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THE PARAHIO FORMATION OF THE TETHYAN HIMALAYA: THE TYPE SECTION, THICKNESS, LITHOSTRATIGRAPHY AND BIOSTRATIGRAPHY OF THE BEST CHARACTERISED CAMBRIAN SUCCESSION IN THE INDIAN SUBCONTINENT

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ABSTRACT

The type section of the Parahio Formation in the Parahio Valley, Spiti, is the best litho- and biostratigraphically documented Cambrian section in the Indian subcontinent. Fundamental issues of the geology of the type section, including its location, thickness, definition as a lithostratigraphical unit, nomenclature, and the stratigraphic position of fossil collections within it, are clarified herein. Our direct estimate of the section thickness made by measurement with tape and Jacob's staff is confirmed by satellite imagery, and reconfirms that H. Hayden, who published the first major monograph on the section in 1904, significantly underestimated the thickness of the body-fossil bearing part of the formation. That estimate has been the root of several subsequent misconceptions about the unit that we also clarify. In particular, we stress that shelly fossils span most of the type section and are not confined only to the upper part, and that there are trace fossils and carbonate layers throughout it. The formation can be traced regionally, and its distribution is used to understand aspects of early Palaeozoic tectonism in the Himalaya. The formation stratotype remains the Parahio Valley section, but a new stratotype is proposed in the section opposite Kuru in the Zanskar Valley for the base of the formation that conformably overlies it, the Karsha Formation. A suitable basal boundary stratotype for the Parahio Formation has yet to be identified. The term Kunzam La Formation is rejected as a junior synonym without superior merit.

Keywords: Parahio Formation, Tethys Himalaya, Spiti, Cambrian succession, Biostratigraphy, Lithostratigraphy.

INTRODUCTION

Although a subject for research since the late 1870's, there has recently been enhanced interest in the Cambrian palaeontology and stratigraphy of the Indian subcontinent. Reasons for this include the evolutionary and environmental changes that took place in association with the transition into the Phanerozoic (see Hughes, 2016a), and also the importance of Cambrian geology for interpreting the more recent uplift and erosional history of the Himalaya (e.g. Myrow *et al.*, 2015). The Cambrian strata exposed in the Parahio Valley of Spiti (Fig. 1) provide the best-documented section of rocks belonging to the System anywhere within the Himalaya, and are the subject of on-going research. The stratigraphic first appearance of a species initially described from this section, *Oryctocephalus indicus* Reed, 1910, is considered to occur widely in rocks around the globe, and will define the base of Series 3 of the Cambrian System. Although the stratotype selected for this boundary will not be Himalayan, documentation of the stratigraphic context of *O. indicus* in the Parahio Formation's original type section in the Parahio Valley in Spiti is a priority for Cambrian studies in India (Singh *et al.*, 2016b).

Building on the work of many others conducted throughout the last 150 years (e.g. Stoliczka, 1865; Griesbach, 1891; Hayden, 1904; Reed 1910; Pascoe, 1959; Srikantia *et al.,* 1980, Srikantia, 1981: Fuchs, 1982; Kumar *et al*., 1984), in 1990 we began a series of investigations of the sedimentology, stratigraphy, and palaeontology of the Parahio Valley Cambrian section, among other sections in the Himalaya. The foundation of our work has been two fold. Firstly, we have provided a comprehensive taxonomic revision of all previously published Cambrian fossil material from the subcontinent available to us, and this has included the great majority of specimens previously figured (Hughes, 2016a,b; Jell and Hughes, 1997; Kruse and Hughes, 2016; Popov *et al.*, 2015). This work includes illustrations of many of these specimens photographically for the first time, clarification of their morphologies, taxonomic identifications in light of present knowledge, and application of this knowledge to help understand the regional stratigraphic history. India's first Cambrian soft-bodied organism, comparable to those from the famous Burgess Shale, has been identified from the Parahio Valley section (Hughes, 2016b). Secondly, we have conducted fieldwork in various parts of the Himalaya, including the Parahio Valley section, where we have measured the section in detail, described the sedimentology and fossil finds, and interpreted the significance of both for broader issues in geology. The result has been a series of publications on the Parahio Valley section (Gilbert *et al.*, 2016; Hughes, 2016b; Hughes *et al.*, 2013; Myrow *et al.*, 2006b), including two major monographic works illustrating trilobites and brachiopods respectively (Peng *et al.*, 2009; Popov *et al.*, 2015). An extensive summary of the Cambrian paleontology of the subcontinent has also been completed (Hughes, 2016a).

There are several matters concerning the geology of the type section of the Parahio Formation that merit further clarification. These include the precise location in which the section was measured and where collections were made, both in its initial description by Hayden and von Kraft, and also by us. Additional topics considered include the stratigraphic thickness of the section, its appropriate stratigraphic nomenclature, and some aspects of fossil occurrence and biostratigraphy. In recent years several authors have preferred to use an alternative name, the Kunzam La Formation (Srikantia *et al.*, 1980), and there has been repeated criticism of our use of the term Parahio Formation (see below). While this nomenclatural debate is of relatively modest significance in the development of regional Cambrian geology, lithostratigraphical terms imply genetic association among rocks sharing the same name and should be as precise and consistent as is possible, and they should also adhere to national and international stratigraphical guidelines (e.g. Balashundaram *et al*., 1971; Salvador, 1994; Murphy and Salvador, 1999, North American Stratigraphic Commission, 2004). Accordingly, this paper reviews the history and status of that nomenclature, including the history of study of the section and a consideration of its fundamental geological attributes.

REGIONAL GEOLOGICAL CONTEXT OF THE PARAHIO FORMATION

The Parahio Formation is in the lower part of the Tethyan Himalayan (TH) succession (Fig. 1), which consists of primarily sedimentary and metasedimentary rocks bounded to the north by the Yarlung–Tsangpo suture zone with the Lhasa block of Tibet, and to the south by the South Tibetan Fault System. In the Parahio Valley a tectonised lowermost unit of the Tethyan Himalaya, locally called the "Batal Formation", separates the Parahio Formation from the detachment fault by over 10 km in map distance (Hayden, 1904; Kumar *et al.,* 1984; Wiesmayr and Grasemann, 2002) (Fig. 2). The status of the Batal Formation as a lithostratigraphical unit is questionable (see below). In Zanskar the South Tibetan Fault System lies close to the base of the Parahio Formation (Myrow *et al.,* 2006a) but overall the fault system cuts down section to the west (Hayden, 1904; Draganits *et al.*, 2008; Myrow *et al.*, 2009). This has resulted in older, Neoproterozoic units, such as the phylitic Chamba Formation, the diamictic Manjir Formation and the overlying Phe Formation, being well preserved in the Udaipur area of the Chenab Valley (Draganits *et al.*, 2008; Srikantia and Bhargava, 1976), but not yet recognised in the Parahio Valley area. Regionally, we consider the Parahio Formation to be conformably underlain by the Phe Formation (Fig. 2). The Haimanta Group extends from the Chamba Formation at the base, through the Manjir and Phe formations, and is caped by three formations in which fossils are obvious. These successively are the Parahio, Karsha and Kurgiakh formations (Bhargava and Bassi, 1998, but also see below). Only the Parahio Formation is easily recognisable in the Pin and Parahio valleys, where it is characterized by its

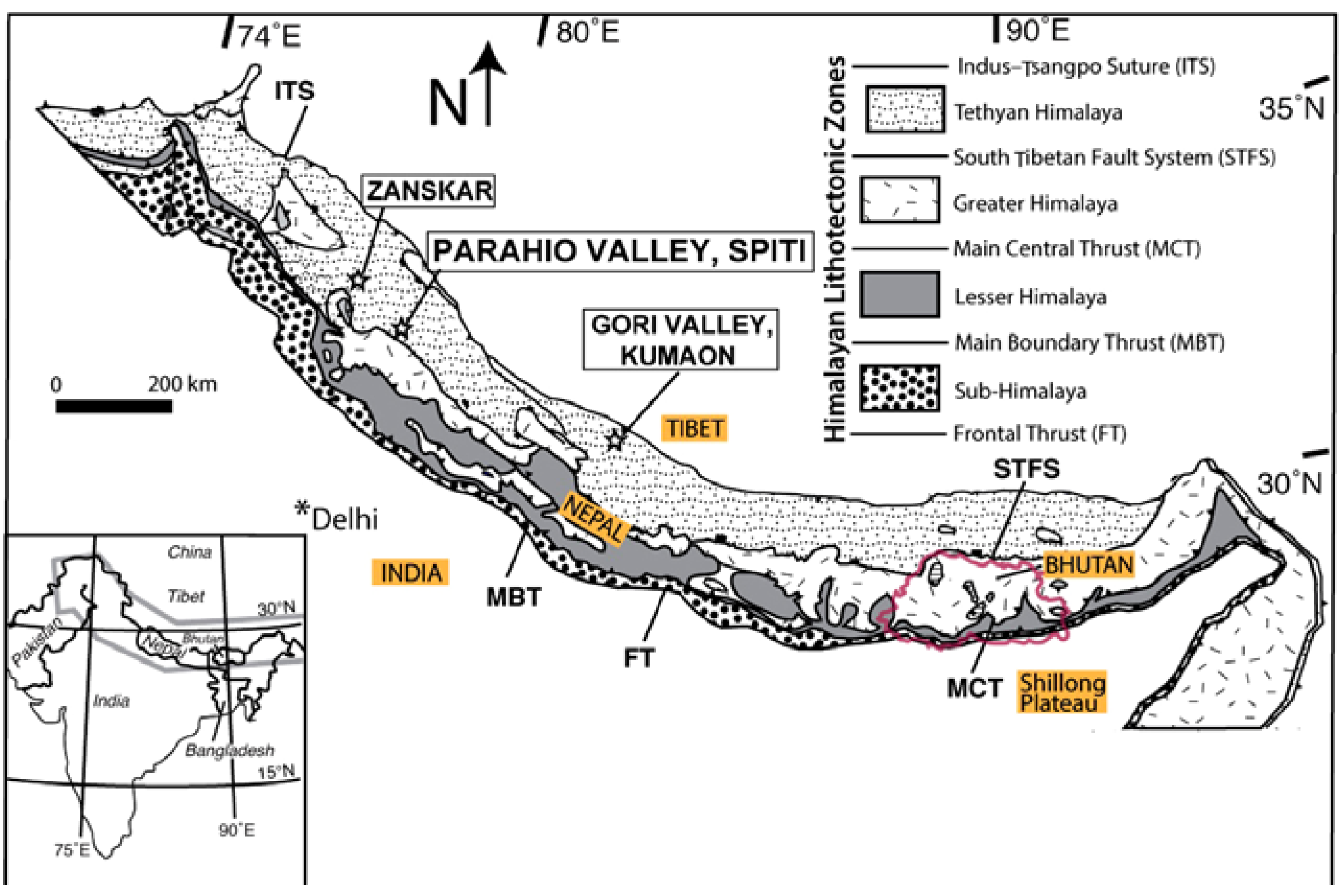


Fig. 1. Simplified lithotectonic map of the Himalaya showing location of Parahio Valley section, with the locations of the Zanskar and Gori valleys shown also. Gray line in inset map shows boundaries of the Himalayan map.

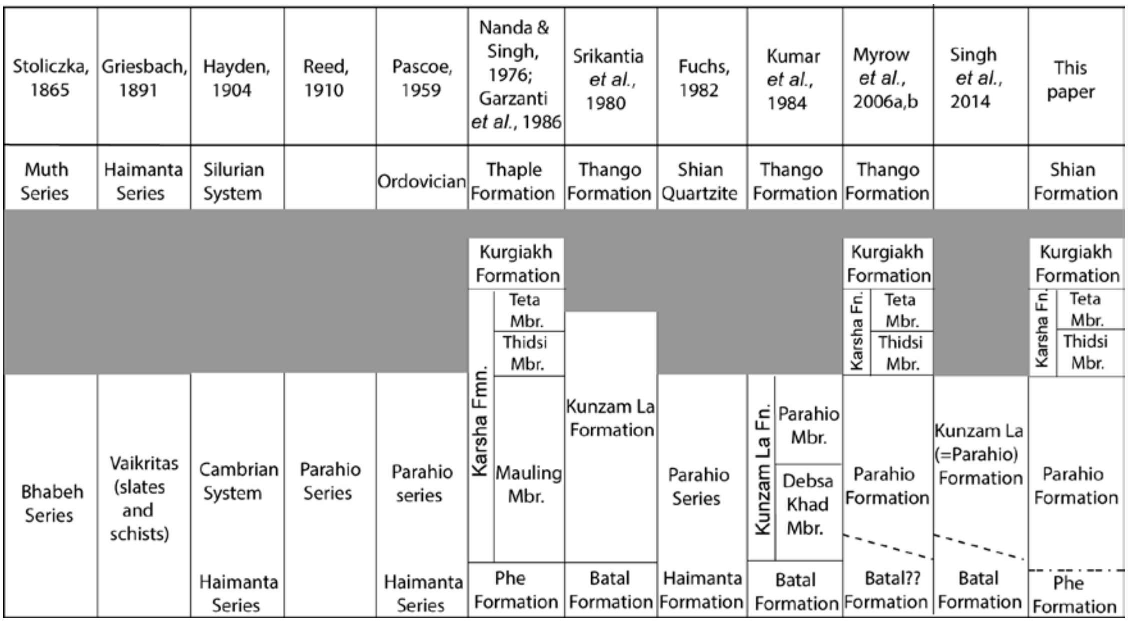


Fig. 2. Various lithostratigraphical schemes for the Cambrian and associated strata in the Spiti and Zanskar valleys of the Tethyan Himalaya. Note that the schemes of Nanda and Singh (1977), Srikantia *et al*. (1980), Myrow *et al*. (2006b), and this paper include Cambrian rocks (the Karsha and Kurgiakh formations) lying stratigraphically above those preserved in the Parahio Valley. This is due to increasing erosional down-cutting beneath the sub-Ordovician unconformity to the east (Hayden, 1904). Dashed horizontal lines indicate units that extend stratigraphically beyond the interval shown here. The dashed slanting line represents a fault contact. The pecked line indicates a boundary yet to be formally defined. For full explanation see text. *Bhargava and Bassi's (1998) scheme referred specifically to the Parahio Valley, where the Karsha and Kurgiakh formations are not preserved, but is essentially similar to that of Srikantia *et al*. (1980).

overall dark grey colour that contrasts sharply with the maroon/purple colour of the unconformably overlying Ordovician Shian Formation. In some areas, including the Parahio Valley itself, the uppermost parts of the Cambrian succession stratigraphically shortly beneath the purple Shian Formation contain striking orange-weathering dolomite beds and dark grey intercalated shale and sandstone. These diagnostic colors are distinctive and easily recognisable from remote imaging, including in Google Earth images (Fig. 3), and are characteristic of the upper part of the Parahio Formation in this region.

