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Cambrian Microfossils of the Tethyan Himalaya

A Thesis submitted in partial satisfaction
of the requirements for the degree of

Master of Science

in

Geological Sciences

by

Ian Ross Gilbert

June 2014

Thesis Committee:

Dr. Nigel C. Hughes, Chairperson

Dr. Peter M. Sadler

Dr. Mary L. Droser

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The Thesis of Ian Ross Gilbert is approved:

Committee Chairperson

University of California, Riverside

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ABSTRACT OF THE THESIS

Cambrian Microfossils of the Tethyan Himalaya

by

Ian Ross Gilbert

Master of Science, Graduate Program in Geological Sciences

University of California, Riverside, June 2014

Dr. Nigel C. Hughes, Chairperson

The Parahio Valley hosts the type section of the Parahio Formation, a unit that occurs widely in the Tethyan Himalaya. Recent revision and recollection of trilobites from multiple horizons within this unit show that it spans the latest part of Stage 4 and much of Stage 5 of the Cambrian Period. Broadly coeval Parahio Formation deposits occur in the Zaskar Valley some 150 km to the northwest. A variety of small shelly fossils have been recovered by acid dissolution of carbonate beds within the Parahio Formation from both these sections, and these are described herein. They include tetract and pentact sponge spicules belonging to hexactinellid sponges, cancelloriid spicules belonging to *Chancelloria* sp. and new species of *Archiasterella*, *A. n. sp.*, shells of a helcionelloid comparable to *Igorella maidipingensis*, the hyolithid-like *Cuptitthea*, sp., a poorly preserved hyolithid, a meraspid ptychopariid trilobite, and an assortment of spinose microfossils of uncertain affinity. No conodont or paraconodont specimens were recovered, in contrast to an earlier report of microfossils from one horizon at this locality,

and inspection of some of these earlier reported microfossils suggest that they may have been detached chancelloriid spicules. The newly recovered microfossils are consistent with the trilobite-based middle Cambrian age determination for this Formation and are inconsistent with the late Cambrian age for the top of the Parahio Formation in its type section as proposed by some earlier workers and still prevalent in recent literature. Individual small shelly fossils taxa exhibit different stratigraphic ranges within the section, but lie within known stratigraphic ranges for comparable forms known from sections elsewhere in the world. The newly described species *A. n. sp.* provides the first biostratigraphic link for the Parahio Formation between the Parahio and Zanskar Valleys.

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INTRODUCTION

The well-exposed sections of Cambrian rocks in the Spiti and Zaskar valleys of the Indian Himalaya 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)(Fig. 1). During fieldwork in this area in 2000 and 2001 samples of carbonate rocks were collected for acid dissolution from the Parahio Formation, primarily with the aim of recovering topotype phosphatic brachiopods in order to clarify the systematic concepts of poorly known Cambrian species. An additional aim was to collect microfossils and, in particular, 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 dolomite band located near the top of the Parahio Formation in the Parahio Valley section (see Myrow et al. 2006a). Such taxonomic attribution, if correct, would seemingly imply a minimal depositional age of Furongian (i.e. within the traditional “late” Cambrian) for the top of this unit. This age determination was broadly consistent with the earliest biozonation of the Parahio Formation (Reed, 1910) in which the presence and the trilobite *Dikelocephalus* was used to infer a late Cambrian age for the top of the Parahio Formation in the Parahio Valley. However, taxonomic reassessment of Reed’s *Dikelocephalus* specimens (1910) determined that these trilobites are, in fact, an older

form (Jell and Hughes, 1997, p. 15), and that the upper part of the Parahio formation in the Parahio Valley is middle Cambrian in age. This conclusion was reaffirmed by Peng et al. (2009), who suggested that the uppermost *in situ* trilobite bearing rocks from the Parahio Valley in fact belong to the *Ptychagnostus gibbus* Zone (i.e. toward the top of Stage 5 of the Cambrian System). This 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 Zaskar 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).

In view of this temporal reassignment, the report of conodonts in the Parahio Formation of Spiti becomes both more remarkable and more important. If corroborated, this would imply one of two things: 1) the trilobite biostratigraphy of Peng et al. (2009) is incorrect, or 2) this is the stratigraphically earliest occurrence yet known of a range of conodont genera, which are known elsewhere only from the upper Cambrian or lower Ordovician.

A two-pronged approach has been used to assess this conundrum. Firstly, Nigel Hughes inspected the original material of Bhatt and Kumar (1980) housed at the Geological Survey of India in Kolkata. There he concluded that while most of the preserved illustrated specimens purported to be conodonts were in fact brachiopods. A few other illustrated specimens are discussed below. Secondly, I have processed carbonate samples from the Parahio Formation for fossils using acid dissolution in order to discover what microfossils, if any, occur with the trilobite specimens used to establish

the refined biozonation of Peng et al. (2009). The collections have included the level PO09 (unzoned 5), at 1242.4m above the base of the Parahio Valley section on the north side of the Parahio River, Spiti region, Parahio Formation (Fig. 2 Parahio section), which, from the description of Bhatt and Kumar (1980) and Nigel Hughes's observations of the hammer marks of relatively recent bulk sampling in the section is very likely the level at which Bhatt and Kumar (1980) sampled.

This study describes the newly recovered microfossils and considers them in stratigraphic context. The only groups that are commonly considered to include microfossils previously described from the Parahio Formation are two hyolithid specimens (Reed, 1910) from about 836.41m (Hayden level 9) in the measured section of Myrow et al., (2006a, Fig. 1) and the putative conodonts (Bhatt and Kumar, 1980). Where available, these previously described specimens have been inspected and the hyolithids will be discussed in forthcoming publications, including, where directly relevant, in this work.

MATERIAL AND METHODS

New limestone and dolostone samples were collected from the Parahio Formation in both valleys. These fossil bearing samples were placed into a 10 to 1 formic acid (HCO_2H) solution for acid digestion. Dissolution times depended on the amount of dolomitization in each sample but ranged from one week to a month or more (see Abrantes et al., 2005). After dissolution the remaining sample residue was sieved to isolate various size fractions. The samples were then sorted through and the microfossils

were isolated from un-dissolved residues using a binocular microscope. Fossils were then mounted on Scanning Electron Microscope (SEM) blanks using a conductive carbon tape and acetone solution. Fossils were then coated with Platinum and Palladium using the 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/>). Following high-resolution SEM imaging the fossils were arranged taxonomically and organized into plates using Adobe Photoshop and Illustrator Version CS6. Specimens figured herein are repositied in the microfossil collections of the Wadia Institute of Himalayan Geology in DehraDun, Uttaranchal, India.

