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Cambrian microfossils from the Tethyan Himalaya

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Abstract.—Cambrian biostratigraphy of the Indian subcontinent is best documented from the Parahio Formation of the Tethyan Himalaya. Recently established trilobite biostratigraphy shows that the formation encompasses the latest part of unnamed Stage 4 and much of unnamed Stage 5. A variety of small shelly fossils have been recovered via acid digestion of carbonate beds and include tetract and pentact hexactinellid sponge spicules, chancelloriid spicules belonging to *Chancelloria* sp. and a new species, *Archiasterella dhiraji*, shells of an helcionelloid comparable to *Igorella maidipingensis*, a meraspid ptychopariid trilobite, the tubular *Cupitheca* sp., a poorly preserved hyolith, and an assortment of spinose microfossils of uncertain affinity. These newly recovered microfossils are consistent with the trilobite-based lower and middle Cambrian age determination and do not support a late Cambrian age for the top of the Parahio Formation advocated in some recent literature. The microfossils reported herein significantly expand the known diversity of such fossils from Cambrian strata in the Himalayan region, and allow for comparison of this fauna with others from Gondwanaland and elsewhere. Integration with trilobite data indicate that the stratigraphic ranges of many small shelly fossils described in this study are greater than previously recognized.

Introduction

The well-exposed sections of the Cambrian Parahio Formation in the Parahio Valley, Spiti region, Himachal Pradesh, and in the Purni section of the Zanskar Valley, Ladakh region, of the Indian Tethyan Himalaya (Fig. 1) have permitted the establishment of a trilobite-based biostratigraphic zonation for rocks of the later part of Series 2 (Stage 4), and the earlier part of Series 3 (Stage 5) of the Cambrian System (Peng et al., 2009) (Figs. 2–4). This has been an important step in erecting a local Cambrian biostratigraphy for the Indian subcontinent and is supplemented by further work on trilobites and other fauna from these and other sections. Carbonate rocks from the Parahio Formation were collected for acid digestion, primarily with the aim of recovering topotype phosphatic brachiopods in order to clarify the systematic concepts of poorly known Cambrian species (Popov et al., 2015). An additional aim was to prospect for microfossils.

A particular need with respect to microfossils has been to assess a report by Bhatt and Kumar (1980) that suggested the presence of conodont and paraconodont specimens assigned to genera such as *Oneotodus*, *Sagittodontus*, *Furnishina*, *Problemoconites*, and ?*Westergaardodina* collected from a prominent dolostone bed located near the top of the Parahio Formation in the Parahio Valley section (see Myrow et al., 2006a). Such an assemblage is curious because elsewhere these taxa occur at different stratigraphic levels. If correct, it seemingly implies an Early Ordovician minimal depositional age for the top of this unit because the first appearance datum (FAD) of the euconodont *Oneotodus* is of that age. However, Bhatt and Kumar (1980) themselves suggested a late Cambrian (= Furongian) age

for the horizon that was consistent with the earliest biozonation of the Parahio Formation (Reed, 1910), in which the putative presence of the trilobite *Dikelocephalus* was used to infer a late Cambrian age for the top of the Parahio Formation in the Parahio Valley (see also Hayden [1904]). This late Cambrian age has long been generally accepted (e.g., Shah and Raina, 1990; Shah et al., 1991), and is advocated in a current textbook (Ramakrishnan and Vaidyanadhan, 2008), despite significant revision to the trilobite taxonomy (Jell and Hughes, 1997; Peng et al., 2009). Hence, a significant discord in age estimates for the upper part of the Parahio Formation at its type section currently exists between this earlier work and that published by Peng and colleagues (2009). This paper aims to explore this discrepancy through a fresh analysis of the microfossil content of the Parahio Formation.

Taxonomic reassessment of Reed's (1910) *Dikelocephalus* specimens showed that they in fact belong to an older form (Jell and Hughes, 1997, p. 15), and on that basis Jell and Hughes suggested the upper part of the Parahio Formation in the Parahio Valley to be middle Cambrian in age. This conclusion was reaffirmed by Peng and colleagues (2009), who suggested that the uppermost in situ trilobite bearing rocks, from the Parahio Valley at ~1050 m in the section measured by Myrow et al. (2006a), belong to the *Ptychagnostus gibbus* Zone (i.e., toward the top of Stage 5 of the Cambrian System). The reassessment was based both on the collection of fossils from the upper part of the Parahio Formation in the Parahio Valley, and on its correlation to the Zanskar Valley section, where the Parahio Formation is conformably overlain by the Karsha Formation, a thick dolomitic unit of Guzhangian or older age (see Peng et al., 2009).
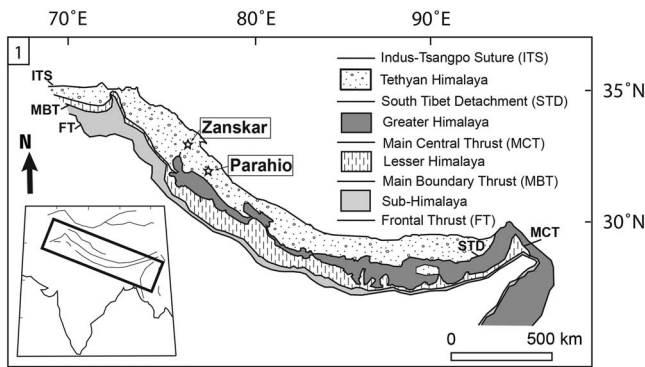
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Figure 1. Location of the Parahio (Spiti region) and Zanskar (Ladakh region) valleys within the Tethyan Himalaya, the most northern of the four lithotectonic zones of the Himalaya.

Peng and colleagues' (2009) reassessment of Parahio Formation trilobites highlights the peculiarity of the report of conodont genera from the formation (Bhatt and Kumar, 1980). The anomaly has four potential causes: (1) the trilobite biostratigraphy of Jell and Hughes (1997) and Peng et al. (2009) is incorrect; (2) there is an unrecognized stratigraphic break between ~1050 m and ~1250 m (the inferred height of the Bhatt and Kumar horizon) in the Parahio Valley section and the uppermost part of the Parahio Formation there is Furongian or later in age; (3) Bhatt and Kumar's collection is middle Cambrian but records the stratigraphically earliest occurrence yet known of a range of conodont genera, some of which are known elsewhere only from the upper Cambrian or lower Ordovician; or (4) the taxonomic identifications of Bhatt and Kumar (1980) were incorrect.

A two-pronged approach has been used to assess this conundrum. First, the original material of Bhatt and Kumar (1980), housed in the paleontology repository in the Geological Survey of India in Kolkata, has been inspected microscopically. Unfortunately, as this material can neither be loaned nor are facilities available in the repository for microfossil imaging, it is not possible to re-illustrate this material here. However, most of the preserved illustrated specimens purported to be conodonts are, in fact, brachiopods (which is evident from the published photographs themselves) and will be discussed elsewhere (Popov et al., 2015). Specimens attributed by Bhatt and Kumar (1980) to *Oneotodus* are not brachiopods and are considered below. Second, carbonate samples collected from the Parahio Formation have been processed to discover what microfossils, if any, occur with the trilobite specimens used to establish the biozonation of Peng and colleagues (2009). These collections have included PO9, located in the Parahio Formation at 1242.40 m above the base of the Parahio Valley section along the Sumna river section, Spiti region, (Figs. 2, 4). Hammer marks consistent with bulk sampling suggest that this is the level that Bhatt and Kumar (1980) collected.

Other small shelly fossils from the Indian subcontinent

Hyoliths were among the first Cambrian fossils described from the Indian subcontinent (Waagen, 1882–1885), and they have been reported sporadically ever since. Early works described several hyoliths from early Cambrian rocks in the Salt Range of Pakistan (Waagen, 1891; Redlich, 1899; Schindewolf, 1955), and middle Cambrian rocks of Kashmir (Reed, 1934) and the Parahio Valley of Spiti (Reed, 1910). Two hyolith specimens were previously described from the Parahio Formation of the Parahio Valley (Reed, 1910) from about 836.41 m (Hayden's [1904] level 9) in the measured section of Myrow et al. (2006a), along with the putative conodonts mentioned above (Bhatt and Kumar, 1980) (Fig. 4). One of these specimens remains accessible and is commented on below.

In later years, lowermost Cambrian rocks from the Lesser Himalaya have yielded a modestly rich assemblage of small shelly fossils attributed to the *Anabarites trisulcatus-Protohertzinia anabarica* Assemblage Zone (Bhatt et al., 1985; Brasier and Singh, 1987), which appears to be a little older than a comparable assemblage known from Abbottabad in Pakistan (Mostler, 1980). A *Protohertzinia-Olivooides*–bearing assemblage has also been reported from low in the Tethyan Cambrian in the Lolab Formation of Kashmir (Tiwari, 1989). The Pakistani assemblage belongs to a second successive fauna of small shelly fossils (Hughes et al., 2005), and contains the chancelloriids *Archiasterella* and *Allonnia*, along with sachitids. The sachitids suggest a pre-trilobitic age and this is consistent with the local lithostratigraphic context. Chancelloriids have also been reported from the Indian Lesser Himalaya above the *Anabarites trisulcatus-Protohertzinia anabarica* Assemblage Zone (Kumar et al., 1987). These finds were interpreted to be pre-trilobitic correlatives of the *Sinosachites flabelliformis-Tannuolina zhangwentangi* Assemblage zone of South China, but the possibility of a younger age has been mooted (Hughes et al., 2005).

An assemblage of coiled mollusks has also been described from the Lesser Himalaya (Kumar et al., 1983; Kumar et al., 1987), slightly above the chancelloriid-bearing level, and belonging to the *Drepanuroides* trilobite Zone (Hughes et al., 2005). All these finds, along with additional poorly preserved hyoliths from the Tethyan Himalaya of Kashmir (Kumar and Verma, 1987) are early Cambrian in age (see review in Hughes et al., 2005). Recently, Singh and colleagues (2015) have also recovered microfossils from the Parahio Valley section, reported to occur at a level approximately 20 m above the *Haydenaspis parvatya* horizon, and interpreted by those authors to belong to Stage 4. Accordingly, to date no small shelly fossils have been described as occurring within the middle Cambrian of the Indian subcontinent, with the exception of those hyoliths mentioned above in the Parahio Formation and from Kashmir (Reed, 1910; Reed, 1934; Kobayashi, 1934). The attributions of several Singh and colleagues' (2015) finds are considered below.

