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Some aspects of current State of Knowledge on Triassic series on both sides of the Central Atlantic Margin / *Quelques aspects de l'état des connaissances des séries triasiques de part et d'autre de la Marge Atlantique*

Miaolingian transgression and the *Oryctocephalus indicus* biozone in the Sumna Valley (Spiti), Himalaya, India

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Abstract. The *Oryctocephalus indicus* biozone (Wuliuan, Miaolingian) is recognised in the Sumna Valley, in the southeastern part of the Spiti region in the Himalaya, based on the first appearance datum and last appearance datum of *Oryctocephalus indicus*. The biozone is approximately 5.6 m thick (17.8–23.4 m), and it contains the trilobites *Oryctocephalus indicus*, *Pagetia significans* and *Kunmingaspis pervulgata*. Comparative studies of the lithological variations across the Cambrian Series 2–Wuliuan (Miaolingian) transition in the Parahio and Sumna valleys (southeastern part of the Spiti region) show that the Wuliuan (Miaolingian) deposits transgressed over the undulatory surface of Cambrian Series 2. The uppermost part of the Cambrian Series 2 deposits in the southeastern part of the Spiti region is characterised by a reddish-brown ferruginous, very coarse grained sandstone unit, which indicates a diastem prior to the Wuliuan (Miaolingian) transgression.

Keywords. *Oryctocephalus indicus* biozone, Sumna Valley, Spiti, Himalaya, Miaolingian transgression.

1. Introduction

Globally, the first appearance datum (FAD) of *Oryctocephalus indicus* is considered the base of the Wuliuan Stage, Miaolingian Series [Zhao et al., 2019]. In the Cambrian of the Spiti region (Himalaya), the *Oryctocephalus indicus* biozone is also considered the base of the Miaolingian Series (~509 Ma) [Singh et al., 016a, 017a]. This has been well documented from the Parahio and Pin valleys of the southeastern part of the Spiti region [Singh et al., 016a, 017a,b]. Although Cambrian rocks are widely distributed in the Himalaya, the Parahio Valley (Spiti region) constitutes the most studied section of the Cambrian deposits [Hayden, 1904, Reed, 1910, Jell and Hughes, 1997, Shah and Paul, 1987, Sahni and Sudan, 1996, Shah et al., 1988, 1991, Peng et al., 2009, Singh et al., 2014, 2015, 016a,b, 017a,b, Popov et al., 2015, Hughes, 016a,b, Gilbert et al., 2016, Yin et al., 2018, Kaur et al.,

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2019]. However, the Cambrian rocks also occur in the Sumna, Pin and Chandra valleys of the Spiti region [Bhargava and Bassi, 1998]. So far, Cambrian body fossils have not been reported from the Chandra Valley. In the Pin Valley, the *O. indicus* biozone was recently demarcated [Singh et al., 017b]. The trilobite fauna reported from the Sumna Valley section (at the confluence of Parahio and Sumna valleys) includes the youngest trilobite level, that is, the *Iranoleesia butes* level [Peng et al., 2009, Singla et al., ress].

The present work pertains to the Sumna Valley, where we demarcate the *Oryctocephalus indicus* biozone. In addition, a comparative account of the variation in lithologies across the Cambrian Series 2–Wuliuan (Miaolingian) transition in the Parahio and Sumna valleys (southeastern part of the Spiti) is presented to interpret the basin configuration during deposition.

2. Geological setting and lithostratigraphy

The Cambrian deposits in the Himalaya are well known to occur in the Tethyan and the Lesser Himalayan lithotectonic zones, which are separated by the metamorphosed Greater Himalayan Lithotectonic Zone (Figure 1a). The Tethyan Himalayan Zone is bounded in the north by the Indo-Tsangpo Suture Zone and in the south by the South Tibetan Detachment System [Burchfiel et al., 1992, Hodges et al., 1992, Searle and Treloar, 1993]. The Spiti region lies in the northernmost part of the state of Himachal Pradesh and constitutes a part of the Tethyan Himalayan Zone [Srikantia, 1981, Bhargava and Bassi, 1998, Srikantia and Bhargava, 2018]. The Cambrian deposits in the Spiti region are well exposed in several localities; for example, Chandra Valley (northwestern part of the Spiti region), Ratang Nala (central part of the Spiti region) and Parahio, Sumna and Pin valleys (southernmost part of the Spiti region).