GEOLOGICAL SETTING

The material described herein was collected from the Tethyan Himalaya, which is 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 (Peng et al., 2009) (Fig. 1). The Spiti and Zaskar valleys are adjacent drainage basins and the Parahio Formation, which has been recognized in both valleys, consists of siliclastic deltaic deposits that are interspersed with relatively thin trilobite-bearing carbonate beds that represent transgressive systems tract deposits developed over marine flooding surfaces (Myrow et al., 2006a,b; Peng et al., 2009). It is these trilobite-bearing carbonate beds from which the material examined herein was collected.

Sedimentological analysis of the Parahio Formation exhibits well-defined decameter-scale depositional cycles that record high sediment accumulation rates of 30.4 cm/1000 yr. (Myrow et al., 2006a,b). Investigation of the sedimentology also indicates that the strata records storm-influenced environments from fluvial facies, to shoreface, and finally to offshore marine environments (Myrow et al., 2006a,b). In addition, paleocurrent data for marine and fluvial facies of the Paraio Formation in both the Spiti and Zaskar valleys indicate northeast sediment transport, and these data support that the Parahio Formation was the ancient passive margin of India during the Cambrian (Myrow et al., 2006a,b).

COMPARISON WITH OTHER SMALL SHELLY FOSSIL FINDS IN THE INDIAN SUBCONTINENT

If hyolithids are included as small shelly fossils, such were among the first Cambrian fossils ever described from the Indian subcontinent (Waagen, 1882-1885), and have been reported sporadically ever since. Early works described several relatively large hyolithids from early Cambrian rocks in Salt Range of Pakistan (Waagen, 1891; Redlich, 1891; Schindewolf, 1955), and lower and middle Cambrian rocks of Kashmir (Reed, 1934; Kumar and Verma, 1987) and Spiti (Reed, 1910).

In recent years, the lowermost Cambrian rocks from the Lesser Himalaya have been shown to contain 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). The Pakistani assemblage belongs to a second successive fauna of small shelly fossils (Hughes et al., 2005), and contains the cancelloriids *Archiasterella* and *Chancelloria*, along with sachitids. The sachitids suggest a pre-trilobitic age and this is consistent with its lithostratigraphic position and association with phosphatic deposits. Cancelloriids 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 *Sinosacites flabelliformis*-*Tannuolina zhangwentangi* Assemblage zone of South China, but the possibility of a later age has not been discounted (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 cancelloriid-bearing level, and belonging to the trilobitic *Drepanuroides* Zone. All these finds, along with additional poorly preserved hyolithids from the Tethyan Himalaya of Kashmir (Kumar and Verma, 1987) are early Cambrian in age (see review in Hughes et al., 2005). 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 large hyolithids described alongside macrofossils in early papers (Reed, 1934; Reed, 1910). The fossils described in this paper are therefore important as the first record of small shelly fossils prepared using carbonate dissolution from the middle Cambrian of India. They provide, for example, a local demonstration of why it is unreasonable to assign rocks to the

Sinosacites flabelliformis-*Tannuolina zhangwentangi* Assemblage zone based on chancelloriids alone (*contra* Kumar et al., 1987).

STRATIGRAPHIC IMPLICATIONS OF THE NEW MATERIAL

The morphologies of hexactinellid sponge spicules described herein are quite simple, thus making higher resolution taxonomic assessment beyond hexactinellid affinity is impossible. As a group, hexactinellid sponges are known to range from the late Ediacaran to 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 early Cambrian to early in the late Cambrian (REFS). Given this, the Parahio Formation *Chancelloria* constrain the depositional age of these rocks to be likely pre-*Prochuangia* Zone (i.e. early late Cambrian) in age and no older than the base of the Cambrian System. This result is thus consistent with the trilobite-based biostratigraphy, as it suggests that no portion of the Parahio Formation is younger than the *Proagnostus bulbosus* Zone. However, specimens found within the literature that are redescribed *Archiasterella* n. sp. suggest that *A.* n. sp. has a range from the lower Cambrian (Bengston et al., 1990; Skovsted and Peel, 2007).

Like *Archiasterella* n. sp., *Igorella maidipingensis* has lower Cambrian occurrence. It has a documented biostratigraphic range from the Nemakit-Daldynian Stage to the Tommotian stages of the Siberian Platform, Yangtze platform, and in Iran

(Devaere et al., 2013; Parkhaev and Demidenko, 2010). The genus *Cupitthea* also occurs in the lower Cambrian of China, Australia, and Kazakhstan (Zhou and Xiao, 1984; Bengtson in Bengtson et al., 1990; Mambetov in Missarzhevsky and Mambetov, 1981). Taken at face value the known ranges of these three taxa might imply an early rather than middle Cambrian occurrence in the Parahio Formation. However, given the well-constrained trilobite biostratigraphy it is much more likely that these taxa simply range longer than previously recorded. Presently, small shelly fossils are poorly described from middle Cambrian strata, where macrofossils such as trilobites are readily available for biostratigraphy. Furthermore other species within the genera *Igorella* and *Archiasterella* at other geographic locations range into the middle Cambrian, thus making an extended range plausible. Furthermore, the observed range of the most common small shelly fossil, *A. dhirajina* within the Parahio Formation (Fig. 4) itself suggests a local 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 of the small shelly taxa.

CONODONT CONUNDRUM

Two of the putative conodont specimens figured as *Oneotodus* by Bhatt and Kumar's (1980, pl. 1 figs. 1, 3) resemble individual rays of of *Archiasterella*. n. sp. Fig. 1 resembles an isolated recurved abapical ray, or possibly an ascending horizontal ray, and

Fig. 3 resembles the linear adapical ray. Oddly, however, the specimens presently repositied in the Geological Survey of India with the same specimen numbers as this putative *Oneotodus* material are evidently not those originally figured, nor are they certainly fossils. They may have been substitutes following damage or loss of the figured material.

As *A. n. sp.* is found in the bed within which Bhatt and Kumar's (1980) material appears to have been collected, this redetermination of the putative *Oneotodus* removes an argument for the later Cambrian or early Ordovician age determination of the rocks. Because of this, and the fact that no conodonts or paraconodonts were found herein, this study seriously questions the late Cambrian age determination suggested by Bhatt and Kumar (1980). The other specimens figured as conodonts or paraconodonts by Bhatt and Kumar (1980) will be considered in a forthcoming study on phosphatic brachiopods.

BIOSTRATIGRAPHY

This study adopted the biostratigraphic zonation for the Tethyan Himalaya of northern India as proposed by Peng et al., (2009), which was based on the local occurrence of well-characterized trilobite taxa, combined with the biostratigraphic study of Hayden's (1904) section in the Spiti Valley, plus three sections in the Zaskar Valley (also see Reed, 1910). Peng et al., (2009) used these trilobite data to develop a formal biostratigraphic succession with six trilobite zones, three levels, and six intervals of no zonation for the Cambrian System of the Spiti and Zaskar Valleys (Figs. 2 and 3),

spanning an interval from the upper informal global Stage 4 through the lower half of the Guzhangian Stage of the Cambrian System. That study also provided a link with well established successions in China and Australia, enabling a precise global correlation for the following Tethyan Himalayan zones.