Material and methods

New limestone and dolostone samples collected from the Parahio Formation in the Parahio and Zanskar valleys were placed into an 8% formic acid (HCO$_2$H) solution for acid digestion. Digestion times depended on the degree of dolomitization in each sample, but ranged from one week to a month or more (see Abrantes et al., 2005).
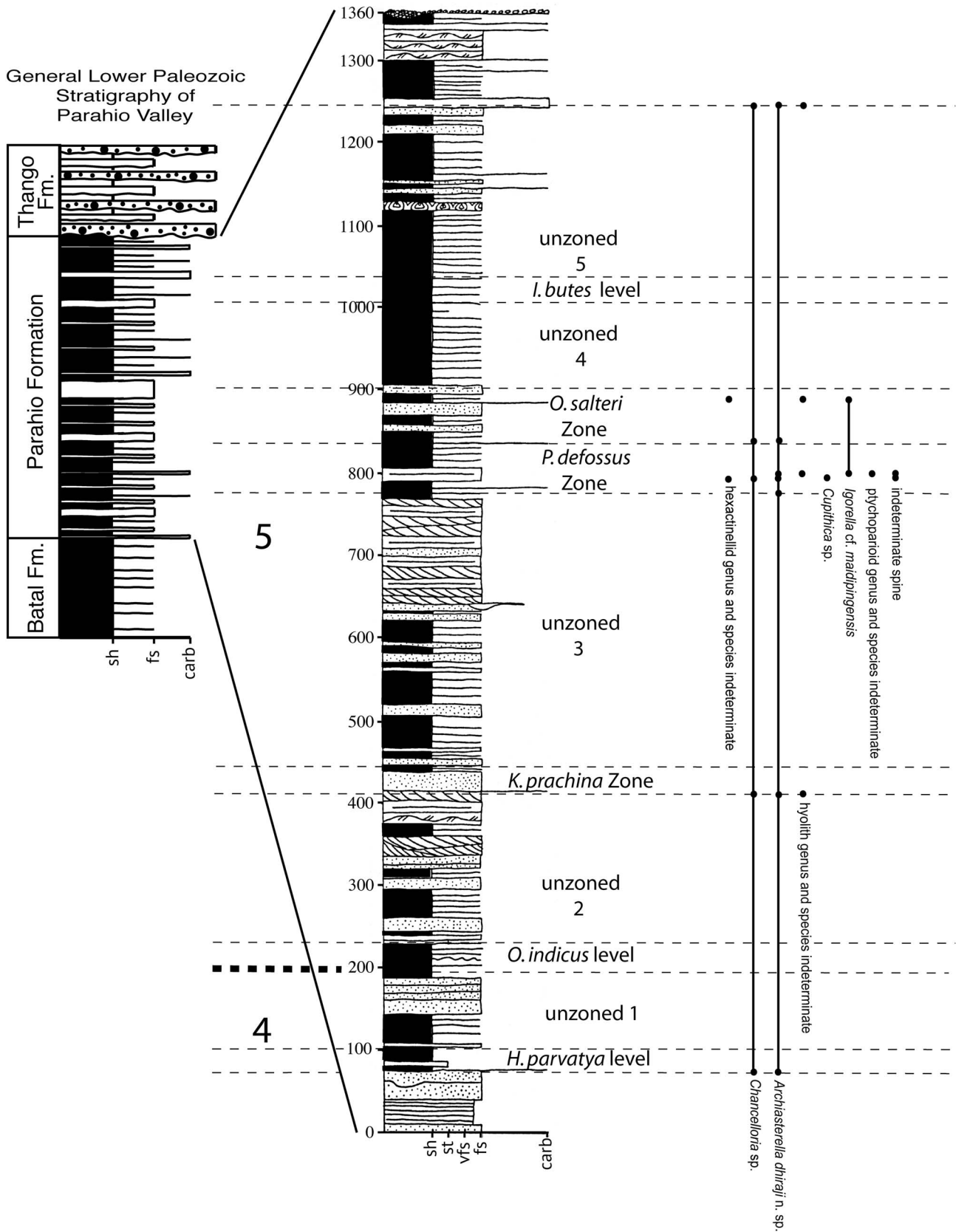
Figure 2. Composite stratigraphic section of the Cambrian rocks of the Parahio Formation in the Parahio Valley, Spiti region, with microfossil occurrence and local ranges, and trilobite biozonation. Unzoned intervals refer to relatively thick intervals of section that yielded no trilobites. (**4**) and (**5**) Informal stages of the Cambrian System. The boundary between them is represented at the first occurrence of *O. indicus*. sh, shale; st, siltstone; vfs and fs, very fine sandstone and fine sandstone, respectively; carb, carbonate.
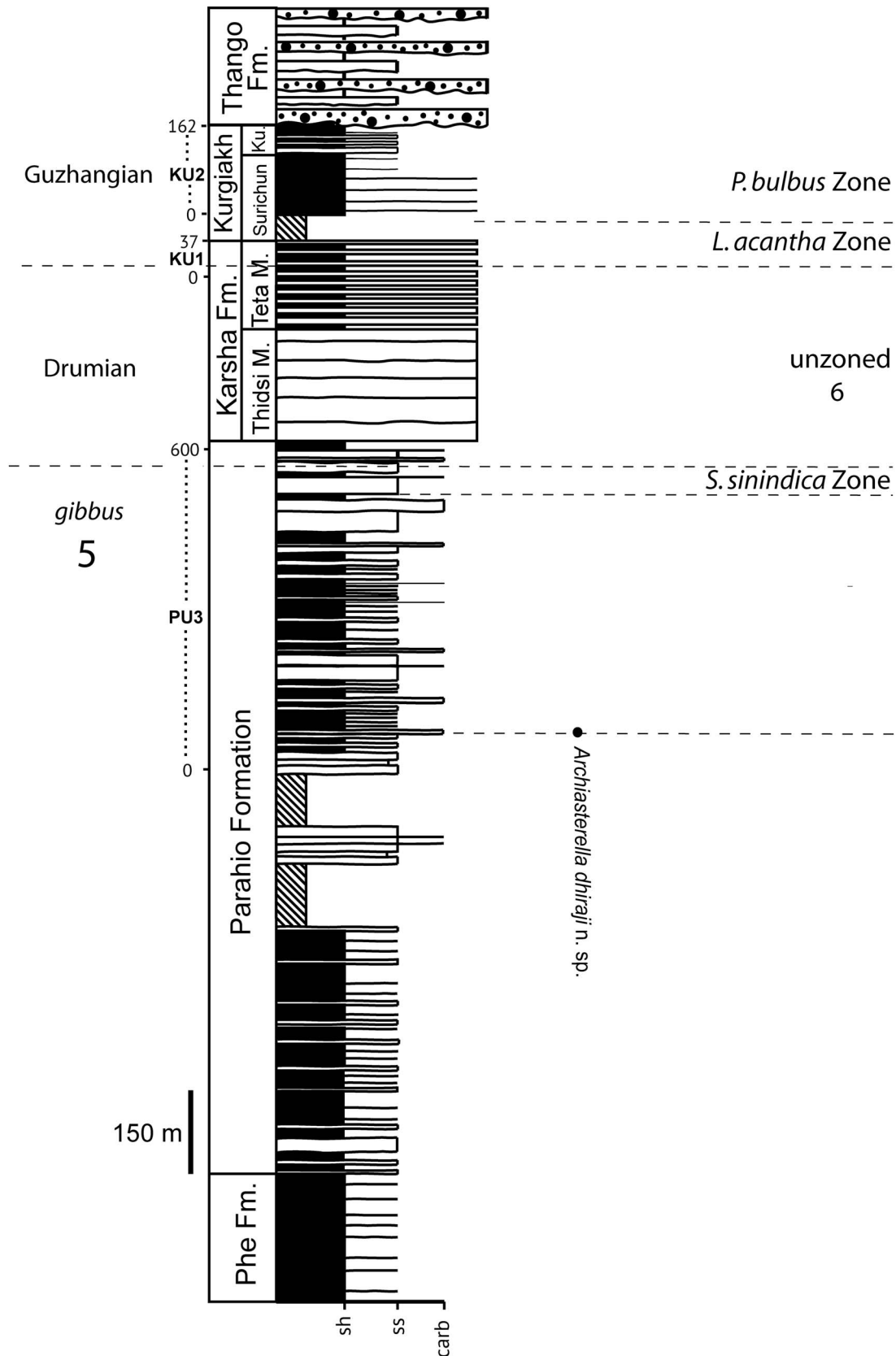
Figure 3. Composite stratigraphic section of the Cambrian rocks of the Parahio, Karsha, and Kurgiakh Formations in the Zanskar Valley, Ladakh region, with microfossil occurrence, local ranges shown, and trilobite biozonation. Unzoned intervals refer to relatively thick intervals of section that yielded no trilobites. Measured sections containing material described herein are indicated. PU, Purni; KU, opposite Kuru. (**5**) The informal fifth stage of the Cambrian System. sh, shale; ss, sandstone; carb, carbonate.

	Stage	Trilobite Zone	Zanskar Valley, Ladakh		Parahio Valley, Spiti		
			Height in section (m)	Collection name	Height in section (m)	Collection name	Hayden/Reed level
SERIES 3	Drumian	*Sudanomocarina sinindica* Zone			1242.4	P09	
	Stage 5	*I. butes* Level			1050		Level 13
		Oryctocephalus salteri Zone			880.93 836.36	PV880 P031	Level 9
		Paramecephalus defossus Zone	74.11	PI13	776.00 775.41 765.14	P025 P024 P021	Level 6
		Kaotaia prachina Zone			580.20 433.44	P015	Level 4
		Oryctocephalus indicus Level			~200		Level 2
S. 2	Stage 4	*Haydenaspis parvatya* Level			78.07	P03	

505
510

Figure 4. Stratigraphic relationship between trilobite zonation, section, height (meters) in section, collection name, and Hayden (1904)/Reed (1910) levels and the microfossil-bearing material of the Parahio Formation in the Zanskar Valley (Ladakh region) and Parahio Valley (Spiti region) sections. Here trilobite zones are given as encompassing unzoned intervals between the fossiliferous horizons indicated in Figures 2 and 3. Hayden's (1904) levels 2, 4, and 13 have not yielded microfossils described herein, but their position is given for clarity.

The residue was then sieved to isolate various size fractions from which microfossils were isolated using a binocular microscope. Choice specimens were mounted on scanning electron microscope (SEM) blanks using a conductive carbon tape and acetone solution. These were coated with platinum and palladium using a Cressington 108 AUTO sputtering device. High-resolution images were obtained using the XL30 FEG SEM at the Central Facility for Advanced Microscopy and Microanalysis (CFAMM) located at the University of California, Riverside (http://micron.ucr.edu/). An attached EDAX device was used to determine elemental composition using EDS.

Geological setting

The material described herein was collected from the Tethyan Himalaya, the northernmost of four major lithotectonic zones that comprise the central part of the Himalaya, just south of the Indus-Tsangpo suture zone, which is the boundary of the Lhasa block of Tibet (Myrow et al, 2006a) (Fig. 1). The Spiti and Ladakh regions are adjacent, and the Parahio Formation, which has been recognized in both, consists of thick siliciclastic deltaic deposits that contain relatively thin, fossil-bearing carbonate beds, which represent transgressive systems tract deposits developed over marine flooding surfaces (Myrow et al., 2006a; Myrow et al., 2006b). It is these carbonate beds from which the material examined herein was collected. The Parahio Formation was deposited along the ancient passive margin of India during the Cambrian (Myrow et al., 2006a, 2006b), and maps and GPS coordinates specifying the locations of sections and samples are available in these publications and others (e.g., Peng et al., 2009).

Biostratigraphy

Biostratigraphic implications of the microfossil finds.—The morphologies of hexactinellid sponge spicules described herein are quite simple, thus making assessment beyond hexactinellid affinity impossible. As a group, hexactinellid sponges are thought to range from the late Ediacaran to the present day (Gehling and Rigby, 1996), and this is all the temporal constraint that these Parahio Formation fossils provide.

Chancelloria is known to range from low in the pre-trilobitic lower Cambrian to the lower part of the upper Cambrian (Mostler and Mosleh-Yazdi, 1976; Mostler, 1980). Given this, the Parahio Formation *Chancelloria* suggest that the youngest depositional age of these rocks is pre-*Prochuangia* Zone (i.e., early late Cambrian), and that they are no older than the base of the Cambrian. This result suggests that no part of the Parahio Formation is younger than the *Proagnostus bulbus* Zone. Specimens from elsewhere belonging to *Archiasterella dhiraji* n. sp. occur both in the lowest trilobite bearing Cambrian (Bengtson, Conway Morris, Cooper, Jell, and Runnegar, 1990) and also in Stage 4 (Skovsted and Peel, 2007), so they are consistent with the occurrence of *Chancelloria* but favor a slightly older youngest age.

Igorella maidipingensis likewise has a lower Cambrian occurrence, ranging from the Nemakit-Daldynian Stage to the Tommotian stages of the Siberian Platform, Yangtze platform, and Iran (Devaere et al., 2013; Parkhaev and Demidenko, 2010). The genus *Cupitheca* is also found in the lower Cambrian of Antarctica, China, Australia, Spain and Kazakhstan (Mambetov *in* Missarzhevsky and Mambetov, 1981; Zhou and Xiao, 1984; Bengtson *in* Bengtson et al., 1990; Wrona, 2003; Malinky and Skovsted, 2004; Kruse et al., 2004; Jensen et al., 2010).

Taken at face value, the known ranges of *Chancelloria*, *Archiasterella*, and *Igorella maidipingensis* might imply an early Cambrian depositional age for the Parahio Formation. However, given the well-constrained trilobite and brachiopod biostratigraphy, we conclude that these microfossil taxa simply ranged higher than previously recorded. Presently, small shelly fossils are poorly described from middle Cambrian strata worldwide, whereas macrofossils such as trilobites and brachiopods have been studied intensely throughout the Cambrian. Furthermore, other species within *Igorella*, *Chancelloria*, and *Archiasterella* range into the middle Cambrian. In addition, the long local range of the most common small shelly fossil, *A. dhiraji* n. sp., within the Parahio Formation (Fig. 2) itself suggests a stratigraphic range that is markedly longer than that of associated trilobites. Accordingly, the stratigraphic occurrence of the material described in this study can be reconciled and integrated with the trilobite-based biozonation given reasonable upward range extensions of some species of the small shelly fauna. This results provides a demonstration of why it was unwarranted to assign other Himalayan rocks to the *Sinosachites flabelliformis-Tannuolina zhangwentangi* Assemblage zone based on chancelloriids alone (see Hughes et al, 2005; *contra* Kumar et al., 1987).

Long temporal ranges for small shelly taxa are complemented by wide geographical distributions for these taxa, with occurrences of *Archiasterella dhiraji* n. sp. occurring in Laurentia and inboard Gondwana, and a widespread inboard peri-Gondwanan, South Chinese, and Siberian distribution for *Igorella* cf. *maidipingensis*. *Cupitheca* and *Chancelloria* likewise have global distributions.

