY section horizon 73.2 m (Fig. 3). Also found at AS168.

Distribution. Goyder Formation, Amadeus Basin, Northern Territory. Georgina Limestone and O'Hara Shale, Georgina Basin, Northern Territory and Queensland. Spurs Formation,

Northern Victoria Land, Antarctica. All occurrences are Cambrian Series 3, Guzhangian (Mindyallan) in age.

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CONCLUSIONS

CONCLUSIONS

The stratigraphically lowest of the examined units in this thesis is the Tempe Formation.

Sampling the Hermannsburg 41 drillcore revealed two trilobite species, including one new taxon *Gunnia fava* sp. nov., together with brachiopods, bradoriid, helcionellids, hyoliths, echinoderms, cancelloriids, sponges and problematic tubes. Of particular interest were the age-diagnostic brachiopods *Schizopholis napuru* (= *Karathele napuru*) (Kruse, 1990) and *Kostjubella djagoran* (= *Vandalotreta djagoran*) (Kruse, 1990); this fauna has close links to faunas in the neighbouring Daly, Georgina and Wiso basins and suggests that the Tempe Formation correlates with the Australian Ordian stage (either the *Redlichia forresti* or *Xystridura negrina* assemblage zones).

Regional stages	Trilobites Zones	WestPertoorrtta Group StratigraphyEast			
Idamean	<i>Glyptagnostus reticulatus</i>				
Mindyallan	<i>Glyptagnostus stolidotus</i>	Goyder Formation			
	<i>Acmarhachis quasivespa</i>	Cleland Sandstone	Petermann Sandstone	Jay Creek Limestone	Shannon Formation
	<i>Erediaspis eretes</i>				
Boomerangian	III <i>Lejopyge laevigata</i> II		?	?	
	I				
	Undillian				
<i>Doryagnostus deltoides</i>					
<i>Ptychagnostus punctuosus</i>					
Floran	<i>Euragnostus opimus</i>	?			
	<i>Ptychagnostus atavus</i>				
Templetonian	<i>Triplagnostus gibbus</i>	Illara Standstone			
	<i>Pentagnostus shergoldi</i>				
	<i>Pentagnostus praecurrens</i>				
	<i>Pentagnostus anabarensis</i>				
Ordian	<i>Xystridura negrina</i> / <i>Redlichia forresti</i>	Tempe Formation			Giles Creek Dolostone

Figure 1. Australian Cambrian stages and zones plotted against the new stratigraphy for the Pertoorrtta Group. Only formations examined in this work have been included. Temporal ranges of units based on the biostratigraphic work presented in this thesis, as well as previous estimates of Kennard & Lindsay (1991). Grey shaded regions indicate significant stratigraphic gaps. The ‘?’ symbol indicates uncertain temporal boundaries in units not sampled during this thesis work.

The Giles Creek Dolostone was sampled via a stratigraphic section (RRG) through outcrop in the Ross River Gorge area and from a single spot locality near Gaylad Dam. Diversity in this unit is slightly higher than in the Tempe Formation, including twelve trilobite taxa (four new species), four bradoriid taxa (one new genus and four new species) as well as nine brachiopod taxa. The trilobites *Pagetia silicunda* Jell, 1975 and *Xystridura filifera* Öpik, 1975 suggest an early Templetonian age, within the *Pentagnostus anabarensis* or *Pentagnostus praecurrens* Zones for the formation. This is supported by the co-occurrence of *Amphoton* Lorenz, 1906, *Deiradonyx*, Öpik, 1982, *Dinesus* Etheridge, 1896 and *Kootenia* Walcott, 1889, all of which occur in Templetonian successions from the Georgina Basin, Gnalta Shelf and the Heathcote Greenstone Belt. Absence of more typical Ordian faunas such as the trilobites *Redlichia* Cossmann, 1902 and *Onaraspis* Öpik, 1968, or the brachiopods *Schizopholis napuru* (= *Karathele napuru*) (Kruse, 1990) and *Kostjubella djagoran* (= *Vandalotreta djagoran*) (Kruse, 1990) also supports a post-Ordian age. Previous reports of Ordian genera from the Giles Creek Dolostone (Öpik 1968, 1970) indicate that either the unit is diachronous or perhaps the reported specimens were not derived from this formation. It also implies that the Giles Creek Dolostone is considerably younger than the Tempe Formation and stratigraphic schemes showing these units as broadly synchronous in the Pertaoorrt Group should be amended.