This work focuses upon material collected solely from the Parahio Formation, which spans from the upper global Stage 4 through the lower Drumian of the Cambrian System. The material has been biostratigraphically correlated to both the trilobite zonations of Peng et al., (2009) and to Hayden/Reeds's stratigraphic levels (Figs. 2-5).

Haydenaspis parvatya level.—This level contains both cancelloriids, *Archiasterella* n. sp. and *Chancelloria* sp. This level also contained the oldest fauna in Hayden's section, which was recorded at 78.07 m above the base of the Parahio Formation, Parahio Valley, Spiti (Fig. 2, 4). Trilobite data collected by Peng et al., (2009) allowed biostratigraphic correlation of this level and suggested 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.—This zone contains both cancelloriids *Archiasterella* n. sp. and *Chancelloria* sp. as well as hyolithid indet. which were collected at PO15 at 439.44m. (Fig. 2, 4). Its inferred stratigraphic position above the *Oryctocephalus indicus* level and below that of *Paramecephalus defossus*, suggests it lies within the lower part of the informal global Stage 5 (Peng et al., 2009).

Paramecephalus defossus Zone.—This is the most diverse zone within this study, containing all taxa described herein: hexactinellid sponge spicules, both cancelloriids, *Archiasterella* n. sp. and *Chancelloria* sp., hyolithid indet., *Cupitthea* sp. *Igorella* cf. *maidipingensis*, a single early meraspid ptychopariid, and the spines indet. collected in beds PO21 (765.14m), PO24 (775.41m), and PO25 (776m) This is the middle part of the Parahio Formation in Hayden's section is inferred to be Hayden's (1904) level 6. Peng et al. (2009) correlated this zone to the middle of the Taijiangian Stage of South China.

Oryctocephalus salteri Zone.—This zone contains hexactinellid-type sponge spicules, both cancelloriids, *Archiasterella* n. sp. and *Chancelloria* sp., hyolithid indet., collected at PO31 (836.36m) and PV880 (880.93m) (Fig. 2, 4). Peng et al. (2009) correlated this Zone with the middle Taijiangian Stage of South China, and with the upper Early or early Late Templetonian stage of Australia.

SYSTEMATIC PALEONTOLOGY

Phylum PORIFERA Grant, 1836 NOT IN REFERENCES

Class HEXACTINELLIDA Sollas, 1875

FIGURE 6

Figured material.—All from the Parahio Formation of the Parahio Valley (WIMF/A/3951, WIMF/A/3952, WIMF/A/3953, WIMF/A/3954, WIMF/A/3955).

Description.— Relatively simple spicule morphologies, including a four-rayed (tetract) spicule, and a five-rayed (pentact) spicule. Of the two morphotypes of tetract spicules, the first (tetract I) 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 (tetract II) has four cylindrical, equilateral rays with circular cross sections that reside in a single plane. Pentact spicules contain five rays that are at approximately ninety-degree 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 spicules have cylindrical rays.

Discussion.—The Parahio Valley sponge assemblages described herein includes simple spicule morphologies, all of which most likely belong to hexactinellid do to their glass-like appearance, which is unlike any phosphatic material seen in this study, and suggests that they have a siliceous composition. While generally well preserved, these isolated sponge spicules are not further taxonomically determinable, as a single sponge scleritome can be composed of more than one type of spicule, and similar spicule types can occur in species belonging to different orders. (Hartman et al., 1980; Dong, 1996). Their

stratigraphic significance is only that that the represent late Neoproterozoic or younger rocks.

Himalayan Occurrence.—New material from Parahio Formation carbonates collected at 775.41m (PO24, *Paramecephalus defossus* Zone) (containing pentacts and thin blade-like rayed tetracts), and 880.93m (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.

Class COELOSCLEROTOPHORA Bengtson and Missarzhevsky, 1981

Bengtson and Missarzhevsky (1981), when establishing this taxon, pointed out that all coeloscleritophoran sclerites were hollow with a scaly or spiny calcareous wall, had an external restricted basal foramen, and grew not by accretion but were shed or augmented by interpolation. Two fossil types with varied morphologies were included in the class: orders Chancelloriida (Walcott, 1920) and Sachitida (He, 1981). Chancelloriid sclerites are typically composed of star-shaped spicular rosettes, while the sachitids, which are interpreted by Bengtson and Conway Morris (1984) as benthic deposit feeders with scale- and/or spine-shaped sclerites, include halkieriids, siphogonuchitids, and possibly also wiwaxiids. According to Bengtson et al. (1990), the class Coeloscleritophora arose near the Precambrian-Cambrian transition and extended into the Furongian (late Cambrian).

Order CHANCELLORIIDA Walcott, 1920

Family CHANCELLORIIDAE Walcott, 1920

Included genera.—*Aldania* Vasil'eva, 1985; *Allonia* Doré and Reid, 1965; *Allonnia* Doré and Reid, 1965; *Archiasterella* Sdzuy, 1969; *Chancelloria* Walcott, 1920; *Chancelloriella* Demidenko, 2000; *Dimidia* Jiang in Luo *et al.*, 1982; *Diplospinella* Vasil'eva in Vasil'eva and Sayutina, 1988; *Eremactis* Bengtson and Conway Morris in Bengtson *et al.*, 1990; *Monospinites* Sayutina in Vasil'eva and Sayutina, 1988; *Rosella* Vasil'eva in Vasil'eva and Sayutina, 1988; *Stallaria* Vasil'eva, 1985.

Diagnosis.—Soft bodied coelosclerotophorans with sclerites consisting of spiny rays with lumen filled cavities and basal foramina. Sclerites usually composite, with individual rays joined at the proximal end of each ray. Cross-section of rays nearly circular, except at proximal end where joined. Foramen restricted by ring.

Discussion.—Articulated specimens were soft-bodied, sessile, sac-like organisms, which had an appearance resembling a barrel cactus, armored with star-shaped calcareous sclerites from which sharp spines radiated (Randell *et al.*, 2005). Sclerite ray structure is 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 designated using the terminology" of Moore *et al.* (2014).

Genus ARCHIASTERELLA SDZUY, 1969

Type species.—*Archiasterella pentactina* Sdzuy, 1969.