Integration with trilobite biostratigraphy.—The biostratigraphic zonation for the Cambrian of the Parahio Formation proposed by Peng et al. (2009) was based on the local occurrence of well-characterized trilobite taxa, integrated with original work at the same sites, namely the Parahio Valley section in the Spiti region (Hayden, 1904; Reed, 1910) and the Zanskar Valley in the Ladakh region (Jell and Hughes, 1997). Peng and colleagues (2009) recognized six trilobite zones, three levels, and six unzoned intervals for the Cambrian System of the Parahio and Zanskar valleys (Figs. 2–4) spanning an interval from the upper informal global Stage 4 through the lower half of the Guzhangian Stage of the Cambrian System. The Peng and colleagues (2009) study also provided a link with well-established successions in China and Australia, enabling a quite precise global correlation. The occurrence of microfossils is discussed below within the context of the trilobite zonation.

Haydenaspis parvatya level.—This level contains both chancelloriids, *Archiasterella dhiraji* n. sp. and *Chancelloria* sp. and is the oldest body fossil fauna yet collected *in situ* from Hayden's section, occurring at 78.07 m above the base of the Parahio Valley section (Figs. 2, 4). Trilobite data (Peng et al., 2009) suggests that it is equivalent to the base of the Maochuangian of North China, or within the top part of the Duyunian Stage of South China. Globally, this level lies within the upper part of the informal Stage 4 of the Cambrian System, and thus to the uppermost part of the second Series of the Cambrian System.

Kaotaia prachina Zone.—Mircofossils from this zone include both chancelloriids, *Archiasterella dhiraji* n. sp. and *Chancelloria* sp., as well as an indeterminate hyolith, and were collected at 439.44 m above the base of the Parahio Valley section as collection PO15 (Figs. 2, 4). Its stratigraphic position, above the inferred level of *Oryctocephalus indicus* and below that of *Paramecephalus defossus*, suggests that it lies within the lower part of the informal global Stage 5 (Peng et al., 2009).

Paramecephalus defossus Zone.—This zone has the most diverse microfossil fauna recorded in this study, containing all taxa described herein: hexactinellid sponge spicules, *Archiasterella dhiraji* n. sp. and *Chancelloria* sp., an indeterminate hyolith, *Cupitheca* sp. *Igorella* cf. *maidipingensis*, a single early meraspid ptychopariid, and indeterminate spines. The collections PO21 (765.14 m), PO24 (775.41 m), and PO25 (776 m) represent this zone. This is the middle part of the Parahio Formation in Hayden's section, and is specifically inferred to be Hayden's (1904) level 6 (Fig. 4). Peng and colleagues (2009) correlated this zone with the middle of the Taijiangian Stage of South China. The PI13 site is the oldest body fossil bearing collection in the Zanskar Valley. Brachiopod biostratigraphy (Popov et al., 2015) locates PI13 stratigraphically within the *P. defossus* Zone (Figs. 3, 4). Its microfossil fauna contains only *Archiasterella dhiraji* n. sp., which occurs in both the oldest and youngest body fossil collections in the Parahio Valley section (Fig. 2) and has a long range globally. Although the age of the PI13 collection is poorly constrained biostratigraphically by small shelly fossils, a biostatigraphically diagnostic brachiopod species allows precise correlation between this level and a horizon approximately 500 m below the top of the Parahio Formation in the Parahio Valley (Popov et al., 2015).

Oryctocephalus salteri Zone.—This zone contains hexactinellid sponge spicules, *Archiasterella dhiraji* n. sp., *Chancelloria* sp., and a indeterminate hyolith collected at PO31 (836.36 m) and PV880 (880.93 m) (Figs. 2, 4). Peng and colleagues (2009) correlated this zone with the middle Taijiangian Stage of South China, and with the late Early or early Late Templetonian stage of Australia.

Above Iranoleesia butes *level/below* Sudananomacarina sinindica *Zone*.—The Parahio Valley PO9 collection (1242.4 m) yielded chancelloriid spicules only. It was made a little over an hundred meters below the top of the Parahio Formation and is the inferred site of Bhatt and Kumar's (1980) collection (Fig. 2).

Resolution of the conodont conundrum

Two of the putative conodont specimens figured as *Oneotodus* by Bhatt and Kumar (1980, pl. 1 figs. 1, 3) resemble individual rays of *Archiasterella dhiraji* n. sp. The figured specimen reported as GSI19604 is similar to an isolated recurved abapical ray, or possibly an ascending horizontal ray, and that reported as GSI19606 is also similar to the linear adapical ray. Oddly, however, the specimens presently reposited in the Geological Survey of India with these specimen numbers are evidently not those originally figured, nor are they certainly fossils.

They may have been substitutes following damage or loss of the figured material. However, the specimen GSI19605, which is a straight-sided tube, could be the specimen illustrated in Bhatt and Kumar's (1980) figure 2. There are no characters that link this specimen to *Oneotodus* or to any other conodont.

Because we have recovered *Archiasterella dhiraji* n. sp. in the bed (PO9) from which Bhatt and Kumar's (1980) material appears to have been collected, our redetermination of the putative *Oneotodus* removes this argument for these rocks being Early Ordovician in age. All other specimens figured as conodonts or paraconodonts by Bhatt and Kumar (1980) are considered in a forthcoming study on linguliform brachiopods (Popov et al., 2015), but none of them suggest late Cambrian or younger age. Because of this, and the fact that no conodonts or paraconodonts were found herein, the grounds for making a late Cambrian age determination for the upper part of the Parahio Formation as suggested by Bhatt and Kumar (1980) are no longer valid. As the trilobites and brachiopods also suggest middle Cambrian age, there is no current biostratigraphic evidence for any part of the Parahio Formation having a late Cambrian or younger age (*contra* Ramakrishnan and Vaidyanadhan, 2008, p. 581).

Systematic paleontology

The systematic part of this paper is by Gilbert and Hughes. Type and figured material are reposited on SEM stubs in the microfossil collection of the Wadia Institute of Himalayan Geology, Dehra Dun, Uttaranchal, India, along with some additional unfigured specimens on the same stubs. Additional Parahio Formation microfossils sorted by major taxon and collection, along with unsorted residues from the major collections, are reposited at the Cincinnati Museum Center, Ohio, under numbers CMC IP71788, IP71791 - 71805, IP71807 - 71812.

Phylum Porifera Grant, 1836
Class Hexactinellida Sollas, 1870
Hexactinellid Family, genus and species indeterminate
Figure 5.1–5.6

Material.—WIMF/A/3951-3955.

Description.—Relatively simple spicule morphologies, including four-rayed (tetract) spicules, and a five-rayed (pentact) spicule. There are two morphotypes of tetract spicules, the first exhibits four equilateral rays that all reside in a single plane. The rays are thin and blade-like, tapering at the edges. The upper surface of each ray is slightly concave and the basal surface is slightly convex. The second tetract morphotype has four cylindrical, equilateral rays that reside in a single plane. Pentact spicules contain five rays that are at approximately 90° angles from each other, with four rays approximately residing in a single plane and a fifth ray protruding orthogonally from this plane. Some pentact spicules can display both straight and curved rays. All pentact rays have a circular cross section.

Remarks.—The Parahio Valley sponge assemblages described herein include simple spicule morphologies, all of which most likely belong to Hexactinellida due to their glass-like appearance, which is unlike any of the phosphatic material seen in this study, and EDS confirms a siliceous composition. While generally well preserved, these isolated spicules are not further determinable taxonomically, as similar spicule types can occur in species belonging to different orders (Hartman et al., 1980; Dong, 1996). Their only stratigraphic significance is that they indicate late Neoproterozoic or younger rocks.

Occurrence.—New material from Parahio Formation carbonates collected at 775.41 m (PO24, *Paramecephalus defossus* Zone) (containing pentacts and thin blade-like rayed tetracts), and 880.93 m (PV880, *O. salteri* Zone) (containing cylindrical-rayed tetracts) above the base of the Parahio Valley section on the north side of the Parahio River, Spiti region, Parahio Formation, informal global Stage 5 of the Cambrian. Approximately 50 spicules inspected in total.

Phylum Incertae Sedis
Class Coelosicleritophora Bengtson and Missarzhevsky, 1981
Order Chancelloriida Walcott, 1920
Family Chancelloriidae Walcott, 1920

Remarks.—The family has recently been comprehensively reviewed by Moore et al., (2014, p. 844, 845). Articulated specimens reveal soft-bodied, sessile, sac-like organisms, which resemble a barrel cactus, armored with star-shaped calcareous sclerites from which sharp spines radiated (Randell et al., 2005). Sclerite ray structure is here designated by using a simplified version of Sdzuy's (1969) system of 'm + n,' with 'm' used to designate the number of lateral rays and 'n' used for the number of central rays. Identification of individual rays within a sclerite are here designated using the terminology of Moore et al. (2014).

Genus *Archiasterella* Sdzuy, 1969

Synonymy.—See Moore et al. (2014, p. 858).

Type species.—*Archiasterella pentactina* Sdzuy, 1969

Other species.—*Archiasterella charma* Moore et al., 2014 (p. 859, figs. 3B, 3C, 3H, 11); *A. elegans* Demidenko *in* Gravestock et al., 2001 (p. 229, pl. 6, fig. 6); *A. fletchergryllus* Randell *in* Randell et al., 2005 (p. 992, figs. 3.1, 3.4–3.7, 4, 5, 7–9); *A. hirundo* Bengtson *in* Bengtson et al., 1990 (p. 55, pl. 29, figs. A–G; p. 56, pl. 30, figs. A–H); *A. palmiformis* Vasil'eva *in* Vasil'eva and Sayutina, 1988 (p. 195, pl. 30 fig. 4a, 4b); *A. quadratina* Lee, 1988 (p. 100, pl. 1, fig. 12); *A. robusta* Vasil'eva, 1985 (p. 168, pl. 45, figs. 7, 8); *A. tetractina* Duan, 1984 (p. 187, pl. 4, figs. 3a, 3b, 4a, 4b); *A. tetractina* (*non* Duan, 1984) Vasil'eva and Sayutina, 1988 (p. 195, pl. 30, figs. 5, 6; p. 95, pl. 32, fig. 2); *A. tetraspina* Vasil'eva and Sayutina, 1993 (p. 138) for *A. tetractina* Vasil'eva and Sayutina, 1988 (p. 195, pl. 30, figs. 5, 6; p. 195, pl. 32, fig. 2).

Diagnosis.—Sclerites lacking a central ray surround lateral rays, but with one ray oriented vertically or recurved over the other rays, with the other rays extending in the plane of the basal facet (abridged from Moore et al., 2014, p. 858).
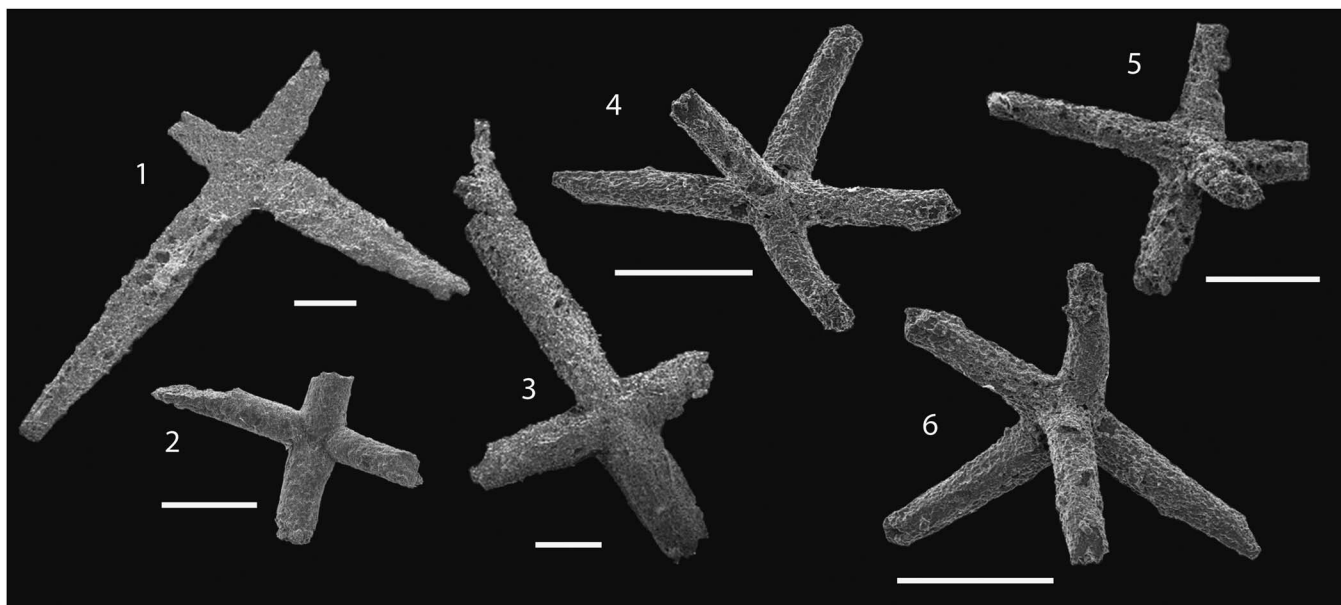
Figure 5. Sponge spicules from the Parahio Formation, Parahio Valley, Spiti region. All specimens coated with platinum/palladium before SEM imaging. Scale bar represents 200 μm. (**1, 3–6**) From 775.41 m (PO24) above base of the section. (**2**) *F*rom 880.93 m (PV880) above base of the section. (**1–3**) Tetract. (**1, 2**) With blade-like rays. (**1**) WIMF/A/3951; (**2**) WIMF/A/3952; (**3**) with cylindrical rays, WIMF/A/3953; (**4–6**) pentact. (**4**) WIMF/A/3954; (**5**) WIMF/A/3955; (**6**) WIMF/A/3954.