HISTORY OF INVESTIGATION

The Palaeozoic sections of the Parahio and Pin valleys are important in Himalayan geology because they were among the first parts of the high Himalaya to have been described geologically. Stoliczka's (1865) geological traverse entered the Pin Valley from the valley of the Sutlej via Bhabeh pass, along which he observed the Palaeozoic succession overlying the "Central Gneiss". These Palaeozoic rocks include those now assigned to the Parahio Formation, but Stoliczka included them in a larger group of sedimentary rocks that he named the "Bhabeh series" (Fig. 2). This broad unit included layers in its upper parts a micaceous siltstone with thicker sandstone and "occasional calcareous beds" that lay stratigraphically beneath a "purple quartzite or quartzose conglomerate" (*op. cit*. p. 18). We consider these uppermost beds to equate to the modern Parahio and Shian formations respectively. Stoliczka considered the contact at the base of the purple conglomerate to mark the top of the Bhabeh series, and that the Bhabeh series was "Silurian" in age, although he did suggest that the basal part might be "Azoic". Poorly preserved brachiopods were mentioned in these rocks but were not described. Stoliczka (1865) was writing before the resolution of modern lower Palaeozoic systems (see Peng *et al*., 2012). His "Azoic" is now known to correspond to the late Proterozoic, and the lowest portion of Stoliczka's "Silurian" succession, situated immediately above the "Azoic", is in the stratigraphic position occupied by the Cambrian. The lithological descriptions given above suggest that Stoliczka observed rocks now assigned to the Parahio Formation within the Pin Valley, and this is supported by recent mapping, but his route turned east at the confluence of the Pin and Parahio rivers and he did not observe the Parahio valley section in its upper reaches. It is nevertheless noteworthy that even this first description mentions the presence of minor carbonate beds within a dominantly siliciclastic succession. The span of the "Bhabeh series" is thus synonymous with what is today generally referred to as the Haimanta Group, discussed below.

Griesbach's (1891) understanding of the geology of the Tethyan Himalaya was founded on his fieldwork in the Kumaon and Garwhal Himalaya, and this was the lens through which he viewed the geology of the Pin Valley. The result was a critical appraisal of Stoliczka's (1865) account and the establishment of an alternative stratigraphic nomenclature for the lowest unit of the Tethyan Himalaya. Based on his own and other's work in Kumaon and Garwhal, Griesbach (1891, p. 50) proposed the term "Haimanta system" for the sedimentary rocks that span "all the thickness of strata lying between the crystallines … and the lower silurians". Slates and schists of the "Vaikritas" were grouped with the crystalline rocks. Unlike the term "Bhabeh series" the "Haimanta system" (now know as the Haimanta Group) has endured although with somewhat variable definitions according to user (see Bhargava and Bassi, 1998). Griesbach (1891, p. 51) stated that the base of the Haimanta system is

Fig. 3. Locations of measured sections (yellow lines) and principal fossil collections (field numbers in the PO series) in the Parahio Valley section based on Google Earth imaging. Green line extending the base of the section up to the unconformity with the Ordovician (red rocks) along the dip direction is used to calculate section thickness (see Fig. 7). Note that Myrow *et al*.'s (2006b) section through the Parahio Formation was a composite of several shorter sections (shown in yellow) that were correlated on the basis of shared distinctive marker beds. Shales bearing the PO26 collection name were collected at two, correlative localities, shown on the figure as PO26a and PO26b. The section 988-1066m ran oblique to dip, but true thickness was measured there. GPS coordinates for the collections marked were given in Peng *et al*. (2009, Appendix 1).

defined by a "quartzite, generally purple, with great thickness of conglomerate" that overlies different rocks in different regions within Garwhal and Kumaon. In the Kumaon this highly distinctive conglomerate is now known as the Ralam Formation. There it overlies deformed slaty rocks of known late early Cambrian age, bears arthropod trace fossils and detrital zircons as young as ~520 Ma (Kacker and Srivastava, 1996; Myrow *et al.*, 2016), and is clearly correlative with the Shian Formation in Spiti (Bhargava and Bassi, 1998; Kumar, 2005; Myrow *et al.*, 2016) which in that region unconformably overlies the Parahio Formation. In the Kumaon the deformed Cambrian rocks beneath show much stronger shear than the Ralam Formation itself, and it is apparent that Griesbach considered these slatey rocks to be part of the Vaikritas (Fig. 2). This issue highlights difficulties with the term Haimanta Group: if the Ralam Formation formed the base of Griesbach's "Haimanta system", according to this original definition all of the rocks it contains are younger than the Parahio Formation, whereas current usage applies the term Haimanta Group to sedimentary rocks in the Tethyan Himalaya that lie *below* the Ordovician unconformity (Bhargava and Bassi, 1998). Furthermore, Griesbach (1891) mapped the base of the Haimanta series as occurring in the village of Milam in the Gori Valley, where the Ralam Formation is not exposed, although large glacial erratics belonging to it are present there (Myrow *et al.*, 2016).

In our view the lower Palaeozoic geology of the Kumaon region remains considerably less well resolved than that of the Spiti region, and it may be a continuing challenge to apply terms that originated in the Kumaon to sections in the Pin/Parahio region. We are not proposing here that the term Haimanta Group should be abandoned or modified from Bhargava and Bassi's (1998) usage, and as a group name for the formations above the south Tibetan fault system and below the Ordovician rocks it is valuable (Fig. 2). Rather, we draw attention to the difficulties sometimes encountered when seeking to integrate modern understanding with that of the earliest workers, who sometimes lacked critical knowledge learned subsequently. Likewise, reconciling Griesbach's (1891) description of the geology of the upper reaches of the Pin Valley with current knowledge of the region is harder than with Stoliczka's (1865) description of the same region. For example, despite outcrop of the Shian Formation at Saybang village (the equivalent of the Ralam Formation of the Kumaon) (Singh *et al.,* 2017), Griesbach (1891) mapped the geological boundary exposed there to be that between what are today understood to be Silurian and Carboniferous rocks, rather the boundary between the Cambrian Parahio Formation and the Ordovician Shian Formation.

The Parahio Valley upstream of Mikkim was first mapped and described by Henry Hayden in 1904 as part of a geological survey of Phanerozoic geology focused on Spiti. Hayden and von Kraft located a series of fossiliferous horizons well exposed in a steep section on the north side of the Parahio River. These were recognised to contain a series of strata bearing different assemblages of Cambrian taxa, mostly trilobites and brachiopods. They also provided a measured section that specified the stratigraphic order in which the collections occurred, the lithologies in the section, and the thicknesses of various rock units, along with preliminary identifications of the fossils (Hayden, 1904). Formal identification of the taxa was by F. C. Cowper Reed who, in 1910, produced a monograph on the fauna. Both Hayden and Reed found that the succession of fossils in the various layers broadly matched the order found in other areas worldwide, even though the species Reed identified were unique to India. Hayden's main task was to geologically map this poorly known region, and his focus was not specifically on the Cambrian. While mapping he noticed several major faults and folds in the area (Fig. 4). When describing the "Haimanta system" he wrote "In the Parahio Valley … numerous folds can still be seen thus proving that the enormous thickness is only apparent .... an estimate of between two and three thousand feet will not err on the side of excess" (Hayden, 1904, p. 13). In this opinion Hayden's view mirrored that of Griesbach (1889, p. 160; 1891, p. 210) who wrote of "very close" and "plicate" folds in the area, but who estimated the total thickness of Cambrian strata to be about 1000 m.

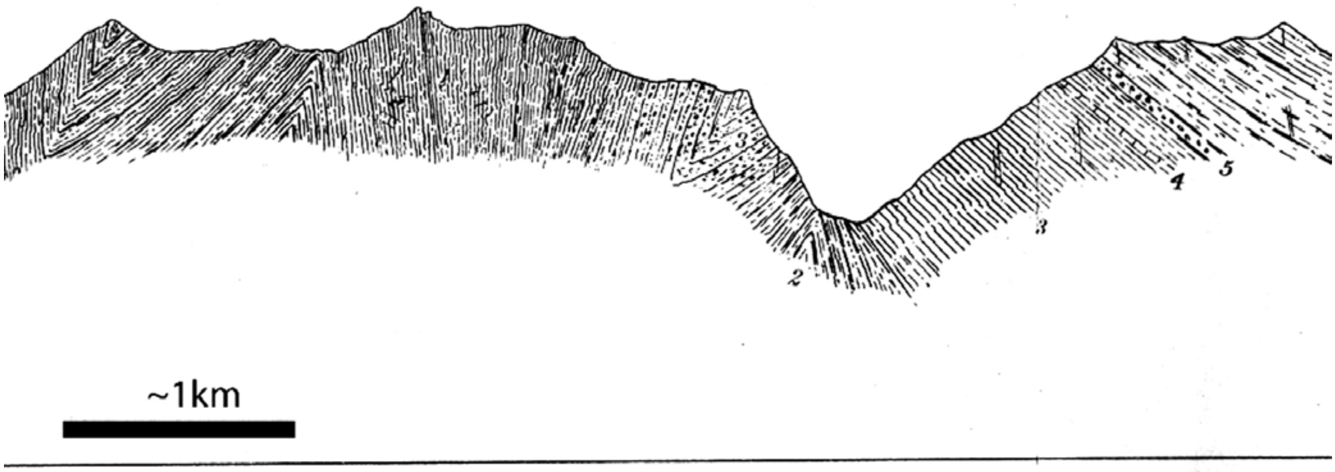
The folds described are visible from the Parahio River valley but not all of the Parahio Formation is significantly folded. Indeed, Hayden's (1904, pl. 1, fig. 2) sketch cross section for the Parahio Valley shows the part labeled the "Cambrian trilobite beds" and the overlying Shian Formation exposed on the steep southwest-facing slope above the Khemangar river to be barely folded (Fig. 4). This was confirmed with structural data and a simplified geologic map in Myrow *et al*. (2006b). Hayden (*op cit.* p. 14-15) gave a set of specific thickness measurements for the Cambrian section immediately beneath the unconformity, which sum to a total of 362 m. As we have shown before (Myrow et al. 2006b; Gilbert *et al.*, 2016; Hughes, 2016a), and explain in detail below, this value for the section thickness is demonstrably incorrect.

Reed (1910) introduced the term "Parahio Series" to describe the fossil-bearing succession, and Pascoe (1959) provided a comprehensive summary of the "Parahio series" that he defined specifically using lithological terms (see below) (Fig. 2). Renewed interest began towards the end of the last century with a series of stratigraphic (Bhargava and Bassi, 1998; Bhargava *et al.*, 1982; Fuchs, 1982; Kumar *et al.*, 1984; Srikantia, 1981; Srikantia and Bhargava, 1983) and palaeontological studies (Jell and Hughes, 1997; Parcha, 1996; 1998; Shah *et al.*, 1991; Shah and Paul, 1987; Shah and Raina, 1990; Shah *et al.*, 1988). These works used a variety of nomenclature for the rocks (Fig. 2). For example, Fuchs (1982, p. 330) used the term Parahio Series for the fossil-bearing part of the section in the Parahio Valley, but not for stratigraphically equivalent rocks in the Pin Valley, which he referred to the Haimanta Group. Alternative lithostratigraphic names were also proposed for the upper part of the Cambrian succession in the Tethyan Himalaya: including both the Mauling Member of the Karsha Formation, based on sections in the Zanskar Valley (Nanda and Singh, 1977), and the Kunzam La Formation, based on a type section located along the pass linking the Chandra and Spiti valleys (see discussion in Draganits, 2000).