The highest stratigraphic unit discussed in detail as part of this thesis is the Goyder Formation. Samples were collected from outcrop material through a measured stratigraphic section (GOY) in the Ross River Gorge, and supplemented by collections from eight other spot localities around the basin. The GOY section only intersects carbonate-dominated units, previously identified as part of the ‘lower Goyder Formation’ (Wells *et al.* 1967, p.42, 43). The succession of white sandstones above the GOY section was traditionally interpreted as ‘upper Goyder Formation’ (see Kennard & Nicoll in Kennard *et al.* 1986, p. 75). However, a

detailed study of the Pacoota Sandstone in the Ross River area by Shergold (1991) showed that these white sandstones, ranging up to 190 m in thickness above the GOY section, are lithologically distinct and likely belong to the basal Pacoota Sandstone. The trilobites and agnostoids are highly diverse in the Goyder Formation, with up to twenty-two different taxa (including one new genus and four new species). Of the two agnostoid species recovered from the formation only *Hadragnostus helixensis* Jago & Cooper, 2005, is age diagnostic; it has previously been reported from the late Mindyallan (*G. stolidotus* Zone) of the Spur Formation, in northern Victoria Land (Jago & Cooper 2005). This age is supported by the co-occurrence of the trilobites *Biaverta reineri* Öpik, 1967, *Blackwelderia repanda* Öpik, 1967, *Henadoparia integra* Öpik, 1967, *Monkaspis* cf. *travesi* (Öpik, 1967), *Nomadinis pristinus* Öpik, 1967, *Paraacidaspis priscilla* (Öpik, 1967) and *Polycyrtaspis* cf. *flexuosa* Öpik, 1967 which have all been reported from age equivalent strata in the neighbouring Georgina Basin (Northern Territory and Queensland). The generic assemblage of the Goyder Formation is also similar to those from the Guzhangian (Mindyallan) of other parts of Australia (New South Wales, South Australia and Western Australia), in addition to East Antarctica and China. A late Mindyallan age agrees with the original age estimate for the Goyder Formation given by Miss Joyce Gilbert-Tomlinson based on undescribed material (Ranford & Cook 1964; Ranford *et al.* 1965; Wells *et al.* 1967).

Taxonomic documentation of fossils from the Tempe Formation, Giles Creek Dolostone and Goyder Formation has vastly increased knowledge of Cambrian diversity in the Pertaoorrtta Group. Previously, only eight species had been described from these formations (Shergold 1986). The palaeontological research presented in this thesis includes formal descriptions of 69 species (two new genera and thirteen new species) in detail. Apart from the taxonomic description of new taxa, this thesis has also updated old taxonomic descriptions that had not been re-examined for nearly fifty years. A critical feature of this thesis has been the detailed logging and sampling of stratigraphic sections which has allowed the full stratigraphic ranges of most taxa to be determined. It has also facilitated high resolution

relative age assessments and regional correlations where little to no biostratigraphic data had previously been available. This thesis, therefore, has provided a new biostratigraphic framework for the Cambrian of the Amadeus Basin that will assist with geospatial modelling, including interpretations associated with future geological mapping, sequence stratigraphy and geophysical surveys of the basin. It also offers a means of tracing key and potentially economically important hydrocarbon source and reservoir rocks within the basin. Whilst more work is required, this thesis provides an important temporal platform that will allow future work to further refine and constrain a high resolution, quantitative biostratigraphy of the Pertaoorrtta Group which will permit accurate correlation of sedimentary packages in surface outcrop and subsurface drillcore.

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APPENDIX

APPENDIX

Smith, P.M., Brock, G.A. & Paterson, J.R., 2014. Biostratigraphy of the Cambrian Pertaoorrtta Group, Amadeus Basin, Northern Territory, Australia. *International Subcommission on Ediacaran Stratigraphy (ISES) jointly with International Subcommission on Cambrian Stratigraphy (ISCS) meeting*, 15th September 2014 to 24th September 2014, Ouarzazate, Morocco. p. 32.

BIOSTRATIGRAPHY OF THE CAMBRIAN PERTAOORRTA GROUP, AMADEUS BASIN, NORTHERN TERRITORY, AUSTRALIA

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The Amadeus Basin is a large sedimentary province in central Australia that covers an approximate area of 170,000 square km. Despite the known occurrence of fossils from the majority of stratigraphic units within the 3 km thick Cambrian succession (Pertaoorrtta Group) there is a dearth of published palaeontological data from this sedimentary succession, including no comprehensive biostratigraphy (see overviews by Shergold 1986; Shergold et al. 1991). The aim of the research presented here to rectify this situation.