Remarks.—*Archiasterella* has been usually diagnosed as having a 5 + 0 or 4 + 0 sclerite ray structure, although 2 + 0 ray sclerites are also known (Sdzuy, 1969; Qian and Bengtson 1989; Bengtson et al. 1990; Randell et al. 2005). A new 3 + 0 sclerite, belonging to *Archiasterella charma*, has recently been described (Moore et al., 2014). Due to this, as well as the fact that sclerite ray numbers can vary within an articulated scleritome (Doré and Reid, 1965; Sdzuy 1969; Randell et al., 2005; Zhao et al., 2011), the number of horizontal rays is not useful in diagnosing the genus.

Moore and colleagues (2014) distinguished *Archiasterella* from *Allonnia* by the arrangement of horizontal rays with the respect to the basal surface, making assignment of previous illustrated material such as *Archiasterella tetractina* Duan, 1984; *Archiasterella tetraspina* Vasil'eva *in* Vasil'eva and Sayutina, 1988; and *Archiasterella quadratina* Lee, 1988 difficult to determine because the basal structures of these species are too poorly known to permit confident taxonomic determination. We include then in the listed species above, but acknowledge the difficulty in placing them securely.

Archiasterella dhiraji new species
Figures 6.1–6.12, 7.1–7.3

1980, *Oneotodus* sp. Bhatt and Kumar, p. 357, pl. 1, figs. 1,3 only.
1990, *Archiasterella* cf. *A. hirundo* Bengtson *in* Bengtson et al., p. 55, pl. 29, figs. D,E.
2007, *Archiasterella* sp. Skovsted and Peel, p. 741, pl. 6, figs. C,D.
2015, *Archiasterella* sp. Singh et al., p. 2193, fig. 3.2 only.

Etymology.—In honor of Prof. Dhiraj M. Banerjee of the University of Delhi for his many contributions to the late Neoprotoerozoic and Cambrian geology of India.

Holotype.—WIMF/A/3956.

Other material.—WIMF/A/3957-3964.

Diagnosis.—*Archiasterella* with 4 + 0 sclerites consisting of one recurved abapical ray, one linear adapical ray, and two ascending horizontal recurved rays. Linear adapical ray and two ascending horizontal recurved rays extend within a single plane. Recurved abapical ray projects abaxially from the basal plane and recurves adapically along the sagittal plane. Basal surface is slightly convex with restricted, rimmed, oval foramina. Transverse articulation facet connects bases of recurved abapical ray and linear adapical ray, ascending horizontal ray bases separated.

Description.—Sclerites bilaterally symmetrical about sagittal plane. Two rays are aligned along the sagittal plane, an abapical ray, which recurves upwards away from the basal plane at angles of 65°–105°, with angle varying among sclerites, and a linear adapical ray, which resides within the basal plane. Two ascending horizontal rays occupy the basal plane and are recurved distally toward the linear adapical ray. Sclerites can be up to 2–3 mm long as measured along the sagittal plane.

Specimens are isolated sclerites preserved in calcium phosphate. Two modes of preservation occur in our material. In one, the surface of the sclerite was replaced and is therefore visible. Porter (2004) inferred that in such cases the originally aragonitic skeleton was secondarily replaced by calcium phosphate. This mode of preservation is seen in samples from PI13 of Zanskar Valley (Fig. 6.1–6.7, 6.9–6.12), including the holotype. A second mode of preservation occurs where the internal void within the sclerite, or lumen, was diagenetically infilled with calcium phosphate, thus preserving several
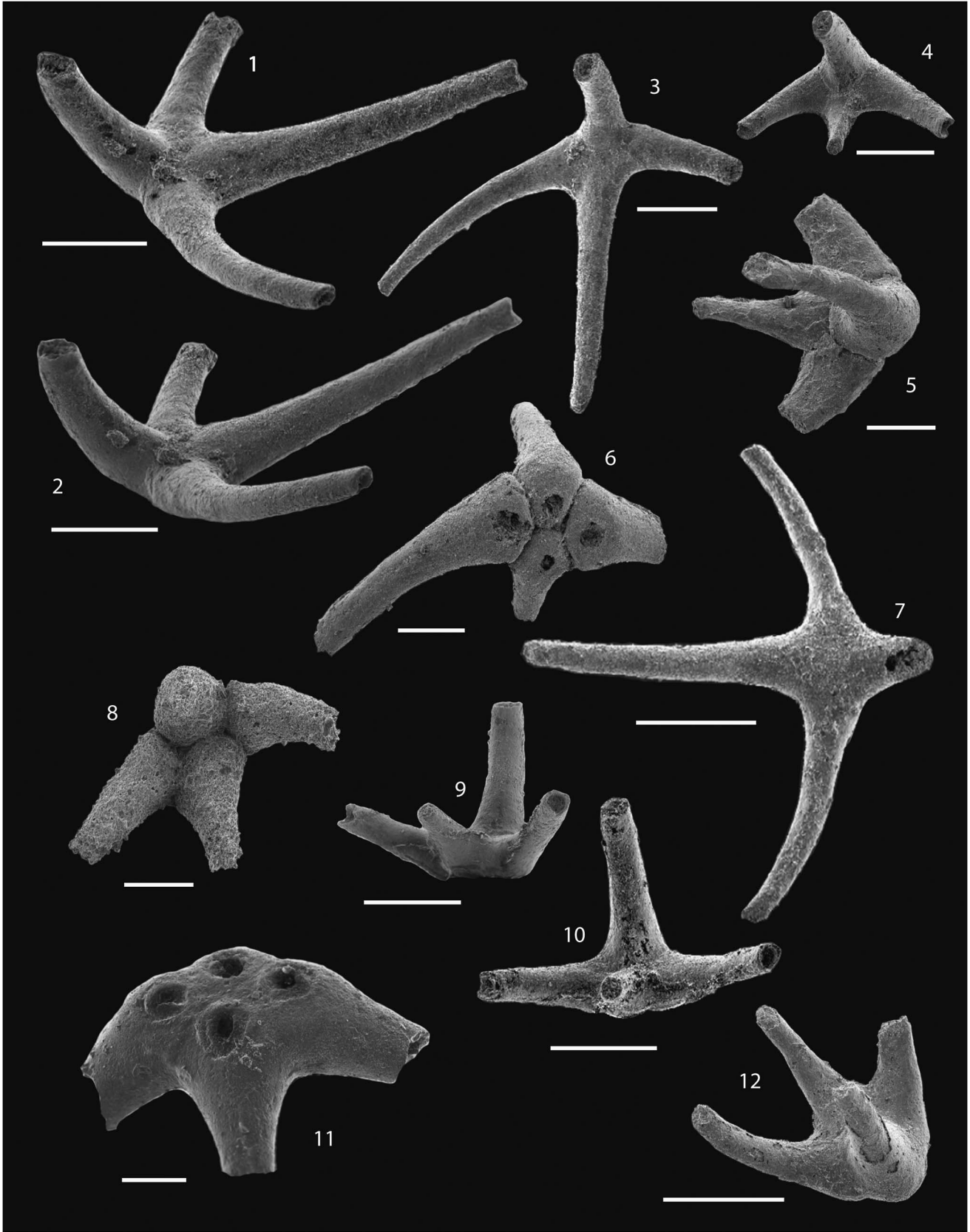
specimens as phosphatic internal molds (Porter, 2004; Qian and Bengtson, 1989) (Fig. 8.6, 8.8). These specimens preserve fewer features than the first mode, and so can be identified with less confidence. This second mode occurs in material from the PO3, PO9, PO15, PO21, PO24, PO25, and PV880 collections.

Remarks.—As individual chancelloriid scleritomes can contain sclerites with varied structure (Qian and Bengtson, 1989; Fernandez Remolar, 2001; Janussen et al., 2002; Randell et al., 2005), it is important to document the degree of variation among disarticulated sclerites collected from single beds before tax-onomoic determination. Our collections include several hundred sclerites that can be assigned to this genus. As there is no variation in ray formula or ray articulation facet condition among any of these sclerites, we conclude that all belong to a single species that was apparently invarient in these characters, both within and among the 8 horizons in the Parahio Formation from which this was collected. Unfortunately, many species of chancelloriid have been established based on a single, or very few, specimens, some of which are poorly preserved. Several such species are assigned to *Archiasterella* and share the 4 + 0 ray structure, and these are potentially senior synonyms of our new species. These are dis-cussed below. Sclerite morphology and terminology are given in Fig. 7.1–7.3.

As mentioned above, many species of *Archiasterella* have ray formulae other than 4 + 0. *Archiasterella dhiraji* n. sp. is invarient in ray formula, and the characters that distinguish it from other species relate specifically to the intersection of the four rays, and so we restrict our comparision here to only those species that share the 4 + 0 condition. We consider that some specimens figures as *Oneotodus* from the Parahio Formation (Bhatt and Kumar, 1980) are detrached rays of *A. dhiraji.* Bengtson (*in* Bengtson et al., 1990, Fig. 29D, 29E) figured a single specimen with a similar ray configuration to that in *A. hirundo* (see below) but lacking the robust structure and flattened base, and with abapical and adapical rays that meet in a tranverse articulation facet. He referred this and similar specimens to *A.* cf. *hirundo*. These individuals appear identical to *A. dhiraji* n. sp., so we place them within the new species. The two specimens attributed to *Archiasterella* sp. from the late early Cambrian Forteau Formation of western Newfoundland (Skovsted and Peel, 2007, fig. 6C, 6D) also share these characteristics, and so we also consider these to be conspecific. The geological implication of this synonymy is that the species has quite a long range, with a first known occurence within some of the earliest trilobite bearing beds in Australia, likely approximately 520 million years old (Bengtson et al., 1990), and ranging into late in Cambrian Stage 5, likely approximately 505 million years old.

Archiasterella dhiraji n. sp. resembles the well characterized species *A. hirundo* in that both have sclerites with four relatively slender rays, but *A. hirundo* has a broader basal surface and larger foramina than *A. dhiraji* n. sp. More importantly, the two species also differ in the articulation facets between the four rays. In *A. hirundo* the ascending horizontal rays meet at a sagittal articulation facet, whereas in *A. dhiraji* n. sp. (Figs. 6.1–6.3, 6.1–6.8) the abapical and adapical rays meet in a tranverse articulation facet and the ascending horizontal rays are isolated from each other, resulting in shorter sclerite length along the sagittal plane. In addition, *A. hirundo* sclerites are more robust and less recurved than those of *A. dhiraji* n. sp. and curvature of the short, barb-like abapical ray is particularly pronounced in *A. hirundo*.

Duan (1984, pl. 4, figs. 3, 4) erected a new species, *Archiasterella tetractina*, based on two illustrated specimens. *Archiasterella tetractina* has 4 + 0 rays per sclerite, but lacks a recurved adapical ray suggesting that it may not actually belong within *Archiasterella* (see Randell et. al., 2005, p. 994). Moore and colleagues (2014, p. 26) pointed out the difficulty in assessing the morphology of this species given the quality of the figured material. While the broad structure of the rays and ray suture of this late early Cambrian form do resemble *A. dhiraji* n. sp., it is difficult to determine if one ray projects upward from the plane of all the other rays, which is the defining characteristic of the genus. For these reasons we recommend isolating the name of *A. tetractina* Duan, 1984 to its type material, pending a more complete description of additional topotype material.