S.V. Srikantia apparently first applied the name Kunzam La Formation in an unpublished Geological Survey of India report from 1974. As it was unpublished, it did not qualify as a formal unit name designation. In later works (e.g., Srikantia, 1981, p. 36) Dr. Srikantia attributed formal establishment of the name to a paper published in 1980 in *Himalayan Geology* in the volume for 1978. However, there was at least one case of the term being published prior to that: in 1977 it appeared in a table, but without any further description (Srikantia, 1977). Nevertheless, on pages 1015 and 1016 of Srikantia *et al*. (1980) the authors described an ~2900 meter thick trilobite- and brachiopod-bearing set of rocks with cyclic patterns of facies succession. The number and thickness of carbonate layers within these increased toward the top of the unit. In the Zanskar Valley near Kuru the top of the Kunzam La Formation was considered to be the base of the overlying Thango Formation conglomerate (the equivalent of the Shian Formation mentioned above). The map for this area (*op. cit.* fig. 1) indicates a prominent dolomite band, which others had earlier recognized to be the Thidsi Member of the Karsha Formation (Gaetani *et al.*, 1986; Nanda and Singh, 1977), a unit that succeeds the Parahio Formation, and does so, in our opinion, in a conformable manner (see correlation in Fig. 2). The name Kunzam La Formation has since been applied to the equivalent rocks in the Parahio Valley by a number of authors (e.g. Bhargava *et al.*, 1982; Bhargava and Srikantia, 1985; Jell and Hughes, 1997; Parcha, 1996; Srikantia, 1981) or some combination of the terms Parahio Formation and Kunzam La Formation has also been used (e.g., Singh *et al.*, 2014; Singh *et al.*, 2016b; Virmani *et al.*, 2015, Yin *et al.*, in press). We argue below that the Kunzam La Formation is effectively a junior synonym of the term Parahio Formation and has no superior merits.

Our research group worked on Hayden's section in August 2000, and six years later we published the first of a series of papers that discussed the sedimentology, stratigraphy and fauna of the Parahio Formation in its type section and elsewhere (Myrow *et al.*, 2006b). In that paper we applied the term Parahio Formation to these rocks, following a detailed review in a Ph.D. thesis by Erich Draganits (2000). We have continued to use the term Parahio Formation in a series of works that have described new sections and fauna, and that have also revised previously described fauna (Gilbert *et al.*, 2016; Hughes, 2016a,b; Hughes *et al.*, 2013; Kruse and Hughes, 2016; Myrow *et al.*, 2010; Myrow *et al.*, 2016; Myrow *et al.*, 2009; Myrow *et al.*, 2006a,b; Peng *et al.*, 2009; Popov *et al.*, 2015). Work by others on these rocks in the Parahio Valley within the present century includes papers on trace fossils (Parcha and Pandey, 2011; Parcha *et al.*, 2005; Virmani *et al.*, 2015), trilobites (Pandey and Parcha, 2013; Singh *et al.*, 2017; Singh *et al.*, 2014), acritarchs (Yin *et al.*, 2018) and small shelly fossils (Singh *et al.*, 2015).

The following sections discuss the scope of the Parahio Formation at its type section, including a review of nomenclatural issues pertaining to the name of the unit.



SECTION ALONG THE PARAHIO RIVER, SPITI.

Fig. 4. A part of Hayden's (1904, fig. 1.2) geological cross-section looking approximately northeast from a vantage near the origin of the Parahio Valley. The left hand side of the section represents the southwestern end of the transect looking approximately northwest along the valley wall of the lowest reaches of the Debsa Khad River, and the right hand side represents the northeastern part of the transect, showing the section above the northeastern side of the Khemangar River. As this is a sketch section, the scale bar given is approximate. The Khemangar River flows in the valley near the base of the unit marked "3", which represents Hayden's "Cambrian trilobite beds" and herein the "Parahio Formation". "4" represents a dolomite layer within the Parahio Formation, and "5" marks the based of the overlying Shian Formation. Note that in this section the Parahio Formation is not shown as significantly folded, and that dip is constant. "2" represents the tectonised beds generally now referred to as the "Batal Formation".

LOCATION AND THICKNESS OF THE TYPE SECTION

The type section of the Parahio Formation is the original section studied by Hayden and von Kraft that lies on the northern (left) bank of the Parahio River above its origin at the merger of the Debsa Khad and Khemangar rivers, upstream of Thango (Fig. 3). Although the Parahio Formation is exposed in the river bank of the Khemangar River near the confluence, a more continuous section whose base is at N 32˚ 02' 41.1", E 077˚ 54' 29.5" extends up the slope to the unconformity with the Ordovician exposed at N 32˚ 03' 5.2", E 077˚ 55' 18.0".

Trilobite Zone	Hayden thickness estimate, Parahio Valley.			Measured thickness Parahio Valley section	
	Hayden/Reed level	Height in section (m)	% height from base	Height in section (m)	% height from base
I. butes Level	Level 13	241	67%	1050	77%
Oryctocephalus salteri Zone	Level 9	205	57%	836.36	61%
Paramecephalus defossus Zone	Level 6	180	50%	765.14	56%
Kaotaia prachina Zone	Level 4	100	28%	580.20	43%
Oryctocephalus indicus Level	Level 2	76	21%	~286	
Total Section thickness (m)		362		1360	

Fig. 5. Comparison of the order of biostratigraphical succession, stratigraphic thickness estimates from Hayden (1904) and from Myrow *et al*. (2006a), Peng *et al*. (2009) and Popov *et al*. (2015) for the Parahio Valley section of the Tethyan Himalaya, and the relative heights in the section shown as percentages above the base of the section (see also Hughes 2016a; Gilbert et al. 2016). The chart indicates that although Hayden's estimate is about one quarter to one fifth of that measured by later workers, the order of succession is maintained and the relative heights of marker horizons within the measured sections are comparable.

Hayden and von Kraft's original field notes are not available in the archives of the Geological Survey of India, Kolkata (D. Mukherjee, pers. comm, 2016), but we are able to discern where they worked from the vantage points of plate 9 in Hayden's (1904) monograph, which was taken at an altitude of about 4500 m, close to the location of N 32˚ 02' 41.4", E 077˚ 55' 05.9" from which we collected the *O. salteri* Zone fauna (our collecting sites PO26b, PO30-PO32 = Hayden's level 9) (Fig. 3). As they progressed up section Hayden and von Kraft evidently recorded the strata sequentially and collected fossils where found.

PMM and student Karl Thompson used a tape and, at times, a Jacob's staff, to measure the entire section, which they determined to be 1352 m thick, a thickness that is approximately four times Hayden's (1904) estimate for the thickness of his trilobite-bearing interval of the Cambrian strata (Fig. 5). Myrow and Thompson measured the section by climbing uphill from the base of the section through uniformly dipping and weakly deformed strata, covering approximately 100–150 m of section thickness per day. They began measuring our section at the lowest point on the slope above which a continuous section could be measured up to the unconformity (Fig. 3). One interval (765–988 m) was measured along strike some distance to the east, and then the section was continued along the original ridge area. Near the top of this ridge, at a stratigraphic height of 1148 m, is the lowermost orange dolostone bed of the section (Fig. 3). Myrow and Thompson reached the second dolostone bed (1164.42 m) at elevations of over 4,500 m. Using the character and thickness of the dolostone beds, as well as the thicknesses of intervening strata, they then moved along strike to the final subsection on the south side of the Parahio River where they then measured the final 187.2 m of section that rests below the Cambrian–Ordovician unconformity (at 1351.62 m). The traces of the sections given in the map of Peng *et al*. (2009, fig. 2) specified the vicinities in which the two parts of the section were measured, not the exact positions where each collection was made. GPS information on that was provided in the appendix to that paper. We note that the GPS coordinates of one collection, PO10, were given incorrectly in that appendix, but that the stratigraphic position of the PO10 collection was shown correctly in all logs published by us to date. This collection was made on the ridge immediately below the PO9 collection and is estimated to be at about 1050 m above the base of the entire measured section.

NCH, sometimes accompanied by S.K. Parcha, made new collections of trilobites, brachiopods and small shelly fossils as the section was measured (Fig. 6). It has long been know that the thickness of the Parahio Formation varies on a regional scale along strike due to differential erosion of the top of the formation along the angular unconformity with the overlying Ordovician Shian Formation. Hayden (1904, p. 17) point out that in this region the Ordovician cuts down section to the south (and east), as was recently verified by Singh *et al*. (2017), with the result that several zones preserved to the north, along with the red dolomites, were cut out in southern/eastern exposures.

Our measured thickness of 1352 m for the complete section can be verified using satellite imaging and structural orientation. The apparent dip shown in Hayden's sketch is about 40˚ (Fig. 4), and this figure is consistent with our measurement at the same section, which recorded a dip and strike of 34˚NE/150˚ at the PO3 collecting horizon. Using 34˚ as the angle of dip of bedding, the estimated thickness of the Parahio Formation in the continuously exposed section can be calculated geometrically (Fig. 7). As measured using Google Earth imaging, when viewed from overhead, the linear map distance measured along the dip direction (i.e., towards 60˚) from the coordinates of the base of our measured section (N 32˚ 02' 41.1", E 077˚ 54' 29.5") to the unconformity with the Ordovician (N 32˚ 03' 5.2", E 077˚ 55' 18.0") is 1262 m (see Fig. 3). By using this figure and the elevation difference between the base and top of the section (862 m), both the average slope of the section above the horizontal, which is 34˚ (=tan 862/1262), and the straight-line distance along the slope of this section, which is 1528 m ($862^2 + 1262^2 = 1528^2$), can be calculated. Using these measurements, we then sum the angle between the average slope of the section above horizontal, and the dip angle (measured below the horizontal), to calculate the angle between the slope of the section and bedding. This angle (= 34˚ + 34˚ = 68˚) is that opposite to the side of the triangle representing the thickness of the strata perpendicular to bedding — i.e. the true thickness of the unit. We can thus estimate the true thickness of the section as the sine of 68˚ x 1528 m (hypotenuse) = 1417 m (opposite) (Fig. 7). Our measured section of the Parahio Formation is 1352 m (Myrow et al., 2006b). A discrepancy of 65 m is about 5% of the measured thickness, and may relate to the fact that the top of Myrow *et al*.'s (2006b) section was measured south of the Parahio River, whereas the map thickness estimate was calculated perpendicular to bedding on the north side with the top being the unconformity on the north side of the river. The unconformity on the southside of the river may be at a slightly lower stratigraphic position than on the north side due to variability in erosion along the angular unconformity. Such variability is evident along the south side exposures where low-angle cut-out of dolostone beds is recorded, and where a locally deep (>100 m) valley fill is preserved (Myrow *et al*., 2006b). Alternatively, the discrepancy may be the result of offset along minor faults, changes in dip/strike across the section, and/or measurement error. The estimate of 362 m for the whole trilobite-bearing section given by Hayden (1904) is inconsistent with either our measurements or the calculated geometric estimate. Nor can it be explained by the fact that Hayden might have started his section in a different place than we did, as the distances below the unconformity and the beds bearing particular trilobite and brachiopod taxa that we both observed are consistently about four or five times the distances given in Hayden's estimates (Fig. 5): the offset is thus systematic.

A recent paper on the Parahio Formation section, although not directly questioning the validity of our thickness estimate for the entire section, presented our figure alongside a series of other estimates for the thicknesses of parts of the Parahio Formation. These estimates include Hayden's original estimate and the thickness for two sections that Singh and colleagues measured (Singh *et al.*, 2016b). The two sections that Singh and colleagues presented in their figure did not extend up to the unconformity with the Ordovician, and the tops of these sections thus simply reflect where within the Parahio Formation the measurement of these particular sections ceased. Their tops are unconstrained by reported lithostratigraphical or biostratigraphical markers, and show only that the entire thickness of the Parahio Formation must be greater than their individual thicknesses. The bases of the two new sections mark the top of the scree slope where bedrock exposure begins.

Are there any alternative ways in which the discrepancy between our estimate and Hayden's might be explained? Tight isoclinal folding with fold axes parallel to bedding might be put forth as an explanation, but the measured Parahio section is both uniform in up-direction throughout and dip/strike is broadly consistent. No folding exists at this scale, and this can be verified in remote sensing images (Fig. 3). Hayden (1904, p. 13) mentioned regional-scale folding within the Parahio Formation his text, but with regard to this particular section from which fossils were collected, Hayden's (1904, pl.1, fig. 2) own sketch shows regularly dipping strata with only minor folding (Fig. 4). This was consistent with his assumption that the order of faunal succession observed was the original stratigraphic order, a view is also supported by subsequent authors (Gilbert *et al.*, 2016; Peng *et al.*, 2009; Popov *et al.*, 2015). The Parahio section faunal succession mimics that seen in undeformed sections in South China (Hughes, 2016a), consistent with a lack of repetition due to folding or faulting. It is thus clear that Hayden did not consider the thickness of the trilobite-bearing section to be exaggerated by significant folding. We can thus offer no explanation as to why Hayden made the underestimate he did but confirm that it was apparently systematic. The relative heights of the various collections common to Hayden (1904) and to later authors (Gilbert *et al.*, 2016; Peng *et al.*, 2009; Popov *et al.*, 2015) are comparable (Fig. 5).