Other species.—*Archiasterella antiqua* Sdzuy, 1969 (p. 147, pl. 16, s. 1-5), *Archiasterella elegans* Demidenko in Gravestock et al., 2001 (p. 229, pl. 6, fig. 6), *Archiasterella fletchergryllus* Randell in Randell et al., 2005 (p. 992, figs. 3.1, 3.4-3.7, 4, 5, 7-9), *Archiasterella hirundo* Bengtson in Bengtson et al., 1990 (p. 55, pl. 29, figs. A-G; p. 56, pl. 30, figs. A-H), *Archiasterella palmiformis* Vasil'eva in Vasil'eva and Sayutina, 1988 (p. 195, pl. 30 fig. 4a, 4b), *Archiasterella pentactinia* Sdzuy, 1969 (p. 147, pl. 15, Figs. 4-12, 13?), *Archiasterella quadratina* Lee, 1988 (p. 100, pl. 1, fig. 12), *Archiasterella robusta* Vasil'eva, 1985 (p. 168, pl. 45, figs. 7-8), *Archiasterella tetractina* Duan 1984 (p. 187 pl. 4, figs. 3a, 3b, 4a, 4b), *Archiasterella tetractina* (non Duan, 1984) Vasil'eva and Sayutina, 1988 (p. 195, pl. 30, figs. 5, 6; p. 95, pl. 32, fig. 2), *Archiasterella tetraspina* Vasil'eva and Sayutina 1993 (p. 138) as *A. tetractina*, Vasil'eva and Sayutina 1988 (p.195, pl. 30, figs. 5, 6; P. 195, pl. 32 ,fig. 2).

Diagnosis.—See Moore et al. (2014, p. 26).

Discussion.—*Archiasterella* has been usually diagnosed as having a 5+0 or 4+0 sclerite ray structure, although 2+0 ray sclerites have also been known for some time (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 et al. (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 *A. tetractina* Duan, 1984, *A. tetraspina* Vasil'eva in Vasil'eva and Sayutina, 1988, and *A. quadratina* Lee, 1988 difficult to determine because the basal structures of these species are too poorly known to permit confident taxonomic determination.

ARCHIASTERELLA n. sp.

FIGURE 8

Oneotodus sp. BHATT AND KUMAR, 1980, pg. 357, pl. 1, figs. 1,3 only.

Archiasterella cf. *A. hirundo* BENGTON in BENGTON et al., 1990, pg. 55, pl. 29, figs. D,E.

Archiasterella sp. SKOVSTED AND PEEL, 2007. pg. 741, pl. 6, figs. C,E.

Types.—The holotype (WIMF/A/3956) is from the PI13 collection, a dolomitic horizon located at 74.11 m in the PU3 section of the Parahio Formation, near Purni in the Zanskar

Valley, Indian Himalaya. Paratypes include WIMF/A/3957 from the PI13 collection, WIMF/A/3958 from the PI13 collection, WIMF/A/3959 from the PI13 collection, WIMF/A/3960 from the PI13 collection, WIMF/A/3961 from the 880.93m in the Parahio section of the Parahio Valley, WIMF/A/3962 from the PI13 collection, WIMF/A/3963 from the PI13 collection, and WIMF/A/3964 from PI13 collection.

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 and recurves adapically along the sagittal plane outward from the plane of the other three rays. Basal surface is slightly convex with restricted, rimmed, oval foramina. Transverse articulatory facet connects recurved abapical ray and linear adapical ray, ascending horizontal rays 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 degrees 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 towards linear adapical ray. Sclerites can be as large as 2-3 mm in length as measured along the sagittal plane.

Preservation.—Specimens are isolated sclerites preserved in 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 phosphate. This mode of preservation is seen in samples from PI13 of Zanskar Valley (Fig. 8.1-8.7, 8.9-8.12). A second mode of preservation occurs where the internal void within the sclerite, or lumen, was diagenetically infilled with phosphate, thus preserving several specimens as phosphatic internal moulds (Porter, 2004; Qian and Bengtson, 1989)(Fig. 8.6, 8.8). These specimens preserve fewer features than in the first mode, and so can be identified with less confidence. This mode occurs in material from the PO03, PO09, PO15, PO21, PO24, PO25, and PV880 collections.

Discussion.—Sclerite morphology and terms can be found in the detailed reconstruction in Fig. 7.1-7.3.

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 making taxonomic determinations. Our collections include over 300 sclerites that can be assigned to this genus. As there is no variation in ray formula or ray articulatory facet condition among any of these sclerites, we conclude that all belong to a single species that was apparently invariant in these characters, both within and among the 8 horizons in the Parahio Formation from which

this was collected. Unfortunately, many species of cancelloriid 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 discussed below.

As mentioned above, many *Archiasterella* genera have ray formulae other than the 4+0 condition. As *A. n. sp.* is invariant in ray formula, and the characters that distinguish it from other species relate specifically to the intersection of the four rays, we restrict our comparison here to only those species that share the 4+0 condition.

Archiasterella 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. n. sp.* More importantly, the two species also differ from each other in the articulatory facets between the four rays. In *A. hirundo* the ascending horizontal rays meet at a sagittal articulatory facet, whereas in *A. n. sp.* (Figs. 8.1-8.3, 8.1-8.8) the abapical and adapical rays meet in a tranverse articulatory 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. n. sp.* and curvature of the short, barb-like abapical ray is particularly pronounced in *A. hirundo*. Bengston (*in* Bengston et al. 1990, Fig. 29D, E) described a single specimen with a similar ray configuration to that in *A. hirundo* but lacking the robust structure and flattened base, and with abapical and adapical rays that meet in a tranverse articulatory facet. He referred these specimens to *A. cf. hirundo*. These individuals appear identical to *A. n. sp.* so we place them within the new species.

The geological implication of this synonymy is that the species has quite a long range, with a first known occurrence within some of the earliest trilobite bearing beds in Australia, likely about 520 million years old (Bengtson et al., 1990), and ranging into late in Cambrian Stage 5, likely about 505 million years ago.

Duan (1984 pl. 4; Figs. 3, 4) (SH1074, SH1076) erected a new species *Archiasterella tetractina*, based on two illustrated specimens. *A. 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 et al. (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. 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 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 *A. tetractina* (*non* Duan, 1984) that were later renamed *A. tetraspina* (Vasil'eva *in* Vasil'eva and Sayutina, 1993) on account of being a junior objective synonym of Duan's species. In *A. tetraspina*, the individual rays appear to be equilateral and are not recurved, as in *A. n. sp.* Based on Moore's (2014, p. 26) criteria for recognizing the genus, this material may also not belong within *Archiasterella*. These specimens, along with a specimen described as *Onychia rossica* (Sayutina *in* Vasil'eva and Sayutina, 1988) closely resemble both *A. hirundo* and *A. n. sp.*

In particular, the basal surface of *O. rossica* closely resembles that of *A. n. sp.* both in ray articulatory facet pattern and 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 this material to *Archiasterella* is also insecure. 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 this 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 4 radiating nearly perpendicular rays within a plane, thus having a cruciform outline 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 isolated this name.