Vasil'eva (*in* Vasil'eva and Sayutina, 1988) illustrated three late early Cambrian specimens that were assigned to a new species *Archiasterella tetractina* (*non* Duan, 1984) that were later renamed *A. tetraspina* (Vasil'eva *in* Vasil'eva and Sayutina, 1993) on account of being a homonym of Duan's species. In *A. tetraspina*, the individual rays appear to be equilateral and are not recurved, as in *A. dhiraji* n. sp. These three specimens, along with a specimen described as *Onychia rossica* (Sayutina *in* Vasil'eva and Sayutina, 1988) closely resemble both *A. hirundo* and *A. dhiraji* n. sp. In particular, the basal surface of *O. rossica* closely resembles that of *A. dhiraji* n. sp. both in ray articulation facet pattern and in possessing a rimmed foramen. However, it is unclear whether one ray curves upward at an angle distinct from those of the others, so assignment of any of this material to *Archiasterella* is insecure if Moore's (2014, p. 858) criteria for recognizing the genus, are accepted. Likewise, the basal ray structure in the material described as *A. tetraspina* is unclear. For these reasons, we recommend isolating the names of *A. tetraspina* and *O. rossica* to the published material, pending better knowledge of topotype material.

Lee (1988) erected a new early Cambrian species, *Archiasterella quadratina* based upon a single incomplete sclerite with a 4 + 0 ray configuration diagnosed as four radiating nearly perpendicular rays within a plane, thus having a cruciform outline

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Figure 6. *Archiasterella dhiraji* n. sp. from the Parahio Formation. All specimens coated with platinum/palladium prior to SEM imaging. (**1–7, 9–12**) Collected 74.11 m above base of PU3 section (PI13), from Zanskar Valley, Parahio Formation. (**1–3**) Holotype, WIMF/A/3956, (**1**) oblique view; (**2**) oblique view; (**3**) vertical view; (**4–12**) paratypes, (**4, 9, 10**) WIMF/A/3957, (**4**) articulation facet between linear abapical ray and recurved adapical ray; (**5**) WIMF/A/3958, near vertical view showing articulation facet between linear abapical ray and recurved adapical ray and robust ascending horizontal rays and linear abapical ray in comparison to recurved adapical ray; (**6**) WIMF/A/3959, basal view showing foramen and articulation facet between linear abapical ray and recurved adapical ray; (**7**) WIMF/A/3960, vertical view; (**8**) WIMF/A/3961, from 880.93 m above base of Parahio Valley section, Parahio Formation, vertical view of an infilled specimen showing articulation facet between linear abapical ray and recurved adapical; (**9**) horizontal view showing linear abapical ray and ascending horizontal rays residing in a single plane, with recurved adapical ray protruding from this plane; (**10**) horizontal view showing linear abapical ray and ascending horizontal rays reside in a single plane, with recurved adapical ray protruding from this plane; (**11**) WIMF/A/3963, basal view showing foramen with raised "rim" representing a restricted foramen; (**12**) WIMF/A/3964, vertical view showing angle variation between ascending horizontal rays and recurved adapical ray. Scale bars represent 500 μm (**1-4, 7, 9, 10, 12**) and 200 μm (**5, 6, 8, 11**).
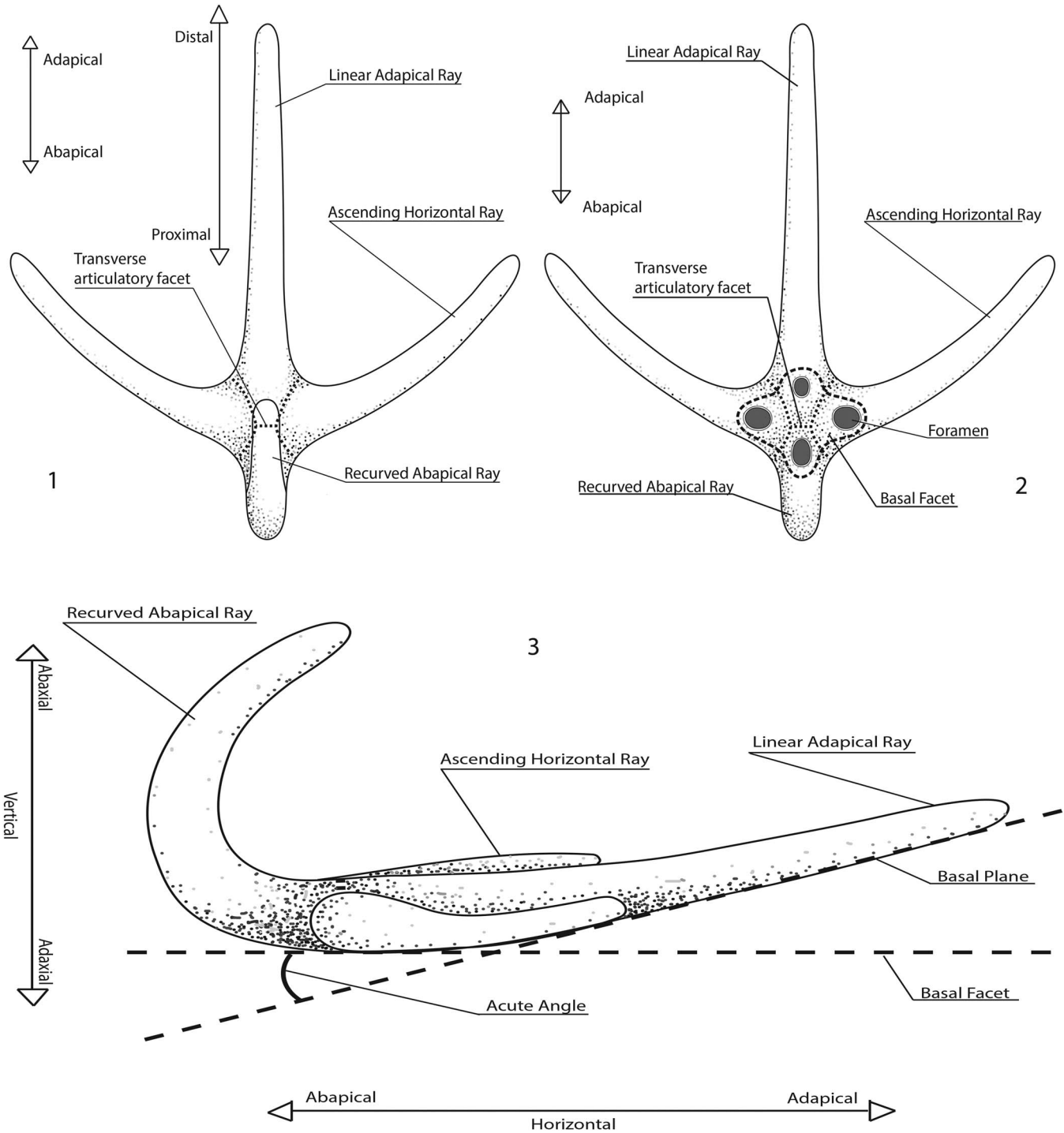
Figure 7. Reconstruction of *Archiasterella dhiraji* n. sp. sclerites with morphological terms used in this paper. (**1**) Profile view, (**2**) top view, (**3**) basal view.

when viewed perpendicularly to the ray plane. This sclerite is too incomplete to determine whether any ray is oriented differently from any other, and thus its assignment to *Archiasterella* is uncertain. We also isolate this name.

Archiasterella dhiraji n. sp. is not the first member of this genus to be illustrated and described from the Himalaya. Fuchs and Mostler (1972) provided representative drawings of the 5 + 0 ray structured *Archiasterella pentactina* (Sdzuy, 1969) and

other sclerites that they described as stauractine "*Archiaster*." The latter appears to belong to the genus *Allonnia* due to a lack of a recurved ray. Mostler (1980) illustrated what he suggested was *Chancelloria* sp. (stauractines "*Archiaster*") in Pakistan. However, the sclerite illustrated in fact belongs to the genus *Allonnia* because of its radial symmetry and lack of a transverse or sagittal articulation facet. Singh and colleagues (2015) referred several specimens reportedly from the upper part of
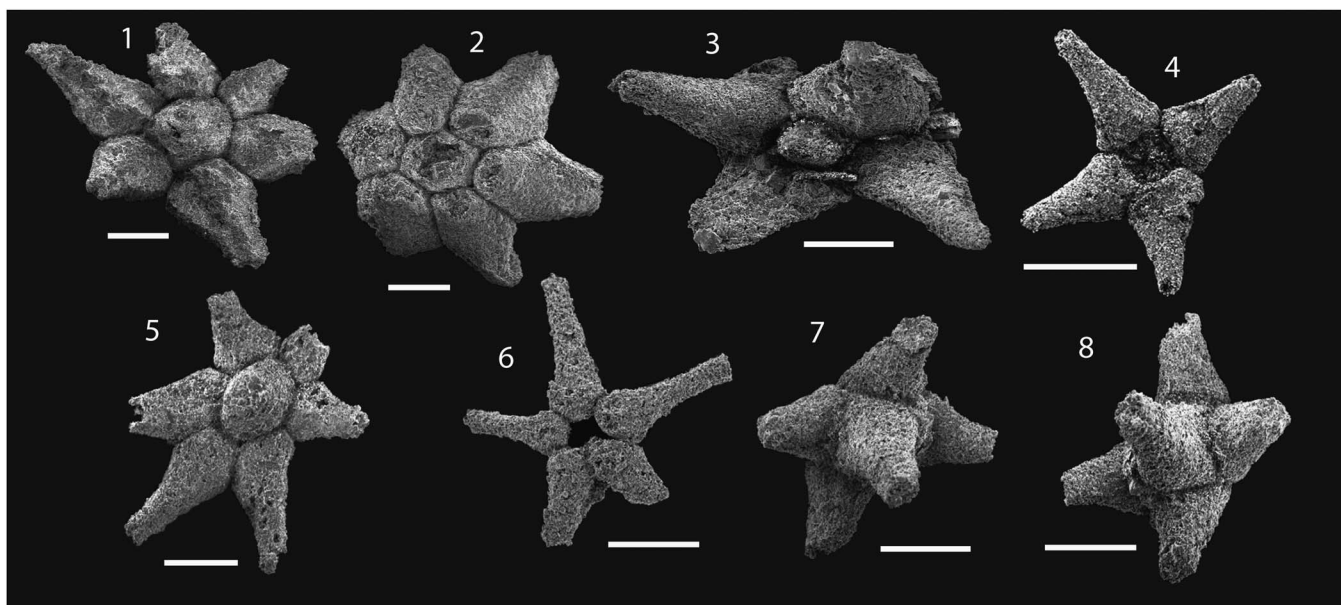
Figure 8. *Chancelloria* sp. Walcott, 1920, all specimens coated with platinum/palladium before SEM imaging. Scale bar represents 200 μm. (**1–4**) From 775.41 m (PO24) above base of Parahio Valley section, Parahio Formation. (**5–8**) From 880.93 m (PV880) above base of Parahio Valley section, Parahio Formation. (**1**) WIMF/A/3965, 775.41 m, 6 + 1 sclerite, view of adaxial surface; (**2**) WIMF/A/3966, 6 + 1 sclerite, view of abaxial surface; (**3**) WIMF/A/3967, 4 + 1 sclerite, oblique view of adaxial surface; (**4**), WIMF/A/3968, 4 + 1 sclerite, view of adaxial surface with central ray broken; (**5**) WIMF/A/3969, 6 + 1 sclerite, view of adaxial surface; (**6**) WIMF/A/3970, 5 + 1 sclerite with central ray missing, making orientation of sclerite difficult to determine; (**7, 8**) WIMF/A/3971, 4 + 1 sclerite, oblique views of adaxial surface.

Stage 4 in the Parahio Formation to *Archiasterella*. In our opinion, only one of their figured specimens (Singh et al., 2015, fig. 3.2) is sufficiently well preserved to warrant assignment to this genus, and we consider it to belong to *A. dhiraji*. The single other relatively complete chancelloriid sclerite illustrated by Singh and colleagues (2015, fig. 3.1) was suggested to belong to *Chancelloria* in the text of that paper (Singh et al., 2015, p. 2193) but was assigned to *Archiasterella* in the figure caption (Singh et al., 2015, p. 2194). Because ray number and its basal attachment is different from that of *Archiasterella dhiraji*, we do not consider it to belong that species or genus, but more comparable to *Chancelloria* (see below). Other putative chancelloriid material (Singh et al., 2015, fig. 3.3–3.9, 3.13–3.19) includes isolated rays that, in our opinion, do not merit assignment at the generic level.

Occurrence.—From carbonates collected at 78.07 m (PO3, *Haydenaspis parvatya* level); reportedly also from ~20 m higher in the section (Singh et al., 2015), 439.44 m (PO15, *Kaotaia prachina* Zone), 765.14 m (PO21), 775.41 m (PO24), and 776 m (PO25) (all *Paramecephalus defossus* Zone); 836.36 m (PO31 *Orytocephalus salteri* Zone); and 1242.4 m (PO9, unzoned 5) above the base of the Parahio Valley section on the north side of the Parahio River, Spiti region, Parahio Formation. The PO3 occurrence is from the top of the informal global Stage 4 of the Cambrian System, and thus would traditionally be considered latest early Cambrian. Other collections span the informal global Stage 5 of the Cambrian. In addition, from carbonates collected at 74.11 m above base of PU3 section (PI13), from Zanskar Valley, Parahio Formation which, based on co-occurrence with a new brachiopod species (Popov et al.,

2015) lies within the *Paramecephalus defossus* Zone and thus also belongs to Cambrian Stage 5. Approximately 300 spicules inspected.