Other geologist's estimates of the thickness of the Parahio Formation in the ridge section above the Khemangar River are also much greater than Hayden's (e.g. Bhargava and Bassi, 1998; Bhargava *et al.*, 1986; Fuchs, 1982; Kumar *et al.*, 1984; Srikantia, 1981). Kumar *et al*. (1984) attempted to reconcile this conflict by confining the interval bearing Hayden's collections to the 360 m beneath the top of the section, and calling that part the "Parahio Member" of the much thicker Kunzam La Formation. These authors referred the remaining section below to the "Debsa Khad Member" of the same formation, with a total thickness of the Kunzam La Formation given as about 2700 m. As the actual thickness of the Parahio Formation (see above)

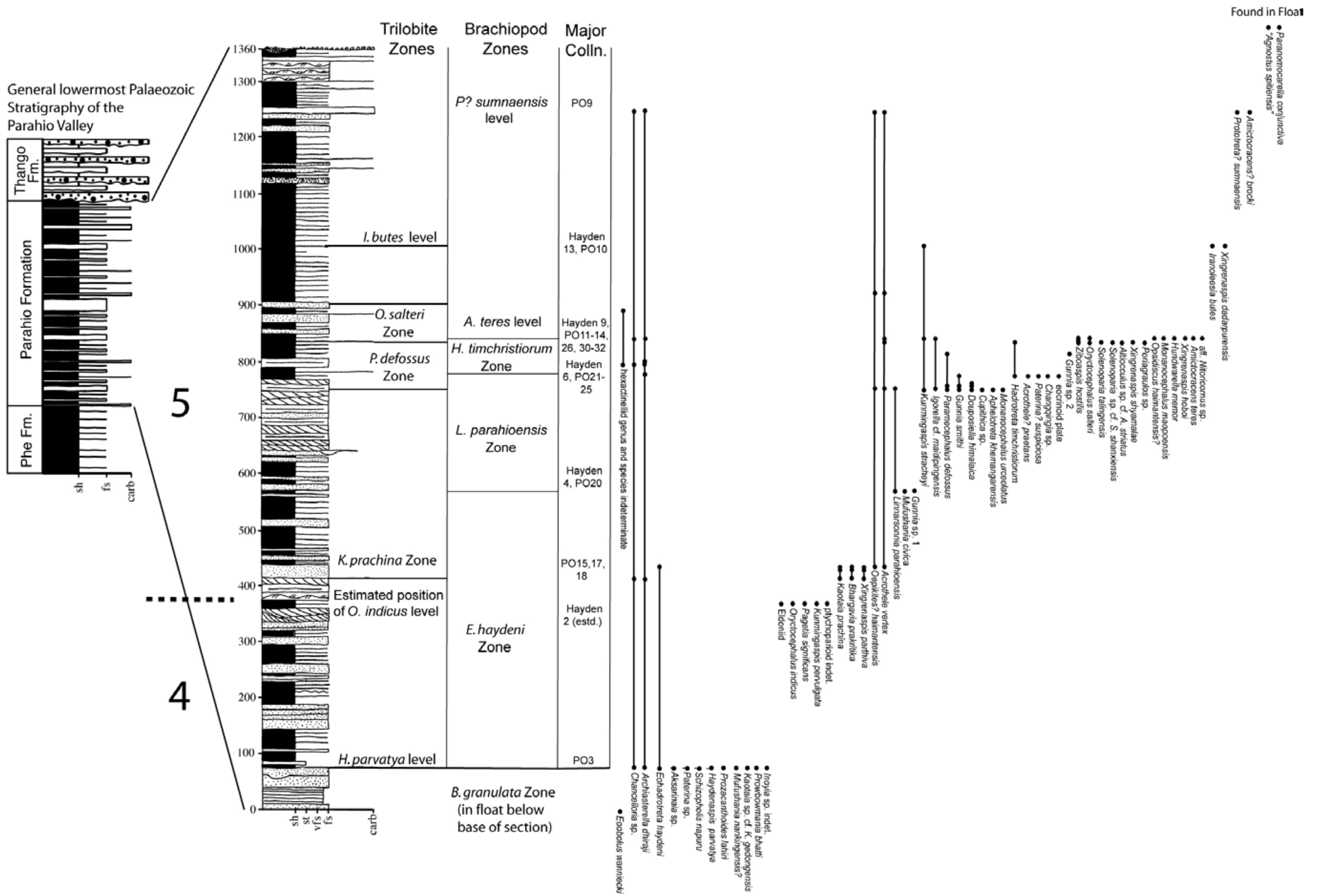


Fig. 6. Summary section of the Parahio Formation in the Parahio Valley type section along with the trilobite and brachiopod zonations, and the stratigraphic locations of the main fossil yielding horizons. For additional information on the section and sedimentology see Myrow *et al*. (2006b). sh: shale or mudstone, st: siltstone, vfs: very fine sandstone, fs: fine sandstone, carb: carbonate. Stratigraphic ranges for body fossils are illustrated. For detailed discussion of fossil occurrence see Hughes (2016a), and references therein. Inferred position of Hayden's level 2, that contains *Oryctocephalus indicus,* revised from that in Hughes (2016a) to a level about 400m in the section based on recovery of specimens by Singh *et al*. (2016).

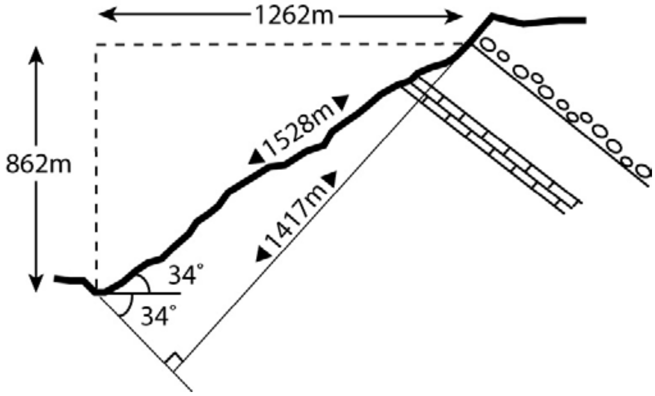


Fig. 7. Diagram illustrating the procedure used for estimating the thickness of the Parahio Formation along the dip direction at the type section based on satellite imagery and trigonometry. This profile is taken from Hayden's (1904) cross-section (Fig. 4) but the height of the base of our section is as described in the text. See text for explanation of the procedure.

at the section exceeds 360 m, the reasoning behind proposing the new members is no longer valid and these member names can be abandoned. In contrast, Parcha (1996, fig. 2; 1998, fig. 3) and Parcha (1998, fig. 3) produced a stratigraphic log for the section indicating successive collection horizons that suggest that the entire formation extending from the unconformity down to the lowest trace fossil is about 400 m thick and reportedly also contains *Redlichia* in situ, although no specimen of this species collected from this locality is available (S.K. Parcha, pers. com., 2000). This estimate, which was made without detailed measurement of the entire formation, is similar to Hayden's own, and is equally unreliable.

DEFINITION OF THE PARAHIO FORMATION AND ITS EQUIVALENTS

The value of consistent rules in applying stratigraphical nomenclature has long been recognised among geologists as an important aid to understanding and communicating geological history. Currently accepted principles for the naming of stratigraphical units were first articulated in the North American Stratigraphic Code of 1961 that was adopted as the basis for the first International Stratigraphic Code in 1976, and upon which the first Indian Stratigraphic Code (Balashundaram *et al.*, 1971) was based. All these works agree that formations are units of rock distinguished from other such units by their distinct lithological properties, and that can serve as mappable units. Both the nature of the rocks within the unit itself and the nature of its boundaries are important in its recognition. This section thus traces the nomenclatural history of these rocks and the bases for the application of lithostratigraphical names.

With regard to the Parahio Formation there is general agreement on the characteristic lithic properties of the stratigraphic unit to which these rock belong, regardless of its specific name. These lithic properties fall into two categories: the unit is fossiliferous, and the unit also shows marked facies cyclicity between mudstone, sandstone and carbonate layers.

Fossiliferous nature of the unit

The name Parahio Series was first proposed based on the fossiliferous nature of the trilobite-bearing beds (Reed, 1910, p. 62). Reed did not specify the occurrence of named taxa when establishing the name Parahio Series itself. Rather the unit, which we here refer to as the Parahio Formation, was defined as containing fossil-bearing beds, in contrast to the apparently unfossiliferous rocks stratigraphically beneath. This is consistent with the use of fossils as lithic characteristics, and accords with the rules of stratigraphic nomenclature established subsequently for defining lithostratigraphical units (also see below).

Later authors have agreed with Reed that the presence of fossils is a defining characteristic of the Parahio Formation. Pascoe (1959, p. 580-584) commented that no fossils have been found in the units lying conformably beneath what he referred to as the "Parahio series". He described body fossils as restricted to the upper part of the unit and mentioned that "fucoid markings", a term referring to trace fossils, are common in the lower part. Srikantia and colleagues' (1980, p. 1014-1016) description of the Kunzam La Formation also mentioned the presence of body fossils as a characteristic of its upper part, and stated that trace fossils extend down into the underlying formation (see below). The impression that body fossils were restricted to the upper part of the unit reflects Hayden's (1904) incorrect thickness estimate, discussed above. Our studies show that body fossils occur in a limestone layer about 78 m above the base of the continuous section in the Parahio Valley (Gilbert *et al.*, 2016; Peng *et al.*, 2009; Popov *et al.*, 2015) (Fig. 5). These body fossils are 1070 m below the first dolomite in this section. The trace fossils that occur in the section beneath it are highly unlikely to predate the evolution of skeletonized fauna (Hughes, 2016a; Hughes *et al.*, 2013).

Cyclical facies succession within the unit

The Parahio Formation contains conspicuous cycles of sedimentary rock that consist, from base to top, of (1) thin mudstone units, (2) upward-coarsening units of interbedded mustone and sandstone, (3) very thick sandstone units, and in some cases (4) thin to thick (6 cm to 12.8 m) carbonate layers (Pascoe, 1959; Srikantia *et al.*, 1980; Myrow *et al.,* 2006b). Authors also agree that beds stratigraphically immediately below the Parahio Formation, belonging to the Phe Formation, also contain alternating mudstone and sandstone intervals, but emphasize the marked facies cyclicity of the Parahio Formation itself, and the presence of distinctive red-weathering dolomite beds towards the top of the unit (Srikantia *et al.* 1980, p. 1015). Pascoe (1959) considered carbonate beds to be restricted to the Parahio Formation, but Srikantia and colleagues' (1980, p. 1014-1016) suggested that the underlying formation also contains scattered carbonate beds.

Unlike the dolomite beds, limestone beds within the Parahio Formation do not weather red/brown and thus do not stand out from the darker colours of the siliciclastic units. Srikantia *et al*. (1980) subdivided the unit based on the presence of the red/brown dolomites but the depth within the formation to which dolomitization penetrated varied locally between Zanskar and Spiti (Myrow *et al.*, 2006a,b; Peng *et al.*, 2009). In the Parahio Valley red dolomites do not extend beneath the *Iranoleesia butes* trilobite level, but in Zanskar the brachiopod *Hadrotreta timchristiorum* occurs in red dolomites. In the Parahio Valley this species occurs throughout much of the *Paramecephalus defossus* trilobite Zone and extends up into the basal part of the *Oryctocephalus salteri* trilobite Zone (Fig. 6) (Hughes, 2016a, fig. 14). Both these zones are below the *I. butes* trilobite level and thus dolomitization in Zanskar extends several hundred metres lower in the section than in the Parahio Valley. Hence the stratigraphically lowest red/brown dolomite does not provide a stratigraphically consistent marker horizon regionally. The comment (Srikantia *et al.*, 1980, p. 1015) that the trilobite *Oryctocephalus* is confined to the upper Kunzam La Formation reflects the incorrect view that Hayden's measured section spanned only the dolomite-bearing part of the section. Furthermore, it is clear than Reed's (1910), Pascoe's (1959), and Srikantia *et al.*'s (1980) concept of the formation extended well below the first red dolomite. Accordingly, the utility of this distinctive lithology for mapping is only apparent, and objections to using the base of the first red dolomite to mark the base of the unit are now even stronger. Nevertheless, all the carbonate beds that do appear form the junctions between sandstone and mudstone units, and this cyclic motif is a notable characteristic of the formation.

We agree with previous authors that both the presence of obvious fossils (including both body and trace fossils) and marked facies cyclicity including carbonate beds are general lithic properties of the Parahio Formation, and that at the present state of knowledge either can be employed as diagnostic lithic properties of it. The section in which the occurrence of fossils as lithic markers and the sedimentology has been best defined for these rocks is the original type section of the Parahio Formation: that in the Parahio Valley.