Archiasterella 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 *A. pentactina* (Sdzuy, 1969) and other sclerites which they described as stauractine „*Archiaster*”. The latter appears to belong to the genus *Allonia* 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 *Allonia* because of its radial symmetry and lack of a transverse or sagittal articulatory facet.

Himalayan occurrence.—From carbonates collected at 78.07m (PO03 *Haydenaspis parvatya* level), 439.44m (PO15 *Kaotaia prachina* Zone), 765.14m (PO21), 775.41m (PO24) and 776m (PO25) all (*Paramecephalus defossus* Zone), 836.36m (PO31 *O. salteri* Zone), and 1242.4m (PO09 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 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 74.11m above base of PU3 section (PI13), from Zanskar Valley, Parahio Formation, which lies some distance below the *Sudanomocarina sinindica* Zone and likely also belongs to Cambrian Stage 5, but whose exact age is poorly constrained.

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 9

Figured material.—Seven sclerites with tapering central ray, the presence of which is either evident or inferred, and lateral rays ranging in number from 4-6 (WIMF/A/3965, WIMF/A/3966, WIMF/A/3967, WIMF/A/3968, WIMF/A/3969, WIMF/A/3970, and WIMF/A/3971).

Description.—Isolated sclerites, poorly preserved as internal moulds of the central cavity (lumen). 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 4-7 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.

Preservation.—Specimens poorly preserved as isolated phosphatic internal molds of sclerites, as in some *A. n. sp.* described above (Fig. 9.1-9.8). 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).

Discussion.—Various sclerite characteristics have been used to diagnose cancelloriid species. One is the number of rays-per-sclerite (Jiang *in* Luo et al., 1982). However, it has been shown that this number can vary within a single cancelloriid 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 4 to 7 lateral rays which is compatible with that reported by Janussen et al. (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 first appearance datum (FAD) of *Chancelloria* is considered to be of biostratigraphic potential (Brasier, 1989; Qian and Bengtson, 1989; Janussen et al., 2002), of the end of its range is less well constrained.

Himalayan Occurrence.—New material from Parahio Formation carbonates collected at 78.07m (PO03 *Haydenaspis parvatya* level), 439.44m (PO15 *Kaotaia prachina* Zone), 775.41m (PO24 *Paramecephalus defossus* Zone), 836.36m (PO31 *O. salteri* Zone), 880.96m (PV880.96 *O. salteri* Zone) and 1242.4m (P09 unzoned 5) above the base of the Parahio Valley section on the north side of the Parahio River, Spiti region 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.

Class HELCIONELLOIDA Peel, 1991a.

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

Discussion.—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 enough preserved to permit assessment. However, as all other features of our shells compare closely with previously described helcionelloid material, we feel confident in our assignment to Helcionelloida.

Order HELCIONELLIDA GEYER, 1994

Family HELCIONELLIDAE WENZ, 1938

Genus IGORELLA, Missarzhevsky in ROZANOV et al., 1969

Type Species.— *Igorella ungulata* Missarzhevsky in Rozanov et al., 1969, p. 141.

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

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

Discussion.—These shells are assigned to this genus because they 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 apertural margin. In addition, the apertures are oval to elliptical in shape and simple in form. Furthermore, our 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 (cyrtconic), which gives them their cap-shaped appearance.

IGORELLA cf. MAIDIPINGENSIS YU, 1974

FIGURE 10

Figured Material.—All specimens from the Parahio Formation of the Parahio Valley, Tethyan Himalaya, all internal molds. (WIMF/A/3972, WIMF/A/3973, WIMF/A/3974, WIMF/A/3975, WIMF/A/3976, WIMF/A/3977, WIMF/A/3978, WIMF/A/3979, WIMF/A/3980, and WIMF/A/3981).

Description of the Himalayan Material.—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 apertural margin by a distance of approximately one eighth of the total shell length, and is rarely 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 yielding smooth apex which is attributed to preservation. Specimens display primary ribs only (apparently invariant in size, shape, and number among individual specimens of similar size). Transverse rib profiles triangular to wedge-shaped with angularity ranging from sharp to well rounded depending on preservation.

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

Discussion.—The Parahio Formation specimens appear to be slightly tectonically deformed, displaying varied degrees of lateral compression likely due to variations their orientation with respect to principal compressional direction. However, some variation observed within the sample may be biological in origin. In fact, *I. maidipingensis* morphology is known to be quite variable, particularly with regards to 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 *I. 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 of the shell length (Figs. 10.2, 10.5, 10.7, 10.9, 10.11, 10.14), an aperture that is oval to elliptical (Figs. 10.1, 10.4), the convex anterior field, and concave posterior field, and the lateral fields that are straight to slightly concave (Figs. 10.1-10.14), and that the exterior ornamentation displays concentric comarginal ribs that are evenly spaced and are triangular in profile. Although our specimens display fewer total number of ribs than *I. maidipingensis*, (between eleven and thirteen, becoming less and less robust until smoothing out entirely as they approach the apex), this is possibly a result of preservation and should not exclude our specimens from the species. However,

our specimens do lack a well-preserved apex and protoconch, thus limiting the 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 it 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*, and *I. arta* (Parkhaev and Demidenko, 2010; Missarzhevsky in Rozanov et al., 1969; Yu, 1979; Esakova and Zhegallo, 1996; Missarzhevsky in Missarzhevsky and Mambetov, 1981). 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, Yangtze platform, and Iran (Devaere et al., 2013; Parkhaev and Demidenko, 2010). If our material in fact belongs to this species, it would extend the range of *I. maidipingensis* into informal Stage 5 of the Cambrian System.

Himalayan 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.

Class TRILOBITA WALCH, 1771

Order PTYCHOPARIIDA SWINNERTON, 1915

Early MERASPID PTYCHOPARIID

Figure 11

Figured Material.—A single specimen from Parahio Formation of the Parahio Valley, Tethyan Himalaya (WIMF/A/3982).

Description.—Cranidium subquadrate: sagittal length $240\mu\text{m}$, maximum width $500\mu\text{m}$. 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.), about 22% of cranidial sagittal length at longest, contiguous with narrow (tr.) lateral border that widens posteriorly into base of stubby genal spine that extends rearward and outward from a location within posterior border.

Discussion.—The apparently phosphatized specimen shows mild tectonic shear. The overall form of this small, evidently early meraspid cranidium is similar to that seen among “ptychopariid” trilobites (e.g. (Lee and Chatterton, 2005a; Lee and Chatterton, 2005b; Cederström et al., 2011; Laibl et al., 2014) in that the glabella expands anteriorly,

the glabella lacks axial carination, and the occipital lobe is inflated. This lone specimen might belong to any of the 5 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.