Genus *Chancelloria* Walcott, 1920

Type species.—*Chancelloria eros* Walcott, 1920; Burgess Shale, middle Cambrian, British Columbia, Canada.

Diagnosis.—See Moore et al. (2014, p. 12).

Chancelloria sp.
Figure 8.1–8.8

Material.—WIMF/A/3965-3971.

Description.—Isolated sclerites, poorly preserved as internal molds of the central cavity (lumen). Sclerites with tapering central ray, the presence of which is either evident or inferred, and lateral rays vary in number. Abundant sclerites represented by 4 + 1, 5 + 1, and 6 + 1 form, with a few poorly preserved 7 + 1 sclerites also present. Sclerites are composed of four to seven distally tapering lateral rays each of similar proportions and radial symmetry arranged around a distally tapering central vertical ray projecting from the basal surface. Lateral rays reside within the basal plane, either parallel to the basal surface or raised slightly forming an acute abaxial angle to it.

Specimens poorly preserved as isolated phosphatic internal molds of sclerites, as in some *A. dhiraji* n. sp. described above (Fig. 6.1–6.8). Although sclerites are preserved as internal

molds of the lumen, the walls between adjacent cavities were perhaps thin enough for rays to adhere together even in acid-etched residues, thus leaving sclerites intact (Qian and Bengtson, 1989).

Remarks.—Various sclerite characteristics have been used to diagnose chancelloriid species. One is the number of rays-per-sclerite (Jiang *in* Luo et al., 1982). However, this number can vary within a single chancelloriid scleritome, and so ray number alone is not appropriate for designating species (Qian and Bengtson, 1989; Fernández Remolar, 2001; Janussen et al., 2002; Randell et al., 2005). Sclerites within our collections vary in possessing from four to seven lateral rays, which is compatible with that reported by Janussen and colleagues (2002), which showed ray configurations of $4+0$, $5+1$, $6+1$, $7+1$, and $8+1$ within a single articulated scleritome of *C. eros*. Similarly, disarticulated sclerites of *C. maroccana* (Sdzuy, 1969) are considered to span the range from $4+1$ to $7+1$, as in our material. Individual collections within this study do display ray configurations that vary from $4+1$ to $7+1$ (i.e., PO24). However, sample sizes within other individual collections are often too small to confidently suggest that the full range of variation is expressed within each collection. Accordingly, there is no reason to consider that *Chancelloria* sclerites in our sample belong to more than a single species.

The earliest recorded occurrence of *Chancelloria* consists of articulated sclerites from the *Purella antiqua* Zone of the Nemakit-Daldynian Stage, Siberia (Khomentovsky et al., 1990; Maloof et al., 2010; Kouchinsky et al., 2012), and *Chancelloria* is known to endure until the *Prochuangia* Zone, low in the upper Cambrian, based on biostratigraphically correlated trilobites reported from the Mila Formation, Alborz Mountains, Iran (Mostler and Mosleh-Yazdi, 1976; Hamdi et al., 1995; Peng et al., 1999). While the FAD of *Chancelloria* is considered to be of biostratigraphic potential (Brasier, 1989; Qian and Bengtson, 1989; Janussen et al., 2002) the end of its range is less well constrained.

A single specimen reportedly from ~20 m above the *Haydenaspis parvatya* level (Singh et al., 2015, fig 3.1) appears to show five or more rays radiating in a plane, and might be a *Chancelloria*.

Occurrence.—New material from Parahio Formation carbonates collected at 78.07 m (PO3, *Haydenaspis parvatya* level), 439.44 m (PO15, *Kaotaia prachina* Zone), 775.41 m (PO24, *Paramecephalus defossus* Zone), 836.36 m (PO31, *Orytocephalus salteri* Zone), 880.96 m (PV880.96, *O. salteri* Zone), and 1242.4 m (P09 unzoned 5) above the base of the Parahio Valley section on the north side of the Parahio River, Spiti region, Himachal Pradesh. The PO3 occurrence is from the top of informal global Stage 4 of the Cambrian System; all others are from informal global Stage 5 of the Cambrian. Approximately 30 spicules inspected.

<div align="center">

Phylum Mollusca Cuvier, 1797
Class Helcionelloida Peel, 1991a.

</div>

Diagnosis.—See Devaere et al., (2013, pg. 6).

Remarks.—Placement of Himalayan material into the class Helcionelloida Peel, 1991a is based on specimens being untorted mollusks that are endogastrically coiled with the apex located posteriorly (Peel, 1991a, 1991b; Geyer, 1994; Gubanov and Peel, 2000). We cannot be certain that the new material figured herein is untorted because no apices are sufficiently well preserved to permit assessment. However, as all other features of our shells compare closely with previously described helcionelloid material, we are confident in our assignment to Helcionelloida.

<div align="center">

Order Helcionellida Geyer, 1994
Family Helcionellidae Wenz, 1938
Genus *Igorella*, Missarzhevsky *in* Rozanov et al., 1969

</div>

Type species.—*Igorella ungulata* Missarzhevsky *in* Rozanov et al., 1969, p. 141, lower Cambrian, Tommotian (*Nochoroicyathus sunnaginicus* Zone), West Anabar, and Uchur-Maya regions, Siberian Platform, Russia.

Diagnosis.—See Devaere et al. (2013, pg. 19-20).

Remarks.—The figured material is assigned to this genus because these coiled shells are moderately high and cap-shaped, and are also moderately laterally compressed. The apices are inclined and are significantly displaced posteriorly, projecting over the posterior apertual margin. In addition, the apertures are oval to elliptical and simple in form. Shells display external ornamentation represented by concentric comarginal ribs (rugae). All these features are consistent with placement in *Igorella*. These Himalayan shells can be excluded from the genus *Oelandiella* (Vostokova, 1962), to which they are similar in several ways, because they are much more loosely coiled (cyrtoconic), which gives them their cap-shaped appearance.

<div align="center">

Igorella cf. *maidipingensis* Yu, 1974
Figure 9.1–9.14

</div>

Material.—WIMF/A/3972-3981.

Description.—Univalves moderately laterally compressed and cap-shaped, slightly cyrtoconic, and loosely coiled to about one-half whorl. Several specimens display a rapidly expanding conch, flaring and widening slightly upon approaching the aperture. Aperture is elongated and elliptical, with the greatest length along anterior-posterior axis. Apertural margin is perpendicular to sagittal plane. Apex is posteriorly displaced over the posterior of aperturual margin by a distance of approximately one eighth of the total shell length, and is not preserved. Umbilicus forms an even, convex curve. The outer surfaces of these internal molds display comarginal ribs that always cross the dorsum. Ribs straight along margin from the dorsum to umbilicus. Ribs symmetrical on both margins and most prominent on dorsal surface tapering and ultimately fading approaching umbilical area. Most specimens contain 11–13 moderately prominent ribs, with decreasing robustness along dorsum until obsolete near apex. Specimens display primary ribs only (apparently invariant in size, shape, and number among individual specimens of similar
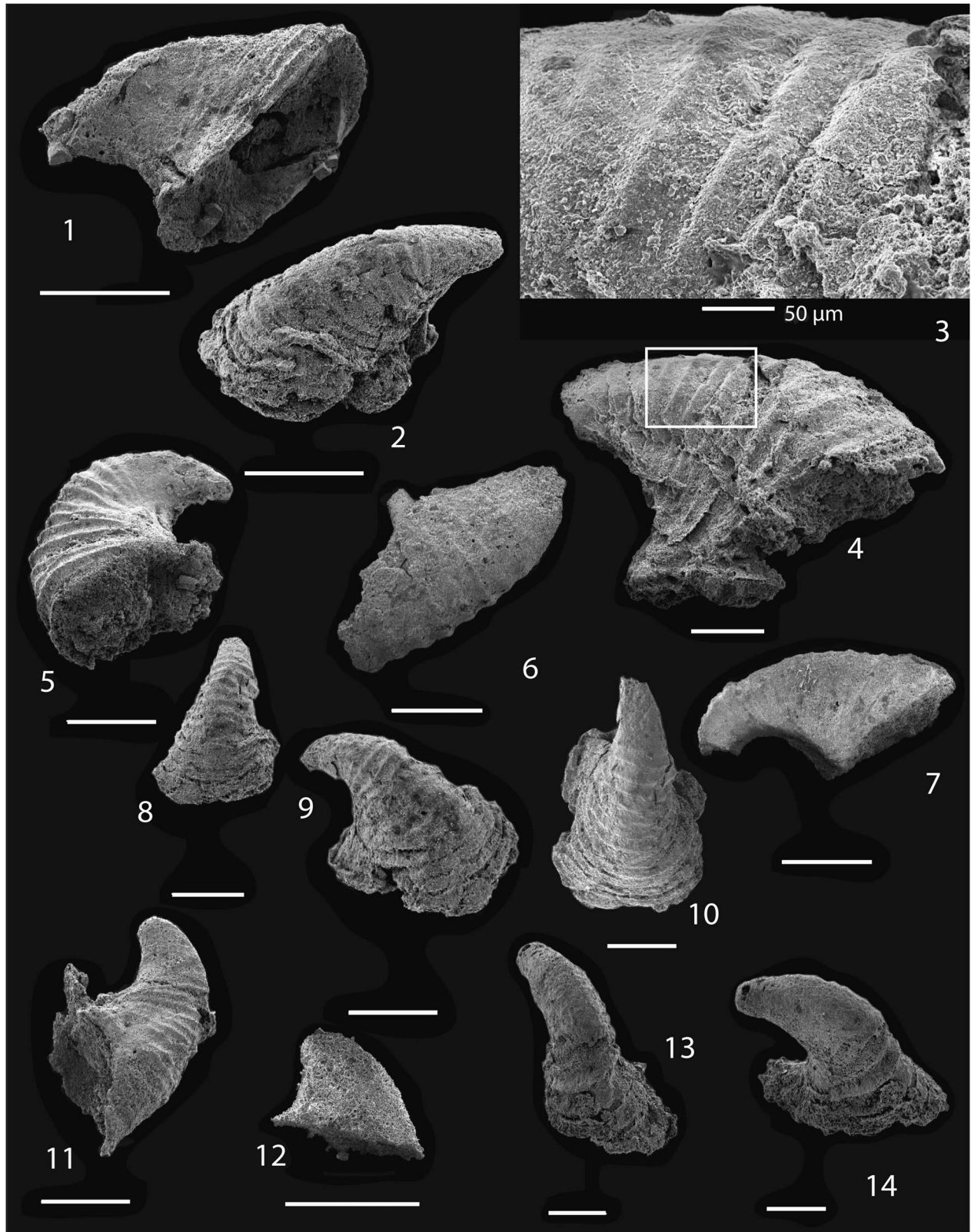
Figure 9. *Igorella* cf. *maidipingensis* (Yu, 1974). All specimens coated with platinum/palladium before SEM imaging. Scale bar represents 200 μm unless otherwise indicated on plate. (**1–11, 13, 14**) From 776 m (PO25) above base of Parahio Valley section, Parahio Formation; (**12**) from 880.93 m (PV880) above base of Parahio Valley section, Parahio Formation. (**1**) WIMF/A/3972, right oblique view, showing elliptical aperture; (**2, 8–10**) WIMF/A/3973. (**2**) Oblique view of conch displaying comarginal ribs crossing dorsum; (**3, 4**) WIMF/A/3974, (**3**) detail of subtriangular rib in transverse view, (**4**) right lateral view with box showing location of (**3**); (**5**) WIMF/A/3975, left oblique view displaying broken apertural opening; (**6**) WIMF/A/3976, lateral view with slightly rounded ribs; (**7**) WIMF/A/3977, right lateral view; (**8**) dorsal view displaying comarginal ribs; (**9**) oblique right lateral view; (**10**) oblique dorsal view, displaying prominent comarginal ribs and smooth apex; (**11**) WIMF/A/3979, right lateral view with prominent ribs and smooth apex; (**12**) WIMF/A/3980, possible infilled apex; (**13, 14**) WIMF/A/3981, (**13**) right oblique view, (**14**) right lateral view.

size). Transverse rib profiles triangular to wedge-shaped with angularity ranging from sharp to well rounded, depending on preservation.

All specimens are preserved in calcium phosphate. These specimens thus display no preserved original surficial details or microstructure of the original organism.