Recognising the base of the Parahio Formation

In addition to defining the general lithic properties of a lithostratigraphical unit, a basal stratotype should be designated. For the Parahio Formation this is problematical because whatever name is used for these rocks, in the Spiti and Zanskar regions of the Himalaya the base of the unit is a tectonic contact

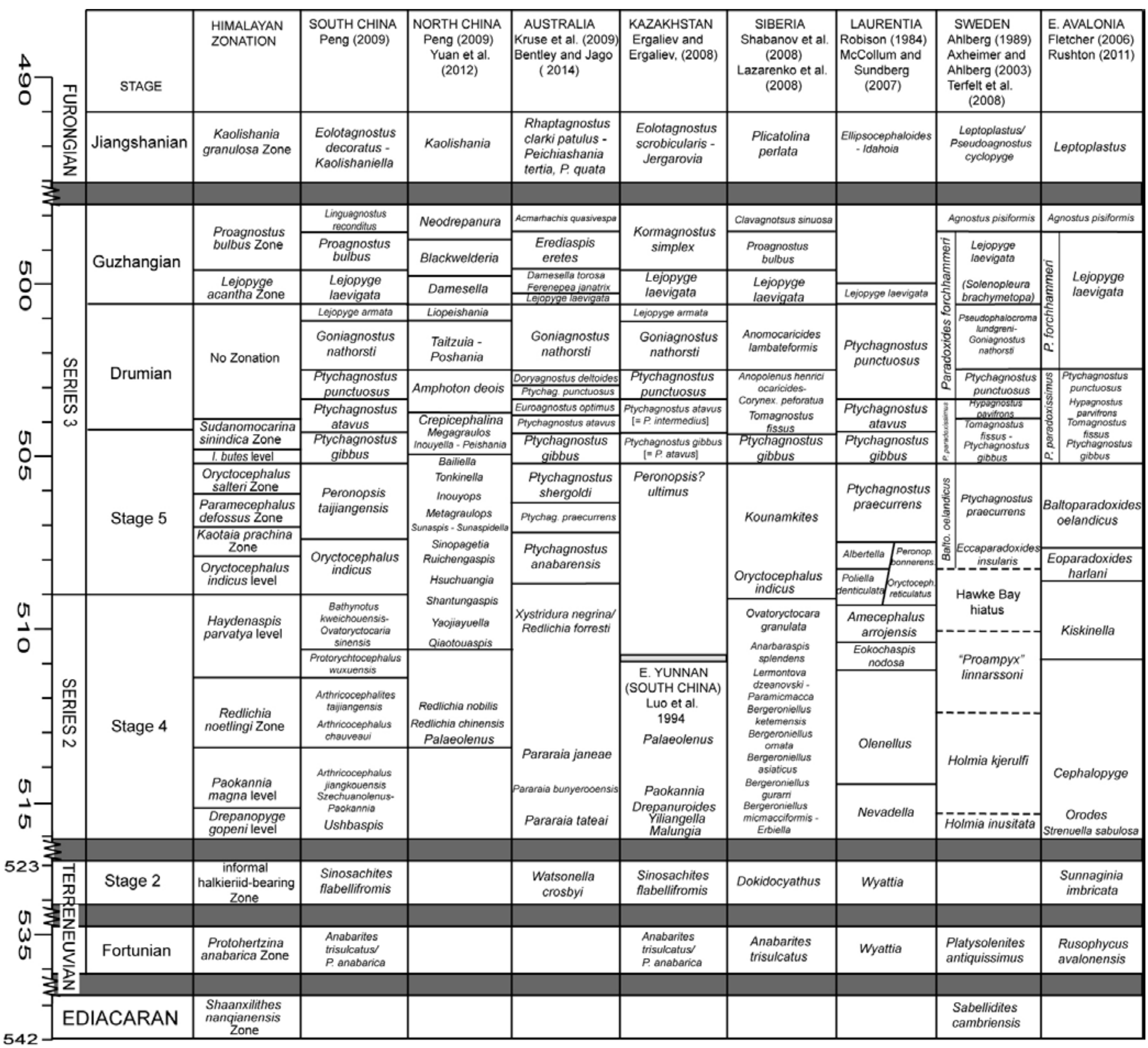


Fig. 8. Global correlation of the Cambrian biostratigraphy of the Indian subcontinent with that of other regions. For the North China stratigraphy generic names only are used mostly herein. At the base of the column for Kazakhstan the traditional succession for Eastern Yunnan (South China) is shown because this correlates most readily with the Indian succession (Hughes, 2016a, fig. 16).

or is strongly tectonised rather than being a straightforward stratigraphic one. In the Parahio section a fault running along the Khemangar valley truncates the base of the formation. Further to the west, the Phe Formation, the thick succession of alternating sandstone and mudstone that rests between the Manjir Formation and the Parahio Formation, is well preserved. Hence a suitable basal stratotype for the base of the Parahio Formation might be found to the west of the Zanskar Valley, perhaps in the Udaipur region (see Frank *et al.,* 1995, https://opac.geologie.ac.at/wwwopacx/wwwopac.ashx?command=getcontent&server=images&value=JB1382_299_A.pdf). An informed decision on whether to the use the first carbonate layer or the first layer bearing obvious fossils to define the base of the unit awaits recognition of such a section, but using carbonates might ultimately prove easier for mapping. Defining a basal stratotype at a section other than the type section of a lithostratigraphical unit is permitted by current stratigraphic codes and a basal boundary stratotype is not required for the definition and use of a formation name (Salvador, 1994; North American Stratigraphic Commission, 2004).

The top of the Parahio Formation

With regard to the type section of the Parahio Formation, Reed (1910) and Pascoe (1959) defined the top of the unit by the unconformity with the Ordovician conglomerate. This same conglomerate is present in Zanskar, but there it rests much higher in the section because the angular unconformity beneath the Ordovician cuts down-section regionally to the east (Hayden, 1904). Recent detailed characterisation of the Parahio Formation both lithostratigraphically and biostratigraphically has enabled its correlation within and between the Parahio Valley of Spiti and Zanskar, where the co-occurrence in both sections of the brachiopod *Hadrotreta timchristiorum* likely constrains the correlation to an interval of perhaps less than one million years (Hughes, 2016a). Use of the same name for rocks that are lithostratigraphically equivalent communicates this similarity. In Zanskar a carbonate-dominated unit called the Karsha Formation, the base of which is a 200 m thick dolomite (Nanda and Singh, 1977) called the Thidsi Member, conformably overlies the Parahio Formation (Gaetanti *et al.,* 1986; Garzanti *et al.*, 1986; Myrow *et al.*, 2006a,b) (Fig. 2). Here we propose the section opposite Kuru in Zanskar as the reference boundary section for the base of the Karsha Formation. The Karsha Formation is in turn overlain by above a siliciclastic unit called the Kurgiakh Formation (Gaetanti *et al.,* 1986; Garzanti *et al.*, 1986)(Fig. 2).

In the original description of the Kunzam La Formation, Srikantia and others (1980) considered rocks within the Karsha and Kurgiakh formations to be within the Kunzam La Formation. We consider this to be inappropriate for two reasons. Firstly, the 200 m thick dolomite at the base of the Karsha Formation is clearly differentiated lithostratigraphically from the lithic properties of the Parahio Formation and can be easily mapped. This accords well with characterizing the Parahio Formation by the cyclic alternation of mudstone–sandstone–carbonate beds, and the Karsha Formation as carbonate-dominated unit, as recognized by Nanda and Singh (1977). Secondly, Srikantia and others (1980) did not discuss the Karsha Formation, which had already been proposed in print when they proposed the Kunzam La Formation. Although the depositional age of sedimentary rocks does not bear directly on their lithostratigraphical nomenclature, as discussed above, the Karsha and Kurgiakh formations are demonstrably younger than the rocks herein referred to as the Parahio Formation.

The appropriate name for the Parahio Formation

Hayden (1904, p. 3) labeled the fossiliferous rocks immediately below the Ordovician unconformity as the "Cambrian System", because he felt that giving local names "merely leads to confusion". The first usage of the term "Parahio" with regard to a stratigraphic unit was thus that of Reed (1910, p. 62) in which he considered the "Parahio Series" to be a unit defined by the presence fossils, as discussed above.

Reed's initial introduction of the term "Parahio series" did not receive widespread attention, and the unit was not included in an authoritative review of Indian geological nomenclature (Holland, 1926). However, in 1959 Pascoe provided a clear and accurate definition of a lithostratigraphic unit for which he used Reed's (1910) name "Parahio series" (although Pascoe incorrectly attributed the name "Parahio series" to Hayden). Pascoe (1959, p. 580-584), publishing before the advent of international and national stratigraphic codes, defined the Parahio series using the two criteria discussed above: the presence of fossils and of cycles of thin mudstone units succeeded by thick sandstone units, along with relatively thin carbonate layers. Pascoe's (1959) description of the Parahio series extended over five printed pages, in which stratigraphic context and relationship of this series to other units above and below, its lithology, its fauna, and the age and affinities thereof where described in detail.

Modern stratigraphic standards require formations to be mappable, and published information on the unit's thickness, and its distinctive and differentiating features. In addition, authors must provide a measured section with photographs, and a geological map of the area including the type locality. The type section in the Parahio Valley was measured (though incorrectly) and photographed, and included in a geological map (Hayden, 1904). The Cambrian part of the Haimanta Group was clearly designated on Hayden's sketch section as the unit 3, the "Cambrian trilobite beds" (Fig. 4). While this interval was not distinguished on Hayden's map, we have shown above that its properties are distinguishable and thus mappable. Furthermore, successful mapping of the Kunzam La Formation by Srikantia and others (1980, fig. 1) confirms the mappability of its senior synonym, the Parahio Formation.

The Code of Stratigraphic Nomenclature of India (Balashundaram *et al.*, 1971) provided guidelines for evaluating whether earlier established stratigraphic units could be recognised as formal lithostratigraphic units. Relevant to this study, these include: that unit definition was lithostratigraphic and recognised by physical characteristics (Articles 4.00, 4.01); that a type section had been defined (Article 4.02); that the unit was not defined by fossils as temporal markers but that fossils may be used as lithological characters in formal unit definition (Article 4.03); that formal unit boundaries were to be defined by lithological change (Article 5.00) including the possibility of using "key beds" in its definition, as long as the lithological characteristics of such beds remained constant (Article 5.02); that to be formally recognised as a formation the unit must be practically mappable (Articles 7.00, 7.04); and that lithological features (including the presence of fossils as a lithological characters) distinguish it from other units in a practical way (Articles 7.01,7.03). The informal term "Parahio Series" as described by Pascoe (1959) fulfilled these criteria. Accordingly, it possessed the stated requirements for recognition as a formal lithostratigraphic unit that pertained at the time that the Code was published.

The Indian code (Balashundaram *et al.*, 1971) also stated (Article 10.06) that use of the term "series" for lithostratigraphic units should be discontinued because "series" is a chronostratigraphic term, that "the rule of priority should be observed in applying names to lithostratigraphic units" (Article 12.00) and that "the geographic component of an established lithostratigraphic name should not be changed as far as possible" (Article 13). These articles indicate that, provided that a pre-existing term fulfilled the formal criteria for lithostratigraphic unit definition outlined above, as was case with Pascoe's (1959) "Parahio series", not only was the term valid as a formal lithostostratigraphic unit when it was assigned an appropriate lithostratigraphic rank (i.e., Parahio Formation in this case), but that the term was to be preferred over alternatives.

Since 1971 there has been considerable revision of international stratigraphic codes in the light of over a half century of practical experience of their application. Examination of the current North American Stratigraphic Code (2004) (upon earlier versions of which the 1971 Indian code was statedly modeled [Balashundaram *et al.*, 1971 p. *iii*]) and International Stratigraphic Code (Salvador, 1994; Murphy and Salvador, 1999) reveals that no recent developments modify the recommendations of the Indian code with respect to the Parahio Formation. Recent codes are clear that precedence alone is not sufficient justification for the preference of an older name over a newer alternative, but also that abandonment of an existing name requires as much justification as establishment of a new unit. They also demonstrate a concern for nomenclatural stability.

Accordingly, a local lithostratigraphical name for these rocks, conforming to the standards of the Indian stratigraphic code of 1971, was established in the formal literature in 1959 and based on a name used previously for the same rocks. Pascoe's clear definition of the unit was published in the classic textbook on Indian geology 21 years before the first detailed discussion of the term Kunzam La Formation (Srikantia *et al.*, 1980) and thus has priority.

Criticism of use of the term Parahio Formation

Our usage of the term "Parahio Formation" has come under repeated criticism, which we here demonstrate to be unwarranted. We also show that the alternative term, Kunzam La Formation, failed to follow the stratigraphic guidelines pertaining at the time that term was first proposed.

As mentioned above, the Parahio Formation and its equivalent the Kunzam La Formation have been successfully mapped at the appropriate scale, and so Virmani *et al.*'s (2015, p. 558) criticism that the Parahio Formation has not been established by mapping is invalid. Virmani *et al.*'s (2015) and Yin *et al.*'s (2018) criticism that the Parahio Formation is markedly thinner than the Kunzam La Formation may be based partly on taking Hayden's thickness estimate literally, shown to be erroneous above, and also by supposing that Myrow *et al.* (2006b) considered the base of the section in the Parahio Valley to be the base of the Parahio Formation. However, Myrow *et al.* (2006b, fig. 5) showed the base of the Parahio Formation in the Parahio Valley to be faulted and, without specifying a basal stratotype, simply said that the incoming of trace fossils might serve to define the base of the Parahio Formation.

The criticism that the Parahio Series was initially established as a biostratigraphical unit (Yin *et al.*, 2018) has more merit in that Reed (1910, p. 62) listed three "stages" within the Parahio Series, and stages are today understood to be biostratigraphical units. However, Reed's three "stages" were based on the grouping of Hayden's (1904) numbered beds, and beds are now recognised as lithostratigraphical units. This argument thus becomes pedantic. The significant point is that Pascoe (1959) provided a clear description of the lithostratigraphical properties of Parahio Series long before the alternative name was proposed. Although Pascoe (1959, p. 580) was also writing before the advent of modern stratigraphical practice, his summary concept of the Parahio Series as "fossiliferous slates, quartzites and dolomites" was lithostratigraphical in modern terms, and consistent with the explicitly lithostratigraphical divisions of the Haimanta Group that he also proposed in the same work. Clearly, Pascoe's use of "fossiliferous" was referring to fossils as lithic objects.