Himalayan Occurrence.—Specimen is 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.

Phylum incertae sedis

Hyolithid indet.

FIGURE 12

Figured material.—All from the Parahio Formation of the Parahio Valley, Tethyan Himalaya, preserved as internal molds. (WIMF/A/3983, WIMF/A/3984, WIMF/A/3985, WIMF/A/3986)

Description.—Elongated, slightly tapered, small conchs decreasing evenly in diameter toward the apex. Subtriangular pyramidal in cross-section; with slightly convex ventral side, and moderately convex dorsal side. Internal surface of conch smooth.

Preservation.— The phosphatic internal molds display no preserved surficial details or microstructure of the original organism. No apices are preserved.

Discussion.—The cylindrical conchs with roughly triangular cross sections identify these specimens as hyolithiids, but no other features are preserved to permit their more accurate taxonomic determination. Hyolithids 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 some 60.36m above the level at which the material described herein was collected. Observations of the available specimen and Reed's (1910) illustrations suggest that his material was many times larger than that preserved described herein. As the material figured here does not differ in any observed characters, other than the size, from *Hyolithes* aff. *danianus*, these forms are conceivably 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 those Himalayan hyolithids published previously.

Himalayan Occurrence.—New material from Parahio Formation carbonates collected at 439.44m (PO15 *Kaotaia prachina* Zone), 776.00m (PO25) all (*Paramecephalus defossus* Zone), 880.93m (PV880 *O. salteri* Zone), and 1242.40m (PO09 unzoned 5) above the

base of the Parahio Valley section on the north side of the Parahio River, Spiti region, Parahio Formation, all of span the informal global Stage 5 of the Cambrian.

Family CUPITHECIDAE DUAN, 1984

Type Genus.—*Cupitthea* Duan in Xing et al., 1984.

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

Discussion.—*Cupitthea* 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 China, Australia, and Kazakhstan.

Genus *Cupitthea* DUAN in XING et al., 1984

Type Species.—*Cupitthea 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 degrees 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.

Discussion.—Himalayan specimens evidently members of this genus because they share many traits that fit the diagnosis, such as a straight edged conical tube with a constriction of tube diameter near the proximal end. The expansion angle of the tube walls in between 6-14 degrees depending on specimen, and the cross-section of the distal part of tube is oval.

Cupitthea sp.

FIGURE 12

Figured material.—All from the Parahio Formation of the Parahio Valley, Tethyan Himalaya, all internal molds. (WIMF/A/3987, WIMF/A/3988, WIMF/A/3989, WIMF/A/3990, WIMF/A/3991).

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

Discussion.—All eight species of *Cupitthea* are diagnosed by their exterior

ornamentation (Parkhaev and Demidenko, 2010). As the Himalayan material are all internal molds, no species level designation is possible. *Cupitthea* occurs in the lower Cambrian of China, Australia, and Kazakhstan (Zhou and Xiao, 1984; Bengtson *in* Bengtson et al., 1990; Mambetov *in* Missarzhevsky et Mambetov, 1981). This is the first occurrence of *Cupitthea* within the middle Cambrian and within the Himalaya.

Himalayan Occurrence.—From Parahio Formation carbonates collected at 775.41m (PO24) (*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.

INDETERMINATE

Spines indet.

FIGURE 13

Figured material.—From the Parahio Formation of the Parahio Valley, Tethyan Himalaya. (WIMF/A/3992, WIMF/A/3993, WIMF/A/3994, WIMF/A/3995, WIMF/A/3996, WIMF/A/3997, WIMF/A/3998, WIMF/A/3999)

Description.—Three morphotypes observed. All morphotypes display long, thin, spines tapering to sharp apical point, circular to elliptical in cross section and protruding orthogonally from a variably shaped base. In addition, all spines are bilaterally symmetrical about medial plane, and are rapidly tapering near the base and become less

tapered to straight as it approaches the apex, which is not preserved in imaged specimens. The differences within the three morphotypes is displayed in the base of the spines. The base is hemispherical in vertical view, and is concave in profile. Some specimens appear to have “pore” like holes preserved on their outer surface, with all pores having a similar size of approximately $10\mu\text{m}$, a similar circular shape, and appear to be equally distributed across the surface of the base at a distance of approximately $20\text{--}30\mu\text{m}$. The second morphotype has a base that is sub-circular to oval in shape when viewed from vertically with the spine protruding from the center of the base. The third morphotype has a thin elliptical base when viewed from vertically and is convex when viewed from horizontally.

Discussion.—The first morphotype is similar to an eodiscid immature pygidium, as illustrated in Zhang and Clarkson, (2012, pl. 18, fig. 6, 8, 10, 16, 18). However, the spine extends from the base horizontally, not orthogonally. The second morphotype has a similar morphology to *Archaeopetatus exavatus* (Bengtson et al., 1990 Fig. 106 A-E), but the 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. 13.6-13.10) as an indeterminate trilobite spine that was presumably axial.

Himalayan occurrence.—New material from Parahio Formation carbonates collected at 775.41m (PO24) and 776m (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.

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FIGURES

FIGURE 1—Location of the Spiti and Zaskar valleys within the Tethyan Himalaya, the most northern of the four lithotectonic zones of the Himalaya.

FIGURE 2—Table showing regional correlation by displaying the relationship of location, collection, height (m) in section, Hayden (1904) level and trilobite zonation of the microfossil fossil bearing material of the Parahio Formation, which allows for global correlation. The bottom of the table indicates the stratigraphically lowest, and therefore oldest collection (PO3, 78.07m, Parahio Valley), and the top of the table is the

stratigraphically highest, and therefore youngest collection (PI13, 74.11m, Zanskar Valley) within this study of the Parahio Formation.

FIGURE 3—Correlation between the Cambrian biostratigraphy of Zanskar and Spiti with that of other regions.

FIGURE 4—Composite stratigraphic section of the Cambrian rocks of the Parahio Formation in the Parahio Valley based on sections shown discussed herein with microfossil occurrence, local ranges shown, and biozonation. Sedimentological and other details of the section are provided in Myrow et al. (2006a, b). The chart includes all taxa systematically described from this section, 4 and 5 refer to the informal stages of the Cambrian System. The boundary between them is represented at the first occurrence of *O. indicus*, sh indicates shale, st indicates silt, vfs and fs indicates very fine sandstone and fine sandstone respectively, and carb indicates carbonate.