Remarks.—The Parahio Formation specimens appear to be slightly tectonically deformed, displaying varied degrees of lateral compression likely due to variation in their orientation with respect to the principal extension direction. However, some variation within the sample may be biological in origin. In fact, *Igorella maidipingensis* morphology is known to be quite variable, particularly concerning shell proportions and extent of apical bending (Parkhaev and Demindenko, 2010). Despite being mildly deformed internal molds, our shells are sufficiently well preserved to permit evaluation at a low taxonomic level.

Material described herein is comparable to *Igorella maidipingensis* in several ways, such as the possession of a moderately high, moderately laterally compressed shell, an apex that is projected posteriorly over the posterior of the apertural margin at a distance of roughly one eighth of the shell length (Figs. 9.2, 9.5, 9.7, 9.9, 9.11, 9.14), an aperture that is oval to elliptical (Figs. 9.1, 9.4), the convex anterior field, and concave posterior field, the lateral fields that are straight to slightly concave (Figs. 9.1–9.14), and that the exterior ornamentation displays concentric comarginal ribs that are evenly spaced and are triangular in profile. Although our specimens display fewer ribs than *I. maidingensis*, (between 11 and 13, becoming less and less robust until smoothing out entirely as they approach the apex), this is possibly a result of preservation and does not justify exclusion of our specimens from the species. However, our specimens do lack a well-preserved apex and protoconch, thus limiting our confidence in taxonomic assignment to *I. maidipingensis*.

Igorella cf. *maidipingensis* differs from *I. ungulata* in that it has a lower shell, lacks radial striations, and displays sharper concentric ribs (Missarzhevsky *in* Rozanov et al., 1969). The presence of sharp concentric ribs also distinguishes *I.* cf. *maidipingensis* from other congeneric species such as *I. monstrosa*, *I. sanxiaensis*, *I. hamata*, *I. levis*, *I. talassica*, *I. durara*, and *I. arta* (Parkhaev and Demindenko, 2010; Missarzhevsky *in* Rozanov et al., 1969; Yu, 1979; Esakova and Zhegallo, 1996; Missarzhevsky *in* Missarzhevsky and Mambetov, 1981; Kruse, 1991). Our specimens also exhibit comarginal ribs that are denser than those in *I. minor* and *I. emeiensis* in the lower section of the shell (Chen and Zhang, 1980; Yu, 1987).

This species has a documented biostratigraphic range from the Nemakit-Daldynian Stage to the Tommotian stages of the Siberian Platform, on the Yangtze platform, in France, and in Iran (Devaere et al., 2013; Parkhaev and Demindenko, 2010). If our material is confirmed in belonging to this species, it will extend the range of *Igorella maidipingensis* into informal Stage 5 of the Cambrian System.

Occurrence.—New material from Parahio Formation carbonates collected at 776m (PO25, *Paramecephalus defossus* Zone) above the base of the Parahio Valley section on the north side of the Parahio River, Spiti region, Parahio Formation,

informal global Stage 5 of the Cambrian. Approximately 15 conchs inspected.

Phylum Arthropoda von Siebold, 1848
Class Trilobita Walch, 1771
Order Ptychopariida Swinnerton, 1915
Indeterminate Ptychopariid
Figure 10.1–10.5

Material.—WIMF/A/3982-3986.

Description.—Cranidium subquadrate: sagittal length 240μm, maximum width 500μm. Glabella occupies entire axis, expanding transversely slightly where intersecting anterior border. Posterior margin of occipital ring strongly arched, occipital furrow weakly incised, occipital ring about one fifth of axial length. Glabellar medial portion less inflated than fixigenae. Fixigenae smooth, anterior and lateral margin defined by sharp break of slope with weakly incised border furrow of modestly inflated border. Anterior border long (exsag.), approximately 22% of cranial sagittal length at longest, contiguous with narrow (tr.) lateral border that widens posteriorly into base of stubby spine that extends rearward and outward from a location within posterior border. Additional specimens include fragments of the posterior lateral margin of several free cheeks, some of which bear marginal tubercles.

Remarks.—The apparently phosphatized cranidium WIMF/A/3982 shows mild tectonic shear. The overall form of this small, evidently early meraspid cranidium is broadly similar to that seen among "ptychopariid" trilobites (e.g. Lee and Chatterton, 2005a, 2005b; Cederström et al., 2011; Laibl, Fatka, Cronier, and Budil, 2014) in that the glabella expands anteriorly, the glabella lacks axial carination, and the occipital lobe is inflated. Notable differences are the wide anterior border and the stubby spines on the posterior border neither of which are typical for a ptychoparioid meraspid, and look more like the form seen in the protolenid *Ichangia inchangensis* (see Zhang and Pratt, 1999). This lone specimen might belong to any of the five trilobite species described from this locality (Peng et al., 2009), the most common of which is *Gunnia smithi*, or to other species as-yet unrecorded.

Occurrence.—All specimens are from Parahio Formation carbonates collected at 776 m (PO25, *Paramecephalus defossus* Zone) above the base of the Parahio Valley section on the north side of the Parahio River, Spiti region, Parahio Formation, informal global Stage 5 of the Cambrian. Five specimens available.

Phylum Incertae Sedis
Hyolith indet.
Figure 11.1–11.5

Material.—WIMF/A/3987-3990.

Description.—Elongated, slightly tapered, small conchs decreasing evenly in diameter toward the apex. Subtriangular in cross-section, with slightly convex venter, and moderately
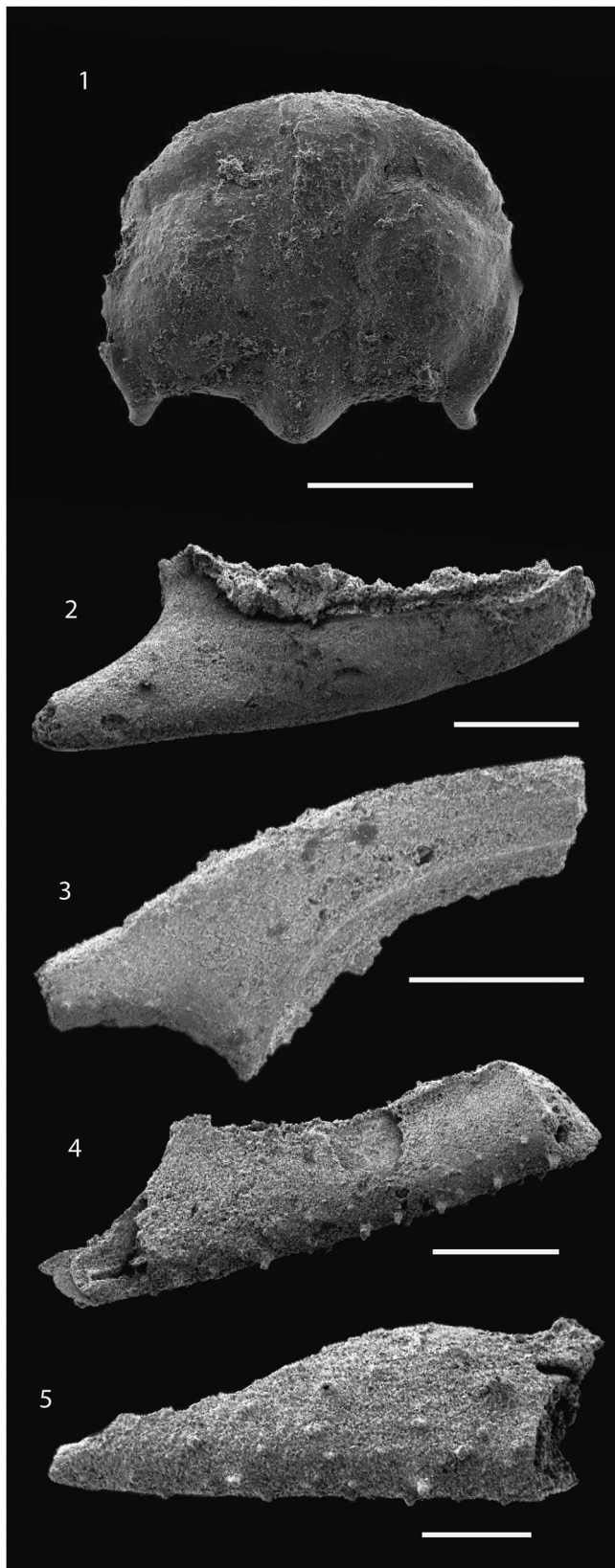
Figure 10. Indeterminate ptychopariid meraspid cranidium and isolated trilobite free cheeks, all specimens coated with platinum/palladium before SEM imaging. (**1–5**) From 776 m (PO25) above base of Parahio Valley section, Parahio Formation. (**1**) WIMF/A/3982, meraspid cranidium; (**2–5**) trilobite free cheeks, (**2**) WIMF/A/3983; (**3**) WIMF/A/3984; (**4, 5**) with small tubercles, WIMF/A/3985; (**5**) WIMF/A/3986. Scale bars represent 200 μm (**1**) and 500 μm (**2–5**).

convex dorsum. Internal surface of conch smooth. The phosphatic internal molds display no preserved surficial details or microstructure of the original organism. No apices are preserved.

Remarks.—The cylindrical conchs with roughly triangular cross sections identify these specimens as hyoliths, but no other features are preserved to permit more accurate taxonomic determination. Hyoliths previously described from the type section of the Parahio Formation have been assigned to two species, *Hyolithes (Orthotheca)* aff. *plicatus* and *Hyolithes* aff. *danianus* (Reed, 1910). These came from Hayden's level 9, which is within the stratigraphic range of the material described herein. Observations of the available specimen and Reed's (1910) illustrations suggest that his material was many times larger than that preserved described herein. Because the material figured here does not obviously differ other than the size from *Hyolithes* aff. *danianus*, these forms are conceivably closely related. Unfortunately the figured material assigned to *Hyolithes (Orthotheca)* aff. *plicatus* is missing from the collections of the Geological Survey of India in Kolkata. That of *Hyolithes* aff. *danianus* is available, and will be re-described in separate review of all those Himalayan hyoliths that have been published previously and are presently still available.

Singh et al. (2015, p. 2193-4, figs. 3.11, 3.12) considered some specimens from the upper part of Stage 4 in the Parahio Valley to be "indeterminate hyoliths" or "indeterminate hylothids." The latter name is a *nomen dubium* and presumably an error because on their pg. 2193 ?*Cupitheca* is also considered "hylothid." The tubular material illustrated is poorly preserved and, based on the illustrations provided, we consider it to be taxonomically indeterminate.

Occurrence.—New material from Parahio Formation carbonates collected at 439.44 m (PO15, *Kaotaia prachina* Zone), 776 m (PO25), *Paramecephalus defossus* Zone), 880.93 m (PV880, *Orytocephalus salteri* Zone), and 1242.40 m (PO9, unzoned 5) above the base of the Parahio Valley section on the north side of the Parahio River, Spiti region, Parahio Formation, all within informal global Stage 5 of the Cambrian. Approximately ten specimens available.

Family Cupithecidae Duan, 1984

Type genus.—*Cupitheca* Duan *in* Xing et al., 1984.

Diagnosis.—See Parkhaev and Demidenko (2010, p. 949).

Remarks.—*Cupitheca* are straight conical tubes, oval in cross-section, with the proximal part having a smaller diameter. The family Cupithecidae contains only the type genus.