Bhargava's (2008, p. 114) concern that employing "Parahio" in a lithostratigraphical name has fallen into disuse is countered by an extended series of publications (e.g. Fuchs, 1982; Gilbert *et al.*, 2016; Hughes, 2016b; Hughes *et al.*, 2005; Kruse and Hughes, 2016; Myrow *et al.*, 2009; Myrow *et al.*, 2006a,b), including two significant monographs that have featured its fossil content (e.g., Peng *et al.*, 2009; Popov *et al.*, 2015), and in a general summary of India's Cambrian palaeontological history (Hughes, 2016a). In terms of historical precedence, it is more than 100 years since the term "Parahio Series" was first proposed (Reed, 1910, p. 62), whereas the term "Kunzam La Formation" has been in the literature for only four decades (Srikantia, 1977, table 2). Pascoe's (1959) book was the standard, authoritative text at time that the term Kunzam La Formation was proposed, and it was well known to all stratigraphic geologists working in northern India. Chaudhuri (2001, p. 68), in his history of the Geological Survey of India, described it as "a landmark contribution in the annals of Indian geology" and the complement to the geological map of India. Bhargava (2008, p. 114) claimed that the term Parahio Formation should not be given priority over of the name Kunzam La Formation simply because it was defined first. This argument is valid but not relevant: the lithic properties of the Parahio Formation were clearly defined by Pascoe (1959) and thus the name Kunzam La Formation was unnecessary.

Bhargava (2008, p. 114) also suggested that if priority is a basis for preference of the term Parahio Formation over Kunzam La Formation, the "Bhabeh series" is the still older name and therefore should be used instead. This criticism is invalid because, as discussed above, Stoliczka's (1865) Bhabeh series included the extensive succession of sedimentary rocks spanning much of what is presently considered Neoproterozoic through Cambrian: its equivalent is the Haimanta Group as generally understood, not the Parahio Formation.

It has also been suggested that the Parahio Valley type section of the Parahio Formation lacks accessibility (B.P. Singh, pers. comm. 2012). The Parahio Valley section is more difficult to access than the Kunzam La section, which has road access up it. The Parahio Formation type section is steep and parts of the ridge section high above base camp at the Khemangar River require moderately strenuous mountain walking to access (Fig. 3). However, the same concern applies to almost any well-exposed, continuous section within the Himalaya. Hayden (1904), who traversed considerable ground in the region, made the choice to study Cambrian rocks in this particular place. We were also able to construct a continuously exposed record by following the ridge crest as we progressed upsection (Figs. 3,5). The ability to prepare a series of monographic, stratigraphic, and sedimentological publications, including descriptions of newly recovered fossil material, related to this section attests to the accessibility and collectability of the Parahio Valley section. The section also has the advantage that the uppermost beds, including those at the unconformity, can be more easily accessed on the south side of the Parahio Valley, on the slopes above the east bank of the Sumna River. Accessing the section is within the standard capacity for Himalayan geologists. In summary, none of the reasons listed above provide adequate grounds for rejecting the term Parahio Formation. What, then might be compelling reasons to prefer the newer term Kunzam La Formation?

It is not credible to argue that the Kunzam La section is superior as a stratotype because its road accessibility offers better opportunity for improved geological knowledge. Intermittent exposure along that section coupled with tectonic deformation is likely a major reason why its geology remains comparatively poorly known and why the only paper on fossils from that section of which we are aware is one on a non-age-diagnostic trace fossil (Sudan and Sharma, 2001). Knowledge of the much better exposed Parahio Valley section far exceeds that of the Kunzam La section: Singh et al. (2014, p. 82) wrote that the Parahio Valley section is "the best studied Cambrian section in the Himalaya". A much smaller fraction of the formation is exposed at Kunzam La Pass. While the age information derived from fossils has no relevance to the establishment of lithostratigraphical units, their presence in the Parahio Valley section confirms its significant superiority in terms of geological knowledge: body fossils are known from at least 10 successive horizons. The Parahio Formation has a name with historical precedence, and a superior stratotype section that is much better known geologically.

Batal bridge lies at the base of the Kunzam La section. Detrital zircon analysis shows that rocks collected at Batal bridge, the type section of the underlying Batal Formation, contain grains as young as 520 Ma (Myrow *et al.*, 2010, fig. 3). Hence these sheared rocks interpreted to lie stratigraphically beneath the Parahio Formation in that section (Srikantia *et al.*, 1980) may have been deposited after the lower parts of the Parahio Formation in the Parahio Valley section were laid down, as the uppermost lower Cambrian strata of the lowermost Parahio Formation there lack detrital zircon grains younger than 550 Ma (Myrow *et al.*, 2010). Such age-overlap between the uppermost Batal and lowermost Parahio formations explains the observation that both carbonate and trace fossils occur in both units at the Kunzam La section. This undermines the claim of Srikantia and others (1980) that both trace fossils and carbonate beds exist in the stratigraphic unit immediately underlying the Parahio Formation.

Finally, when a new formal name is proposed to substitute for an existing name, as was the case when the term "Kunzam La Formation" was first proposed, stratigraphic guidelines state that there should be sufficient justification to demonstrate a concern for nomenclatural stability (e.g., Salvador, 1994; North American Stratigraphic Commission, 2004). Although this practice was not formally stated in the Code of Stratigraphic Nomenclature of India (Balashundaram *et al.*, 1971), the provisions for stability detailed in Articles 12 and 13 of that code mean that Srikantia *et al*. (1980) would have been expected to have justified replacing an established term that was then standard (Pascoe, 1959). No such discussion and justification were presented when the Kunzam La Formation was introduced, nor in any other paper that we are aware of prior to 2006. Indeed, the "Parahio series" was not mentioned in Srikantia *et al.*'s (1980) paper. Rather, arguments seeking to justify preference for the term Kunzam La Formation (see above) only began to appear after the name Parahio Formation was applied in print by Myrow *et al.* (2006b). Hence the initial proposition of the term Kunzam La Formation failed to establish why the existing name should be abandoned, and thus to justify the need for the new term. None of the recent papers defending the term "Kunzam La Formation" have demonstrated either that Pascoe's "Parahio series" was inappropriately or too vaguely defined to qualify as a formal geological formation, or that the initial proposition of the term Kunzam La Formation justifiably established the case for replacement of the "Parahio series". Thus we see no merit in the arguments for using the term Kunzam La Formation, a name that from inception, in our opinion, was neither necessary nor justified according to published standards pertaining at the time or any stratigraphic codes, including India's code.

Critics have suggested that in using the name Parahio Formation we have "overlooked" (Singh *et al.*, 2014, p. 83) the term Kunzam La Formation, and have also implied that this has contributed to "a considerable degree of avoidable confusion" in Himalayan stratigraphy (Singh *et al.,* 2014, p. 82). The charge of overlooking Srikantia *et al.*'s term is untrue: we have used it in some publications (e.g. Hughes, 1997; Jell and Hughes, 1997), and from our first use of the term Parahio Formation we have explained explicitly why it is preferable to the term Kunzam La Formation (see Myrow *et al.,* 2006b, p. 496). With regard to "avoidable confusion", above we have shown in detail why preference for the term Parahio Formation has been and remains an informed and considered choice, and why it is the correct one according to Indian and international stratigraphical guidelines.

The Kurgiakh orogeny

Stratigraphical geology is a science in which reference to our forbears has particular significance, and we much respect the many important contributions of Drs. Srikantia and Bhargava, among many others. Thus, given the particular circumstances of this debate over the term Parahio Formation, we are pleased that the principal of priority has recently allowed us to champion the use of the term "Kurgiakh orogeny", a term also introduced by Dr. Srikantia and others (1980) in the same paper that formally introduced the Kunzam La Formation. The Kurgiakh orogeny is the substantial tectonic event that took place along the northern Indian margin during the early Middle Ordovician and was also first recognized by Hayden in 1904 through the unconformity at the base of Ordovician sequence. An alternative term, "Bhimphedian orogeny" was introduced by Cawood *et al*. (2007), and has been used quite frequently in international literature thereafter (e.g. Yao *et al.*, 2014). Our group has recently published a paper on this event that included arguments as to why the term "Kurgiakh orogeny" should be used henceforth (Myrow *et al.*, 2016).

BIOSTRATIGRAPHICAL CONTENTIONS

The combination of taxonomic revision of the specimens Hayden originally collected in the light of current knowledge of Cambrian palaeontology, and our collection of new material *in situ*, has enabled progress in the biostratigraphical zonation of the Parahio Formation in its type section and elsewhere (summarised in Hughes, 2016a). This work has resulted in the erection of a regional biostratigraphical scheme for the Cambrian of the Indian subcontinent that can be compared with that of the rest of the world with some confidence (Fig. 8).

Several recent publications have questioned some of the biostratigraphical conclusions from these papers and/or provided new data. We agree with Virmani *et al*. (2015) that the age of the trace fossil assemblage on the banks of the Khemangar River is unlikely to be much older than late Stage 4 of the Cambrian (Hughes *et al*., 2013), contrary to the claims of a significantly earlier Cambrian age (Parcha *et al*., 2005) or even that the interval contains the Precambrian–Cambrian boundary (Parcha and Pandey, 2011). Even accepting the trace fossil identifications that Parcha and colleagues proposed, of which we are dubious in some cases, we have consistently stressed that the identification of *Treptichnus pedum* alone suggests only that the rocks containing this ichnofossil are Cambrian or early Ordovician in age, as that is the range of occurrence of this ichnotaxon (Hughes, 2002; 2016a). Thus the chronostratigraphic conclusions presented in Parcha et al. (2005) and Parcha and Pandey (2011) must be rejected (Hughes, 2017). Although trace fossils and body fossils rarely occur together in the same beds, it is well established that trace fossils are abundant within heterolithic beds throughout the Cambrian of the Himalaya (e.g., Hughes, 2016a, fig. 14) and are not concentrated in the pre-trilobitic Cambrian, despite continuing assertions to the contrary (Parcha and Pandey, 2016, p. 16). In this, the Himalayan record is similar to other sections worldwide.

A recent paper describing new species of the eodiscid trilobite genus *Opsidicus* (Pandey and Parcha, 2013) is interesting in that the morphology of these specimens, particularly evident in the scrobiculate nature of the cephalic anterior margin, shows that they belong to the one other eodiscid genus known from the section, the species *Pagetia significans*. Material belonging to that well known species from the section was first described by Reed (1910) and was illustrated photographically by Jell and Hughes (1997, pl. 5, figs. 1-4, 7-11, 15), and also by Singh et al. (2016b, fig. 6). As trilobites grew by moulting, the size differences of the kind claimed by Pandey and Parcha (2013, fig. 5a,b) to represent two species in fact represent different ontogenetic stages of the same species, *P. significans*. The revised identification is consistent with the reported stratigraphic location of these specimens, which occur relatively low in the Parahio Formation in the Parahio Valley section.

The discovery of articulated specimens of *Bhargavia prakritika* has improved understanding of this form (Singh *et al.*, 2016a) but requires additional comment from both morphological and stratigraphical perspectives. Singh *et al*.'s (2016a) partially articulated and tectonically deformed exoskeletons show the relationship between the cranidium, free cheeks and the anterior portion of the thorax. A complete specimen described by Singh et al. (2014, fig. 5A,D) as *Yuehsienszella* cf. *Y. szechuanensis* shares all significant characters with the specimens illustrated as *B. prakritika* in Singh *et al*. (2017), and with the type suite of the species (Peng *et al.,* 2009), and we here synonymize it with *B. prakritika*. All Singh and colleagues' illustrated specimens of *B. prakritika* are composite moulds preserved in mudstone in which the features of the external and parial (internal) surface of the exoskeleton became superimposed during compaction. This, and tectonic deformation, has resulted in some morphological differences between these mudstone specimens and the type suite that was preserved as internal and external surfaces in calcite. In our opinion, biologically significant new morphological data on the species provided by Singh and others specimens includes the following: the markedly narrow (tr.) free cheeks, which include a narrow border with a genal spine that extended at least as far as the fifth thoracic segment; the presence of 14 thoracic segments in the holaspid; and the fulcrate thoracic segments with deeply incised pleural furrows.