FIGURE 5— Composite stratigraphic section of the Cambrian rocks of the Parahio, Karsha and Kurgiakh Formations in the Zanskar Valley, with microfossil occurrence, local ranges shown, and biozonation. Sedimentological and other details of the section are provided in Myrow et al. (2006b). Measured sections containing material described herein are indicated. PU is Purni, KU is opposite Kuru. 5 refers to the informal fifth stage of the Cambrian System. sh indicates shale, ss indicates sandstone, and carb indicates carbonate.

FIGURE 6—Sponge spicules from the Parahio Formation, Parahio Valley. All specimens coated with platinum/palladium before SEM imaging, scale bar is 200 μ m unless otherwise indicated. 1, 3-6 from 775.41m (PO24) above base of the section. 2, from 880.93m (PV880) above base of the section. 1, Tetract I, WIMF/A/3951; 2, Tetract I WIMF/A/3952; 3, Tetract II WIMF/A/3953; 4, Pentact WIMF/A/3954; 5, Pentact WIMF/A/3555; 6, Pentact WIMF/A/3954.

FIGURE 7.1-3 Reconstruction of *Archiasterella* n. sp. sclerites displaying morphological terms used in this paper. 7.1 profile view, 7.2 top view, 7.3 basal view.

FIGURE 4—*Archiasterella* n. sp. from the Parahio Formation. All specimens coated with platinum/palladium prior to SEM imaging. 1-7, 9-12 collected 74.11m above base of PU3 section (PI13), from Zanskar Valley, Parahio Formation. 1, Holotype, WIMF/A/3956, large specimen, oblique view, 500 μ m scale; 2, Holotype, WIMF/A/3956, PI13, oblique view, 500 μ m scale; 3, Holotype, WIMF/A/3956, vertical view, 500 μ m scale; 4, Paratype WIMF/A/3957, showing articulatory facet between linear abapical ray and recurved adapical ray; 5, Paratype WIMF/A/3958, near vertical view showing articulatory facet between linear abapical ray and recurved adapical ray and robust ascending horizontal rays and linear abapical ray in comparison to recurved adapical ray, 200 μ m scale; 6, WIMF/A/3959, basal view showing foramen and articulatory facet between linear abapical ray and recurved adapical ray, 200 μ m scale; 7, Paratype

WIMF/A/3960, vertical view, 500 μm scale; 8, Paratype WIMF/A/3961, from 880.93m above base of Parahio Valley section, Parahio Formation, vertical view of an infilled specimen showing articulatory facet between linear abapical ray and recurved adapical, 200 μm scale; 9, Paratype WIMF/A/37962, horizontal view showing linear abapical ray and ascending horizontal rays residing in a single plane, with recurved adapical ray protruding from this plane, 500 μm scale; 10, Paratype WIMF/A/3962, horizontal view showing linear abapical ray and ascending horizontal rays reside in a single plane, with recurved adapical ray protruding from this plane, 500 μm scale; 11, Paratype WIMF/A/3963, basal view showing foramen with raised “rim” representing a “restricted foramen”, 200 μm scale; 12, Paratype WIMF/A/3964, vertical view showing angle variation between ascending horizontal rays and recurved adapical ray, 500 μm scale.

FIGURE 5—*Chancelloria* sp. Walcott 1920, all specimens coated with platinum/palladium before SEM imaging, scale bar is 200 μm . 1-4 from 775.41m (PO24) above base of Parahio Valley section, Parahio Formation. 5-8 from 880.93m (PV880) above base of Parahio Valley section, Parahio Formation. 1, WIMF/A/3965, 775.41m, 6+1 sclerite, view of adaxial surface; 2, WIMF/A/3966, 775.41m, 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.

Figure 7.—*Igorella* cf. *maidipingensis* (Yu. 1974). All specimens coated with platinum/palladium before SEM imaging, scale bar is 200 μ m unless otherwise indicated. 1, 3-5 from 776m (PO25) above base of Parahio Valley section, Parahio Formation; 2 from 880.93m (PV880) above base of Parahio Valley section, Parahio Formation; 6-10 from 775.41m (PO24) above base of Parahio Valley section, Parahio Formation. 1, WIMF/A/3972, 776m, right oblique view, showing elliptical aperture; 2, WIMF/A/3973, 880.93m, oblique view of conch displaying comarginal ribs crossing dorsum; 3, 4, WIMF/A/3974, 3, detail of sub triangular 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; 8-10, WIMF/A/3978, 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.

FIGURE 8—Phosphatized early meraspid ptychopariid, WIMF/A/3982, from 776m (PO25) above base of Parahio Valley section, Parahio Formation. Specimen coated with platinum/palladium before SEM imaging. Scale bar is 200 μ m.

FIGURE 6—Hyolithid indet. and *Cupitheca* sp. All specimens are internal molds. All specimens coated with platinum/palladium before SEM imaging. 1-5 from 776m (PO25) above base of Parahio Valley section, Parahio Formation; 6-10 from 775.41m (PO24) above base of Parahio Valley section, Parahio Formation. 1, WIMF/A/3983, close-up view of hyolithid indet. displaying smooth interior surface of 3, marked by the white box; 2, WIMF/A/3984, dorsal view of poorly preserved hyolithid indet.; 3, WIMF/A/3983, dorsal view displaying smooth internal surface; 4, WIMF/A/3985, ventral view of poorly preserved hyolithid indet.; 5 WIMF/A/3986 dorsal view of hyolithid indet.; 6, WIMF/A/3987, lateral view of *Cupitheca* sp., displaying that the hemispherical proximal part is distinct and has a smaller diameter than the tube; 7, WIMF/A/3988, lateral view of *Cupitheca* sp., showing that the hemispherical proximal part is distinct and has a smaller diameter than the distal tube; 8, WIMF/A/3989, apical view of *Cupitheca* sp. showing the “step” of that separates proximal and distal parts of the tube; 9, WIMF/A/3990, slightly oblique apical view of *Cupitheca* sp. showing the “step”; 10, WIMF/A/3991, oblique view of apex of *Cupitheca* sp. Scale bars: 1= 50 μ m; 2-4, 6-10 = 200 μ m; 5 =500 μ m.

FIGURE 9—Cap-like fossils of indeterminate affinity, All specimens coated with platinum/palladium before SEM imaging, scale bar is 200 μ m unless displayed otherwise. 1-10 from 776.XXm (PO25) above base of Parahio Valley section, Parahio Formation. 1, WIMF/A/3992, close-up of 2, showing possible surface ornamentation of equally distributed and sized pores?; 2, WIMF/A/3992, unknown cap-like shell; 3, WIMF/A/3993, Detailed view of 4 displaying possible well preserved outer surficial

detail; 4, WIMF/A/3993, unknown cap-like shell; 5, WIMF/A/3994, unknown cap-like shell; 6, WIMF/A/3995, Possible trilobite spine?; 7, WIMF/A/3996, Possible trilobite spine?; 8, WIMF/A/3997, Possible trilobite spine?; 9, WIMF/A/3998, Possible trilobite spine?; 10, WIMF/A/9991, Possible trilobite spine?