Occurrence.—Lower Cambrian of Antarctica, Greenland, China, Australia, and Kazakhstan, Spain, and middle Cambrian of the Himalaya.
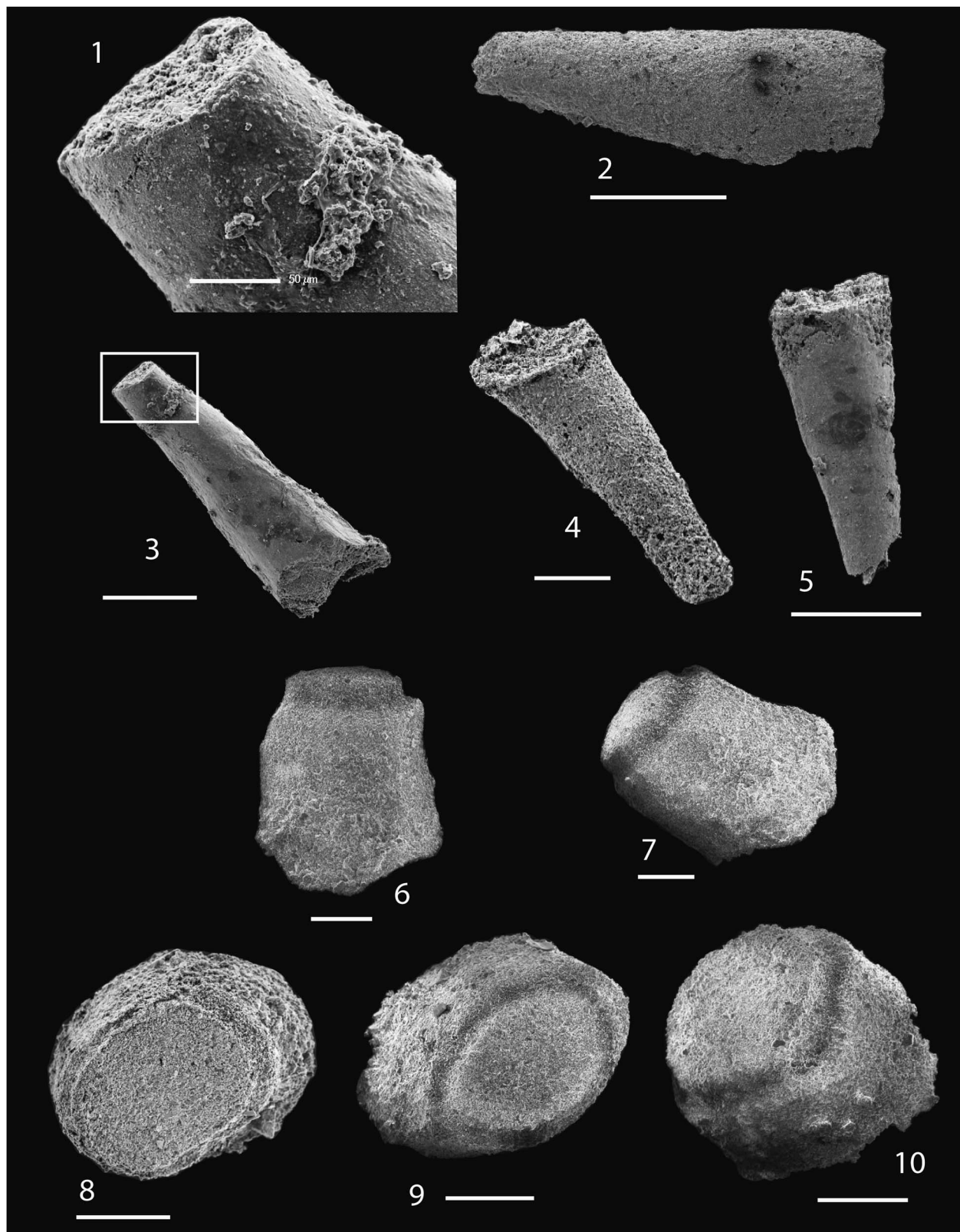
Genus *Cupitheca* Duan *in* Xing et al., 1984

Figure 11. Hyolith indet. and *Cupitheca* sp. All specimens are internal molds. All specimens coated with platinum/palladium before SEM imaging. (**1, 3–5**) From 776 m (PO25) above base of Parahio Valley section, Parahio Formation; (**6–10**) from 775.41 m (PO24) above base of Parahio Valley section, Parahio Formation. (**1–5**) Hyolith genus and species indeterminate. (**1**) WIMF/A/3987, close-up view displaying smooth interior surface of (**3**), marked by the white box; (**2**) WIMF/A/3988, from PV880, dorsal view; (**3**) WIMF/A/3987, dorsal view displaying smooth internal surface; (**4**) WIMF/A/3989, ventral view; (**5**) WIMF/A/3990 dorsal view; (**6–10**) *Cupitheca* sp., (**6**) WIMF/A/3991, lateral view displaying that the hemispherical proximal part is distinct and has a smaller diameter than the tube; (**7**) WIMF/A/3992, lateral view showing that the hemispherical proximal part is distinct and has a smaller diameter than the distal tube; (**8**) WIMF/A/3993, apical view showing the "step" of that separates proximal and distal parts of the tube; (**9**) WIMF/A/3994, slightly oblique apical view showing the "step"; (**10**) WIMF/A/3995, oblique view of apex. Scale bars represent 50 μm (**1**), 200 μm (**2–4, 6–10**), and 500 μm (**5**).

Type species.—*Cupitheca brevituba* Duan *in* Xing et al., 1984; lower Cambrian, Meishucunian Stage, Kuanchuanpu Formation and Qiongzhusian Stage, Xihaoping Formation of China (= *C. mira* [He in Qian, 1977]).

Diagnosis.—Straight edged or slightly bent conical tubes with distinct constriction of tube diameter at short distance from sealed proximal end. Expansion angle of tube walls 6°–14° in distal part of tube. Cross-section of distal part of tube circular or oval. Proximal parts of tube usually decollate. Ornamentation absent or represented by distinct transverse and longitudinal ribs. Internal surface of tube smooth.

Remarks.—Himalayan specimens are evidently members of this genus because they share the diagnostic straight edged conical tube with a constriction of tube diameter near the proximal end. The expansion angle of the tube walls varies between 6° and 14°, depending on specimen, and the cross-section of the distal part of tube is oval.

Cupitheca sp.
Figure 11.6–11.10

Material.—WIMF/A/3991-3995.

Description.—All specimens are preserved in calcium phosphate and display no internal details or microstructure of the original organism.

Remarks.—As the Himalayan material are all internal molds, no species level designation is possible. *Cupitheca* occurs in the lower Cambrian of China, Antarctica, Australia, Greenland, Spain and Kazakhstan (Mambetov *in* Missarzhevsky et Mambetov, 1981; Zhou and Xiao, 1984; Bengtson *in* Bengtson et al., 1990; Wrona, 2003; Malinky and Skovsted, 2004; Jensen et al., 2010). This is the first occurrence of *Cupitheca* within the middle Cambrian and within the Himalaya. Singh et al. (2015, fig 3.10) referred a specimen from Stage 4 in the Parahio Formation to ?*Cupitheca*. This specimen lacks clear preservation of the tubular constriction characteristic of this form, and we consider it to be indeterminate.

Occurrence.—From Parahio Formation carbonates collected at 775.41 m (PO24, *Paramecephalus defossus* Zone) above the base of the Parahio Valley section on the north side of the
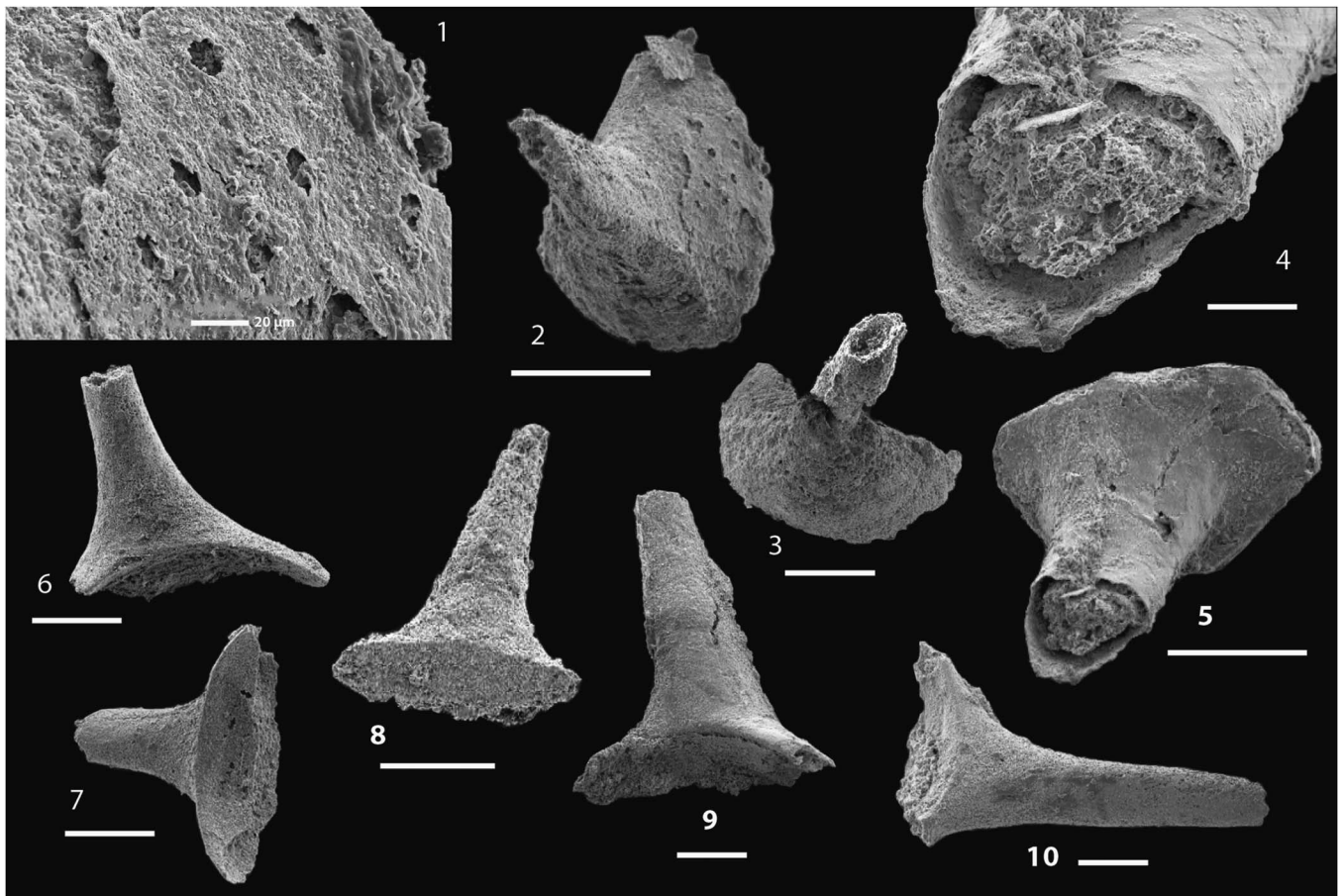

Figure 12. Spines indet. All specimens coated with platinum/palladium before SEM imaging. Scale bar represents 200 µm unless displayed otherwise. (**1–10**) From 776 m (PO25) above base of Parahio Valley section, Parahio Formation. (**1–3, 5**) Forms with straight and curved basal margins. (**1**) WIMF/A/3996, close-up of (**2**), showing possible surface ornamentation of equally distributed and sized pores; (**2**) WIMF/A/3996; (**3**) WIMF/A/3997, detailed view of (**4**) displaying possible well-preserved outer surficial detail; (**4**) WIMF/A/3998, elliptical base; (**5**) WIMF/A/3998; (**6**) WIMF/A/3999, elliptical base; (**7**) WIMF/A/4000, circular base; (**8**) WIMF/A/4001, circular base; (**9**) WIMF/A/4002; (**10**) WIMF/A/4003, elliptical base.

Parahio River, Spiti region, Parahio Formation, informal global Stage 5 of the Cambrian. Five specimens available.

<div align="center">

Spines indet.
Figure 12.1–12.10

</div>

Material.—WIMF/A/3996-4003.

Description.—All three morphotypes display long, thin, spines tapering toward apex, circular to elliptical in cross section and protruding from a variably shaped base. Spines are bilaterally symmetrical about medial plane, and taper rapidly near the base, becoming less tapered towards apex, which is not preserved. In one morphotype the base is hemispherical in plane view, and concave in profile. Specimens apparently have pores on their outer surface, with all pores having a similar size of approximately 10 μm, a similar circular shape, and appear to be equally distributed across the surface of the base at a distance of approximately 20–30 μm. Base of second morphotype subcircular to oval when viewed from above, with the spine protruding from the center of the base. Third morphotype has a thin elliptical base when viewed from above and is convex when viewed laterally.

Remarks.—The first morphotype is superficially similar to an eodiscid meraspid pygidium, as illustrated in Zhang and Clarkson, (2012, pl. 18, fig. 6, 8, 10, 16, 18), with a straight margin on one side confluent with curved opposite margin. However, the spine extends from the base towards the straight margin, not towards the curved margin, and there is no articulating facet. The second morphotype has a similar morphology to *Archaeopetasus exavatus* (Bengtson et al., 1990, fig. 106 A–E), but those spines appear to have a variable length unlike the specimens described herein. Lee (2008, fig. 5.3, pg. 1157) imaged a spinous specimen with a similar morphology to the third morphotype described herein (Figs. 12.6–12.10) as an indeterminate trilobite spine that was presumably axial. Other microfossil material illustrated from the Parahio Formation that might include trilobite fragments is some or all of that attributed to "*Helkiaria*" by Singh et al. (2015, p. 2194, figs. 3.20–3.24). This new generic name is a *nomen dubium*, being unaccompanied by a description. Perhaps the authors intended to refer to this material as halkieriid, a suggestion supported by the spelling that they gave on pg. 2193 of their paper.

Occurrence.—New material from Parahio Formation carbonates collected at 775.41 m (PO24) and 776 m (PO25) (both *Paramecephalus defossus* Zone) above the base of the Parahio Valley section on the north side of the Parahio River, Spiti region, Parahio Formation. Approximately 15 specimens available.

Acknowledgments

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