The basis for our here assigning CAS BPS 1080 to *Bhargavia prakritika* (a specimen assigned by Singh *et al*. (2014) to *Yuehsienszella* cf. *Y. szechuanensis*) is the presence of two evolutionarily derived features (apomorphies) that the genus *Yuehsienszella* lacks (see Zhang *et al.* 1980, pl. 101) and are important in the definition of *Bhargavia*. These are the isolation of the SO furrow from the axial furrow, and the distinctive sweeping of the posterior border furrow into the posterior margin of the glabella: both are defining features of the more derived genus. The pygidium of CAS BPS 1080 has also fewer pleural furrows than *Y. szechuanensis,* but is similar to that of *B. prakritika.* Some structures do differ between CAS BPS 1080 and the type specimens of *Bhargavia prakritika*. Most notable is the difference in the marked incision of the axial furrow in CAS BPS 1080 that is effaced in the holotype of *B. prakritika*. These differences are related to CAS BPS 1080 being a composite mould (see Hughes, 1995). The proportions of the frontal area in CAS BPS 1080, which is mildly deformed, lie within the ontogenetically independent phenotypic variation seen within the *B. prakritika* type suite (see Peng *et al.,* 2009, fig. 27), and so we disagree with the opinion of Jell (quoted in Singh *et al.,* 2014) that its frontal area is significantly longer. Although we agree that *Yuehsienszella szechuanensis* and *Bhargavia prakritika* are likely closely related, the specimen clearly contains the apomorphic features that place it within *Bhargavia*. During discussions before the publication of Singh *et al*. (2014) Dr. Singh conducted a blind test of Hughes's identification of CAS BPS 1080, in which Peng and Dr. Xuejian Zhu gave him their independent opinions without knowledge of Hughes's views on the matter. This test confirmed identification of the specimen as *B. prakritika*. Although other expert opinion was quoted in support of identification as *Yuehsienszella* cf. *Y. szechuanensis* by Singh *et al*. (2014) when giving their views, none of the authorities listed had seen first hand either the type material of *Bhargavia* or CAS BPS 1080. While we respect these authorities, their arguments supporting identification as *Yuehsienszella* cf. *Y. szechuanensis* remain unconvincing for the reasons given above.

The stratigraphic conclusions of this revision remain to be fully resolved. The articulated specimens reported as *B. prachina* by Singh *et al*. (2016a) occur 18.87 meters above the base of the *Oryctocephalus indicus* Zone in the Parahio Valley section (Singh *et al*., 2016a,b), and this is consistent with the occurrence recorded in the Pin Valley (Singh *et al*., 2017), in which *B. prachina* occurs 12.7 m above the base of the *O. indicus* Zone. There the photograph given in Singh *et al*. (2017) confirms that there is a short stratigraphic interval of only a few tens of meters at most between the occurrences of *O. indicus* and *B. prakritika*. In 2009, we wrote that Hayden's level 2 in our section was inferred to be at about 200 m in our section. This was based on estimation of the difference between Hayden's thickness estimates and those of the measured section (Fig. 5). We are pleased that our estimate of occurrence of *indicus* below the *Kaotaia prachina* Zone has been confirmed, and note that the level of occurrence is likely higher in our section than we estimated, and closer to 400 m (Hughes, 2016a) (Fig. 6).

More problematical is the reported occurrence of the articulated specimen CAS BPS 1080, which was suggested to occur 237 m below the level of *O. indicus* (Singh *et al.*, 2014). As far as we can determine from that paper, CAS BPS 1080 was collected from the top of a relatively short section (their "B" section) that was correlated with the base of another section (their "C" section) beginning 237 m below the level of *O. indicus* (Singh *et al.,* 2014, figs. 2,3). If Singh *et al.*'s (2014) projection is correct it would imply that *B. prakritika* has a longer stratigraphical range than most of the other trilobite species in the section (see Fig. 5). However, given the strike of the section, from the geographical position of the top of section B in their map (Singh *et al.,* 2014, fig. 1a) CAS BPS 1080 appears to have been collected at a higher stratigraphical position than the *Haydenaspis parvatya* level (see Fig. 3). Without published GPS information of the sites of Singh and colleagues collections we see no immediate way to assess this further.

CONCLUSIONS

This paper seeks to clarify important aspects of the Parahio Formation and its definition. We have documented the location and thickness of the type section, shown why the term Parahio Formation is the correct name for this rock unit, both on the basis of the scientific information it conveys, and by adherence to procedural guidelines, and clarified aspects of the biostratigraphy.

Recent years have seen significant progress in understanding the sedimentological, palaeontological, stratigraphical and tectonic history of the Cambrian within the Indian subcontinent. Principal among this is the establishment of the first continuous section (Parahio Valley) for the Indian Cambrian in which fossils have been collected in situ at more than 10 successive horizons. The description, illustration and identification of these fossils, which was done according to international standards, led to establishment of a regional biostratigraphic scheme for the Cambrian of the Indian subcontinent that can be correlated with that used globally. This work also allows for the enhanced correlation across the Himalaya and onto the Indian craton, as well as the application of the improved knowledge of regional Cambrian geology to broader geological questions, such as the uplift and erosional history of the Himalaya and changes in global seawater composition (see Hughes, 2016a). We also note several important new discoveries, such as the recent localisation of the *indicus* level shortly below the *prachina* Zone (Singh *et al.*, 2016b), and constraint of the extent to which the Ordovician unconformity cuts downsection in the Pin Valley (Singh *et al.*, 2017), as these contribute substantively to further understanding of the lower Palaeozoic geological history of the margin.

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REFERENCES

Axheimer, N. and Ahlberg, P. 2003. A core drilling through Cambrian strata at Almbacken, Scania, South Sweden: trilobites and stratigraphical assessment. *Geologiska Föreningens i Stockholm Förhandlingar*, **125:** 139-156.

Balashundaram, M. S., Sastri, V. V., Dar, K. K., Radhakrishna, B. P., Chakraborty, S. L., Prakash, R., Pande, I. C., Sen, S. N., Mitra, R. C. and Sastry, M. V. A. 1971. Code of stratigraphic nomenclature of India. *Geological Survey of India Miscellaneous Publication*, **20:** 1-28.

Bentley, C. J. and Jago, J. B. 2014. A Cambrian Series 3 (Guzhangian) trilobite fauna with *Centropleura* from Christmas Hills, northwestern Tasmania. *Memoirs of the Association of Australasian Palaeontologists*, **45:** 267-296.

Bhargava, O. N. 2008. An updated introduction to the Spiti geology. *Journal of the Palaeontological Society of India*, **53:** 113-129.

Bhargava, O. N. and Bassi, U. K. 1998. Geology of Spiti-Kinnaur Himachal Himalaya. *Geological Survey of India Memoirs*, **124:** 1-210.

Bhargava, O. N., Bhandari, A. K. and Sharma, R. K. 1986. Lower Cambrian trace fossils from the Kilung Valley, Lahaul and Spiti District, Himachal Himalaya. *Bulletin of the Indian Geologists' Association*, **19:** 66-68.

Bhargava, O. N., Kumar, G. and Gupta, S. S. 1982. Cambrian trace fossils from the Spiti Valley, Himachal Himalaya. *Journal of the Geological Society of India*, **23:** 183-191.

Bhargava, O. N. and Srikantia, S. V. 1985. Trilobite and other trace fossils from the Kunzam La Formation, eastern Lahaul valley, Himachal Himalaya. *Journal of the Geological Society of India*, **26**: 880-886.

Cawood, P. A., Johnson, M. R. W. and Nemchin, A. A. 2007. Early Palaeozoic orogenesis along the Indian margin of Gondwana: Tectonic response to Gondwana assembly. *Earth and Planetary Science Letters*, **255:** 70-84.

Chaudhuri, N. P. 2001. Story of GSI 1851-2001. Geological Survey of India, Kolkata.

Draganits, E. 2000, The Muth Formation in the Pin Valley (Spiti, N. India): Depositional environment and ichnofauna of a Lower Devonian barrier island system, Ph.D. thesis, University of Vienna, Vienna.

Draganits, E., Schlaf, J., Grasemann, B. and Argles, T. 2008. Giant submarine landslide grooves in the Neoproterozoic/Lower Cambrian Phe Formation, northwest Himalaya: Mechanics of formation and palaeogeographic implciations. *Sedimentary Geology*, **205**: 126-141.

Ergaliev, G. K. and Ergaliev, F. G. 2008. Agnostidy srednego i verkhnego Kembriya Aksayskogo Gosudarstvennogo Geologicheskogo Zakaznika v yushnom Kazakhstane (Kyrshabakty, Malyy Karatau) [Middle and Upper Cambrian Agnostida from the Aksai National Geological Reserve in southern Kazakhstan (Kyrshabakty River, Malyi Karatau Range)], Part 1. Gylym, Alma Ata.

Fletcher, T. P. 2006. Bedrock geology of the Cape St. Mary's Peninsula, southwest Avalon Peninsula, Newfoundland. Report 06-02, Government of Newfoundland and Labrador, Geological Survey, Department of Natural Resources, St. John's.

Frank, W., Grasemann, B., Guntli, P. and Miller, C. 1995. Geological map of the Kishtwar, Chamba, and Kulu region, NW Himalaya, India. *Jahrbuch der Geologischen Bundesanstakt*, **138**: 299-308.

Fuchs, G. 1982. The Geology of the Pin Valley in Spiti, Himachal Pradesh, India. *Jahrbuch der Geologischen Bundesanstalt Wien*, **124**: 325-359.

Gaetani, M., Casnedi, R., Fois, E., Garzanti, E., Jadoul, F., Nicora, A. and Tintori, A. 1986. Stratigraphy of the Tethys Himalaya in Zanskar, Ladakh. *Rivista Italiana di Paleontologia e Stratigraphia*, **48**: 237-265.

Garzanti, E., Casnedi, R. and Jadoul, F. 1986. Sedimentary evidence of a Cambro-Ordovician orogenic event in the northwestern Himalaya. *Sedimentary Geology*, **48:** 237-265.

Gilbert, I. R., Hughes, N. C. and Myrow, P. M. 2016. Cambrian microfossils from the Tethyan Himalaya. *Journal of Paleontology*, **90**: 10-30.

Griesbach C. L. 1889. Geological notes. *Records of the Geological Survey of India*, **22**: 158-167.

Griesbach C. L. 1891. Geology of the Central Himalayas. *Memoirs of the Geological Survey of India*, **23**: 1-232.

Hayden, H. H. 1904. The Geology of Spiti with parts of Bashahr and Rupshu. *Memoirs of the Geological Survey of India*, **36**: 1-121.

Holland, T. C. 1926. Indian Geological Terminology. *Memoirs of the Geological Survey of India*, **51**: 1-184.

Hughes, N. C. 1995. Trilobite taphonomy and taxonomy: a problem and some implications. *Palaios*, **10**: 283-285.

Hughes, N. C. 1997. Cambrian trilobite biostratigraphy for the Himalaya. *Current Science*, **73**: 736-737.

Hughes, N. C. 2002. Late Middle Cambrian trace fossils from the *Lejopyge armata* horizon, Zanskar Valley, India and the use of Precambrian/Cambrian ichnostratigraphy in the Indian subcontinent. *Special Papers in Palaeontology*, **67**: 135-151.

Hughes, N. C. 2016a. The Cambrian palaeontological record of the Indian subcontinent. *Earth-Science Reviews*, **159**: 428-461.

Hughes, N. C. 2016b. Soft-bodied fossil preservation in the Cambrian Parahio Formation of Spiti. *Current Science*, **110**: 774-775.

Hughes, N. C. 2017. Biostratigraphical dating conundrums in the Cambrian and earlier stratigraphy of the Indian subcontinent. *The Palaeobotanist*, **66**: 1-15.

Hughes, N. C., Peng, S.-C., Bhargava, O. N., Ahulwalia, A. D., Walia, S., Myrow, P. M. and Parcha, S. K. 2005. The Cambrian biostratigraphy of the Tal Group, Lesser Himalaya, India, and early Tsanglangpuan (late early Cambrian) trilobites from the Nigali Dhar syncline. *Geological Magazine*, **142**: 57-80.

Hughes, N. C., Sell, B. K., English, L. T., Myrow, P. M. and Singh, B. P. 2013. Cambrian trace fossils from the Parahio Formation (Tethyan Himalaya) in its type section and elsewhere. *Journal of the Palaeonotological Society of India*, **58**: 175-193.

Jell, P. A. and Hughes, N. C. 1997. Himalayan Cambrian trilobites. *Special Papers in Palaeontology*, **58**: 1-113.

Kacker, A. K. and Srivastava, M. C. 1996. *Redlichia* from Milam Formation of Martoli Group, Kumaon Himalaya, India - systematics and significance. *Proceedings of Symposium on Recent Advances in Geological Studies of Northwest Himalaya and the Foredeep. Geological Survey of India Special Publication*, **21**: 291-293.

Kruse, P. D. and Hughes, N. C. 2016. Himalayan Cambrian hyoliths. *Papers in Palaeontology*, **2**: 323-341.

Kruse, P. D., Jago, J. B. and Laurie, J. R. 2009. Recent developments in Australian Cambrian biostratigraphy. *Journal of Stratigraphy*, **33**: 35–47.

Kumar, G. 2005. The Geology of Uttar Pradesh and Uttaranchal. Geological Society of India, Bangalore.

Kumar, G., Raina, B. K., Bhargava, O. N., Maithy, P. K. and Babu, R. 1984. The Precambrian-Cambrian boundary problem and its prospects, northwest Himalaya, India. *Geological Magazine*, **121:** 211-219.

Lazarenko, N. P., Gogin, J. Y., Pegel, T. V., Sukhov, S. S., Abaimova, G. P., Egorova, L. I., Federov, A. B., Raeskaya, E. G. and Ushatinskaya, G. T. 2008. Excursion 1b. Cambrian stratigraphy of the northeastern Siberian platform and potential stratotypes of lower boundaries of the proposed upper Cambrian Chekurovkian and Nelegerian stages in the Ogon'or Formation section at the Khos-Nelege River; the boundaries are defined by the FAD of *Agnostotes orientalis* and *Lotagnostus americanus,* p. 60-140. In: *The Cambrian of the Siberian Platform, part 2: north-east of the Siberian platform* (Eds. Rozonov A. Y. and Varlamov A. I.), PIN RAS, Moscow, Novosibirsk.