This contribution presents results of detailed investigation of faunas from two formations within the lower part of the Pertaoorrtta Group. The Tempe Formation and Giles Creek Dolostone outcrop in central and eastern parts of the basin respectively, and have previously been regarded as coeval units, despite almost complete lack of detailed investigation of fossil faunas. This research has revealed a considerable diversity of new and biostratigraphically-informative fossils, including a total of fifteen trilobite taxa (three new species), four new bradoriid taxa and a varied shelly fossil assemblage including brachiopods, helcionellids, hyoliths, echinoderms, cancelloriids, sponges and problematic tubes. The described taxa provide evidence that these two sedimentary units were deposited at different times and that regional stratigraphic schemes need to be amended. The fauna from the Tempe Formation belongs to the *Xystridura negrina* trilobite Zone which is Ordian in age following the Australian stage scheme (equivalent to the Cambrian Series 2-3, Stage 4-5 boundary). This assemblage correlates with similar faunas from the neighbouring Daly, Georgina and Wiso

Basins. The fauna from the Giles Creek Dolostone is distinctly younger in age and correlates with the overlying *Pentagnostus anabarensis* or *Ptychagnostus praecurrens* trilobite Zones of early Templetonian age (equivalent to Cambrian Series 3, Stage 5). This work has important implications for understanding regional geology, stratigraphy and age relationships in central Australia.

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THE ORDIAN-TEMPLETONIAN CARBON ISOTOPE EVENT (OETE) AND BIOSTRATIGRAPHY IN THE GILES CREEK DOLOSTONE, AMADEUS BASIN, CENTRAL AUSTRALIA.

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Recently, a number of large scale multi-authored syntheses have advocated the use of carbon isotope chemostratigraphy in preference to biostratigraphy for national and international correlation for the Cambrian period. Cambrian (especially Terreneuvian) biostratigraphy has long been hindered by high levels of endemism and perceived diachroneity of first appearance datum points (FADs) of key fossil taxa - resulting in difficulties in defining truly global time lines. However, the proposition of using carbon isotopic excursions as the key means for defining regional and global stage subdivisions without adequate biostratigraphic control is fraught with difficulties and potential miscorrelation. We advocate a multiproxy approach to all stratigraphic correlation and provide a cautionary example of the type of misalignment that can happen if correlation is based solely on chemostratigraphy.

Detailed regional investigation using stable carbon isotopes across the Ediacaran-Cambrian boundary in central Australia reported the presence of a sharp +4.0 per ml shift in $\delta^{13}\text{C}_{\text{carb}}$ values in the middle of the Giles Creek Dolostone at Ross River Gorge, Amadeus Basin, Northern Territory. The positive shift in $\delta^{13}\text{C}_{\text{carb}}$ values through this interval was called the “Ordian-Templetonian Isotope Event (= OETE)”, which was very poorly constrained with fossil data. Regionally, the OETE signal matched closely and was correlated with similar positive shifts in drill cores from apparently coeval rocks within the neighbouring Daly, Georgina and Wiso Basins. Previous palaeontological work on these respective cores contained the age diagnostic trilobites *Redlichia* cf. *foraminifera* and *Redlichia gumridgensis*.

Based on recent revisions of the Australian Cambrian stage timescale these trilobites and their associated fauna suggest that the OETE in the core material from the Daly, Georgina and Wiso Basins occurs within the Ordian stage (*Xystridura negrina* assemblage Zone). However recent documentation of trilobites and associated fauna from the Giles Creek Dolostone in Ross River Gorge indicates this formation belongs in the overlying Templetonian stage (*Pentagnostus anabarensis* or *Ptychagnostus praecurrens* Zones). Therefore the isotopic excursion identified in the Giles Creek Dolostone at Ross River Gorge cannot be correlated with OETE reported from the core material within the neighbouring basins.

This highlights the importance of a multi-proxy approach with a well constrained biostratigraphy in combination with chemostratigraphy as a means to build confidence in regional and wider correlation. Without a biostratigraphic framework, positive or negative shifts in isotope ratios may appear superficially similar in shape and magnitude, yet be of significantly different ages.