FIGURE 1

Location	Collection	Height in section (m)	Hayden (1904) Level	Trilobite zone
Zanskar Valley	PI13	74.11		<i>S. sinindica</i>
Parahio Valley	PO9	1242.4	Level 13	Unzoned 5
		1050.0		
	PV880	880.93		<i>O. salteri</i>
	PO31	836.36	Level 9	<i>P. defossus</i>
	PO25	776.0		Unzoned 3
	PO24	775.41		
	PO21	765.14		
		580.2	Level 4	<i>K. prachina</i>
	PO15	433.44		
		~200	Level 2	<i>H. parvatya</i>
	PO3	78.07		

FIGURE 2

Ma	Global Stages	SPITI & ZANSKAR This study	SOUTH CHINA Peng & Robison, 2000 Yuan et al., 2004	AUSTRALIA Opik, 1979 Shergold, 1996	KAZAKHSTAN Ergaliev, 1980	SIBERIA Egorova et al., 1980	LAURENTIA Robison, 1984; Palmär, 1999 Sundberg & McCollum, 2003	SWEDEN Ahlberg, 1998; Axheimer and Ahlberg, 2006	E. AVALONIA Illing, 1916 Rushton, 1978
500	GUZANGIAN	<i>Proagnostus</i> <i>bulbus</i> Zone	<i>Linguagnostus</i> <i>reconditus</i> <i>Proagnostus</i> <i>bulbus</i>	<i>Acmarhachis</i> <i>quasivspa</i> <i>Erediaspis</i> <i>eretes</i>	<i>Kormagnostus</i> <i>simplex</i>	<i>Peninacephalina</i> - <i>Toxotis</i> <i>Acrocephalella</i> <i>granulosa</i> - <i>Koldiniella</i> <i>prolixa</i>	<i>Kounamkites</i>	<i>Agnostus</i> <i>pisiformis</i>	<i>Agnostus</i> <i>pisiformis</i>
		<i>Lejopyge</i> <i>acantha</i> Zone	<i>Lejopyge</i> <i>laevigata</i>	<i>Damesella</i> <i>torosa</i> <i>Ferenepea</i> <i>janitrix</i> <i>Lejopyge</i> <i>laevigata</i>	<i>Lejopyge</i> <i>laevigata</i>	<i>Lejopyge</i> <i>laevigata</i> - <i>Oidalgagnostus</i> <i>trispinifer</i>	<i>Lejopyge</i> <i>laevigata</i>	<i>Lejopyge</i> <i>laevigata</i> (<i>Solenopleura</i> <i>brachymetopa</i>)	<i>Lejopyge</i> <i>laevigata</i>
505	DRUMIAN	<i>Sudanomocarina</i> <i>sinindica</i> Zone	<i>Goniagnostus</i> <i>nathorsti</i> <i>Ptychagnostus</i> <i>punctuosus</i> <i>Ptychagnostus</i> <i>atavus</i>	<i>Goniagnostus</i> <i>nathorsti</i> <i>Doryagnostus</i> <i>deltoides</i> <i>Ptychagnostus</i> <i>punctuosus</i> <i>Euragnostus</i> <i>opimus</i> <i>Ptychagnostus</i> <i>atavus</i>	<i>Lejopyge</i> <i>armata</i> <i>Goniagnostus</i> <i>nathorsti</i> <i>Ptychagnostus</i> <i>punctuosus</i> <i>Ptychagnostus</i> <i>atavus</i> [= <i>P. intermedius</i>]	<i>Anomocaricides</i> <i>limbataeformis</i> <i>Anopolenus</i> <i>henrici</i> <i>ocaricides</i> - <i>Corynexochus</i> <i>perforatus</i> <i>Tomagnostus</i> <i>fissus</i>	<i>Ptychagnostus</i> <i>punctuosus</i> <i>Ptychagnostus</i> <i>atavus</i>	<i>Paradoxides</i> <i>forchhammeri</i> <i>Paradoxides</i> <i>sinuatus</i> <i>Paradoxides</i> <i>praeacutus</i> <i>Paradoxides</i> <i>praeacutus</i>	<i>Paradoxides</i> <i>davidis</i> (<i>Hartshillia</i>) <i>Hydrocephalus</i> <i>hicksi</i>
	STAGE 5	<i>Iranoleesia</i> <i>butes</i> Lv. <i>Oryctocephalus</i> <i>salteri</i> Zone <i>Parmaccephalus</i> <i>defossus</i> Zone <i>Kaotia</i> <i>prachina</i> Zone <i>Oryctocephalus</i> <i>indicus</i> Level	<i>Ptychagnostus</i> <i>gibbus</i> <i>Oryctocephalus</i> <i>orientalis</i> <i>Oryctocephalus</i> <i>indicus</i>	<i>Ptychagnostus</i> <i>gibbus</i> <i>Ptychagnostus</i> <i>shergoldi</i> <i>Ptychagnostus</i> <i>praeacutus</i> <i>Ptychagnostus</i> <i>anabarensis</i> <i>Xystidura</i> <i>regina</i> /	<i>Ptychagnostus</i> <i>gibbus</i> [= <i>P. atavus</i>] <i>Peronopsis</i> <i>ullimus</i> No zonation	<i>Ptychagnostus</i> <i>gibbus</i> <i>Kounamkites</i> <i>Ovatoryctocara</i> <i>granulosa</i> - <i>Schistocephalus</i> <i>antiguus</i>	<i>Ptychagnostus</i> <i>gibbus</i> <i>Ptychagnostus</i> <i>praeacutus</i> <i>Peronopsis</i> <i>bonnerensis</i> <i>Albertella</i> <i>Poliella</i> <i>denticulata</i> / <i>Oryctocephalus</i> <i>indicus</i>	<i>Paradoxides</i> <i>gibbus</i> <i>Ptychagnostus</i> <i>praeacutus</i> <i>Eccapadoxides</i> <i>insularis</i> Hawke Bay hiatus	<i>Paradoxides</i> <i>aurora</i> <i>Paradoxides</i> <i>harknessi</i> ?
510	STAGE 4	<i>Haydenaspis</i> <i>parvatya</i> Level	<i>Ovatoryctocara</i> <i>granulosa</i> - <i>Bathynotus</i> <i>holopygus</i>	<i>Redlichia</i> <i>forresti</i>			<i>Amecephalus</i> <i>arrojosensis</i>	<i>Proampyx</i> <i>linnarssoni</i>	

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7.1

FIGURE 7.2

FIGURE 7.3

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11

FIGURE 12

FIGURE 13