McCollum, L. B. and Sundberg, F. A. 2007. Cambrian trilobite biozonation of the Laurentian Delamaran Stage in the southern Great Basin, U.S.A.: Implications for global correlations and defining a Series 3 global boundary stratotype. *Memoirs of the Association of Australasian Palaeontologists*, **34**: 147-156.

Murphy, M. A. and Salvador, A. 1999. International Subcommission on Stratigraphic Classification of IUGS International Commission on Stratigraphy. International stratigraphic guide: An abridged version. *Episodes*, **22**: 255-271.

Myrow, P. M., Hughes, N. C., Derry, L. A., McKenzie, N. R., Jiang, G.-Q., Webb, A. A. G., Banerjee, D. M., Paulsen, T. S. and Singh, B. P. 2015. Neogene marine isotopic evolution and the erosion of Lesser Himalayan strata: implications for Cenozoic tectonic history. *Earth and Planetary Science Letters*, **417**: 142-150.

Myrow, P. M., Hughes, N. C., Goodge, J. W., Fanning, C. M., Peng, S.-C., Bhargava, O. N., Tangri, S. K., Parcha, S. K. and Pogue, K. R. 2010. Extraordinary transport and mixing of sediment across Himalayan central Gondwanaland during the Cambrian-Ordovician. *Geological Society of America Bulletin*, **122**: 1660-1670.

Myrow, P. M., Hughes, N. C., McKenzie, N. R., Pelgay, P., Thompson, T. J., Haddad, E. E. and Fanning, C. M. 2016. Cambrian-Ordovician orogenesis in Himalayan equatorial Gondwana. *Geological Society of America Bulletin*, **128**: 1679-1695.

Myrow, P. M., Hughes, N. C., Searle, M. P., Fanning, C. M., Peng, S.-C. and Parcha, S. K. 2009. Stratigraphic correlation of Cambrian-Ordovician deposits along the Himalaya: implications for the age and nature of rocks in the Mt. Everest region. *Geological Society of America Bulletin*, **120**: 323-332.

Myrow, P. M., Snell, K. E., Hughes, N. C., Paulsen, T. S., Heim, N. A. and Parcha, S. K. 2006a. Cambrian depositional history of the Zanskar Valley region of Indian Himalaya: Tectonic implications. *Journal of Sedimentary Research*, **76**: 364-381.

Myrow, P. M., Thompson, K. R., Hughes, N. C., Paulsen, T. S., Sell, B. K. and Parcha, S. K. 2006b. Cambrian stratigraphy and depositional history of the northern Indian Himalaya, Spiti Valley, north-central India. *Geological Society of America Bulletin*, **118**: 491-510.

Nanda, M. N. and Singh, M. P. 1977. Stratigraphy and sedimentation of the Zanskar area, Ladakh and adjoining parts of the Lahaul region of Himachal Pradesh. *Himalayan Geology*, **6** (for 1976): 365-388.

North American Stratigraphic Commission 2004. North American Stratigraphic Code. *American Association of Petroleum Geologists, Bulletin*, **89**: 1547-1591.

Pandey, S. and Parcha, S. K. 2013. Systematics, biometry of the species *Opsidiscus* from the middle Cambrian succession of the Spiti basin, India. *Journal of the Geological Society of India*, **82**: 330-338.

Parcha, S. K. 1996. Cambrian sequences in the Tethyan zone of Spiti Himalaya and its boundary problems. *Newsletters on Stratigraphy*, **34**: 3-11.

Parcha, S. K. 1998. Biostratigraphy of the Middle Cambrian sequences of Spiti Himalaya and its correlation with analogous sequences in Kashmir Himalaya. *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen*, **209**: 231-246.

Parcha, S. K. and Pandey, S. 2011. Ichnofossils and their significance in the Cambrian successions of the Parahio Valley in the Spiti Basin, Tethys Himalaya, India. *Journal of Asian Earth Sciences*, **42**: 1097-1116.

Parcha, S. K. and Pandey, S. 2016. Trace fossils and microbially induced sedimentary structures from the early Cambrian successions of the Chandratal area, Spiti basin, Tethys Himalaya. *Journal of the Palaeontological Society of India*, **61**: 9-18.

Parcha, S. K., Singh, B. P. and Singh, B. P. 2005. Palaeoecological significance of ichnofossils from the Early Cambrian succession of the Spiti Valley, Tethys Himalaya, India. *Current Science*, **88**: 158-162.

Pascoe, E. H. 1959. A Manual of the Geology of India and Burma. Volume 2. Third Edition. Geological Survey of India, Calcutta.

Peng, S. C. 2009. The newly-developed Cambrian biostratigraphic succession and chronostratigraphic scheme for South China. *Chinese Science Bulletin*, **54**: 4161-4170.

Peng, S. C., **Babcock L. E. and Cooper R. A.** 2012. The Cambrian Period, p. 437-488. In: *The Geologic Time Scale 2012* (Eds. Gradstein, F. M, Ogg, J. G, Schmitz, M. and Ogg, G.), Elsevier.

Peng, S. C., **Hughes, N. C., Heim, N. A., Sell, B. K., Zhu, X. -J., Myrow P. M. and Parcha S. K.** 2009. Cambrian trilobites from the Parahio and Zanskar Valleys, Indian Himalaya. *Paleontological Society Memoirs* (supplement to the Journal of Paleontology), **71**: 1-95.

Popov, L. E., Holmer, L. E., Hughes, N. C., Ghobadi Pour, M. and Myrow, P. M. 2015. Himalayan Cambrian Brachiopods. *Palaeontology*, **1**: 345-399.

Reed, F. R. C. 1910. The Cambrian fossils of Spiti. *Palaeontologia Indica*, Series 15, **7:** 1-70.

Robison, R. A. 1984. Cambrian Agnositida of North America and Greenland, part 1. Ptychagnostidae. *University of Kansas Paleontological Contributions*, **Paper 109**: 1-59.

Rushton, A. W. A. 2011. Chronostratigraphical subdivisions of the Cambrian Period, p. 3-5. In*: A revised correlation of the Cambrian rocks in the British Isles* (Eds. Rushton A. W. A., Brück P. M., Molyneux S. G., Williams, M. andWoodcock, N. H.), Geological Society Special Report No. 25, The Geological Society, London.

Salvador, A. 1994. International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology, and Procedure. International Union of Geological Scientists and Geological Society of America, Trondheim and Boulder.

Shabanov, Y. Y., Korovnikov, I. V., Pereladov, V. S. and Fefelov, A. F. 2008. Excursion 1a. The traditional lower-middle Cambrian boundary in the Kuonamka Formation of the Molodo river section (southeastern slope of the Olenek uplift of the Siberian platform) proposed as a candidate for GSSP of the lower boundary of the middle Cambrian and its basal (Molodian) stage, defined by *Ovatoryctocara granulata,* p. 9-59. In: *The Cambrian of the Siberian Platform, part 2: north-east of the Siberian platform* (Eds. Rozonov A. Y. and Varlamov A. I.), PIN RAS, Moscow, Novosibirsk.

Shah, S. K., Parcha, S. K. and Raina, A. K. 1991. Late Cambrian trilobites from Himalaya. *Journal of the Palaeontological Society of India*, **36**: 89-107.

Shah, S. K. and Paul, S. 1987. Oryctocephalid fauna from the Cambrian of Spiti. *Journal of the Geological Society of India*, **30**: 187-193.

Shah, S. K. and Raina, A. K. 1990. Middle-Late Cambrian transition in Kashmir and Spiti Himalaya. *Memoirs of the Geological Society of India*, **16**: 41-50.

Shah, S. K., Sudan, C. S., Parcha, S. K. and Raina, A. K. 1988. Revision of the genus *Hundwarella* Reed and its significance in Himalayan Cambrian. *Journal of the Palaeontological Society of India*, **33**: 47-58.

Singh, B. P., Bhargava, O. N., Juyal, K. P., Negi, R. S., Virmani, N., Sharma, C. A. and Gill, A. 2015. Skeletal microfauna from the Cambrian Series 2 (Stage 4) Kunzum La Formation, Parahio valley, Spiti region (Tethyan Himalaya), India. *Current Science*, **109**: 2191-2195.

Singh, B. P., Chaubey, R. S., Bhargava, O. N., Prasad, S. K. and Negi, R. S. 2017. The Cambrian trilobite fauna from the Shian (Saybang) section, Pin Valley (Spiti) and its biostratigraphic significance. *Palaeoworld*, **7**: 25-36.

Singh, B. P., Virmani, N., Bhargava, O. N., Kishore, N. and Gill, A. 2014. *Yuehsienszella* (Cambrian Series 2) trilobite from the Parahio Valley, Spiti region (Zanskar-Spiti sub-basin), India and its biostratigraphic significance. *Journal of the Palaeontological Society of India*, **59**: 81-88.

Singh, B. P., Virmani, N. Bhargava, O. N. Gill, A. and Kishore, N. 2016a. Revision of the diagnostic features of the trilobite genus *Bhargavia* (Ellipsocephaloidea) from the Parahio valley (Spiti), northwest Himalaya, India. *Journal of the Palaeontological Society of India,* **61**: 1-7.

Singh, B. P., Virmani, N., Bhargava, O. N., Negi, R. S., Kishore, N. and Gill, A. 2016b. Trilobite fauna of basal Cambrian Series 3 (Stage 5) from the Parahio Valley (Spiti), Northwest Himalaya, India and its biostratigraphic significance. *Annales de Paléontologie*, **102**: 59–67.

Srikantia, S. V. 1977. Sedimentary cycles in the Himalaya and their significance on the orogenic evolution of the mountain belt. *Colloques Internationaux du Centre National de la Recherche: Himalaya-Sciences de la Terre*, **268**: 395-407.

Srikantia, S. V. 1981. The lithostratigraphy, sedimentation and structure of Proterozoic-Phanerozoic formations of Spiti basin in the higher Himalaya of Himachal Pradesh, India, p. 31-48. In: *Contemporary Geoscientific Researches in India,* (*a commemorative volume in honour of S. P. Nautiyal*) (Eds. Sinha, A. K. and Nautiyal, S. P.) Vol. 1, Bishen Singh Mahendra Pal Singh, Dehra Dun.

Srikantia, S. V. and Bhargava, O. N. 1976. Tectonic evolution of the Himachal Himalaya: seminar volume on tectonics and metallogeny of south and east Asia. *Geological Survey of India Miscellaneous Publications*, **34**: 217-336.

Srikantia, S. V. and Bhargava, O. N. 1983. Geology of the Palaeozoic sequence of the Kashmir Tethys Himalayan basin in the Lidder Valley, Jammu and Kashmir. *Journal of the Geological Society of India*, **24**: 363-377.

Srikantia, S. V., Ganesan, T. M., Rao, P. N., Sinha, P. N. and Tirkey, B. 1980. Geology of Zanskar area, Ladakh Himalaya. *Himalayan Geology*, **8 (for 1978)**: 1009-1033.

Stoliczka, F. 1865. Summary of the geological observations during a visit to the provinces Rupshu, Karnag, south Ladakh, Suroo, and Dras of western Tibet. *Memoirs of the Geological Survey of India*, **5 (for 1866)**: 1-337.

Sudan, C. S. and Sharma, U. K. 2001. Trace fossil from the Cambrian rocks of Kunzum La section, Spiti, H.P., India. *Journal of the Palaeontological Society of India*, **46**: 161-171.

Terfelt, F., Eriksson, M. E., Ahlberg, P. and Babcock, L. E. 2008. Furongian Series (Cambrian) biostratigraphy of Scandinavia – a revision. *Norwegian Journal of Geology*, **88**: 73–87.

Virmani, N., Singh, B. P. and Gill, A. 2015. Integrated litho-ichnofacies and ichnofabric analysis of the lowermost part of the Kunzum La Formation along the Khemangar khad and the Parahio Valley sections, Spiti Region (Zanskar-Spiti-Kinnaur Basin), Northwest Himalaya, India. *Journal of the Geological Society of India*, **85**: 557-566.

Wiesmayr, G. and Grasemann, B. 2002. Eohimalayan fold and thrust belt: Implications for the geodynamic evolution of the NW-Himalaya, India. *Tectonics*, **21** (6) 6 TC001363 doi:10.1029/2002TC001363.

Yao, W. -H., Li, Z. -X., Li, X. -H. and Yang, J. -H. 2014. From Rodinia to Gondwanaland: A tale of detrital zircon provenance analyses from the southern Nanhua Basin, South China. *American Journal of Science*, **314**: 278-313.

Yin L.-M., Singh B. P., Bhargava O. N., Zhao Y.-L., Negi R. S., Meng F.-W. and Sharma C. A. 2018. Palynomorphs from the Cambrian Series 3, Parahio valley (Spiti), Northwest Himalaya. *Palaeoworld*, **27**: 30-41.

Yuan, J., Li, Y., Mu, X., Lin, J. and Zhu, X. 2012. Trilobite fauna of the Changhia Formation (Cambrian Series 3) from Shandong and adjacent area, North China. *Palaeontologia Sinica New Series B*, **197:** 1-758.

Zhang W.-T., Lu Y.-H, Chu C.-L., Qian Y.-Y., Lin H.-J., Zhou Z., Zhang S.-G. and Yuan J.-L. 1980. Cambrian trilobite faunas of southwestern China. *Palaeontologia Sinica New Series B*, **16**: 1-497.

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