Lithostratigraphically, the Cambrian deposits of the Spiti region are classified under the Haimanta Group [Srikantia, 1981, Bhargava and Bassi, 1998]. The anchi-metamorphosed sedimentary rocks of the Haimanta Group rest tectonically or nonconformably over the highly metamorphosed rocks of the Greater Himalayan Zone. However, various authors have referred to the tectonic contact as the South Tibetan Fault System [Burchfiel et al., 1992, Hodges et al., 1992, Searle and Treloar, 1993, Myrow

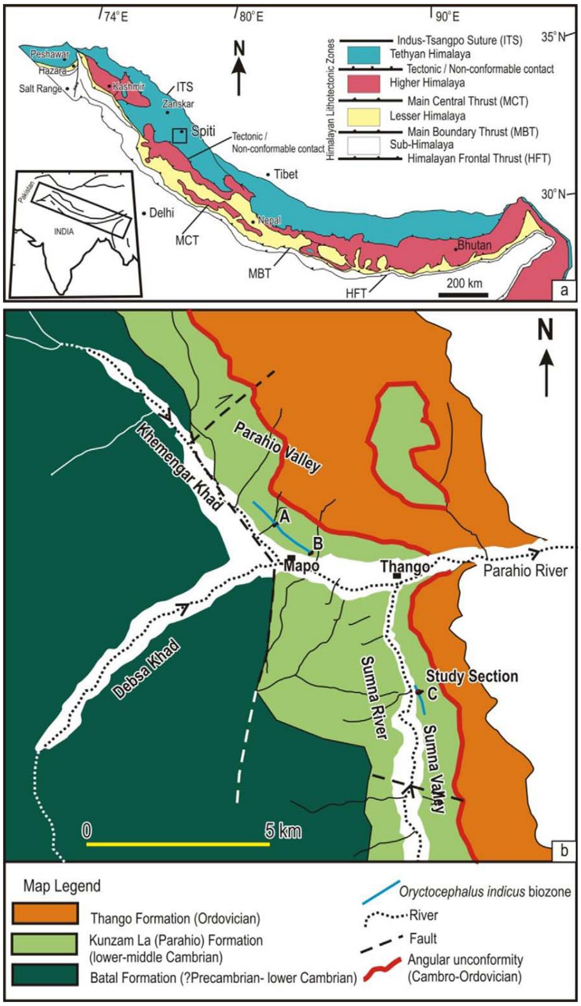

Figure 1. Location map of the southeastern part of the Spiti region and locations of the Parahio and Sumna valleys (modified after Bhargava and Bassi, 1998). Points A, B and C on the map show the section locations and blue line indicates the *Oryctocephalus indicus* biozone along the studied sections in the Parahio and Sumna valleys.

et al., 2003, 2009, Webb et al., 2007, Kellett and Grujic, 2012, Leloup et al., 2015, Lui et al., 2017] even though it has not been properly delineated on a map.

In the Spiti region, the Haimanta Group (?Precambrian–Cambrian) is divided into the Batal and Kunzam La (Parahio) formations [Srikantia, 1981, Bhargava and Bassi, 1998, Myrow et al., 2006, 2010, Hughes et al., 2018, Srikantia and Bhargava,

Table 1. Generalised lithostratigraphic scheme of the Spiti region, Himalaya

<table>
<tr><th>Age</th><th>Stoliczka (1865)</th><th>Griesbach (1891)</th><th>Hayden (1904)</th><th>Pascoe (1959)</th><th>Srikantia (1981)</th><th colspan="2">Kumar et al. (1984)</th><th>Singh et al. (1991)</th><th>Myrow et al. (2006a)</th><th>Bhargava (2008, 2011)</th><th>Singh et al. (2014, 2016)</th></tr>
<tr><td rowspan="3">CAMBRIAN</td><td rowspan="3">“Bhabeh Series”</td><td rowspan="3">Haimanta</td><td rowspan="3">Cambrian System</td><td>Parahio series</td><td rowspan="2">Kunzam La Formation</td><td rowspan="2">Kunzam La Formation</td><td>Parahio Member</td><td>Parahio Formation</td><td rowspan="2">Parahio Formation</td><td rowspan="2">Kunzam La Formation</td><td rowspan="2">Kunzam La (= Parahio) Formation</td></tr>
<tr><td rowspan="2">Upper Haimanta series</td><td>Debsa Khad Member</td><td>Kunzam La Formation</td></tr>
<tr><td>Batal Formation</td><td colspan="2">Batal Formation</td><td>Batal Formation</td><td>Batal Formation</td><td>Batal Formation</td><td>Batal Formation</td></tr>
</table>

2018]. Body fossils are not known to occur in the Batal Formation; therefore, its age is controversial and purely based on assumptions about its stratigraphic relationship with the overlying fossiliferous Cambrian Series 2/Stage 4 to Wuliuan (Miaolingian) Kunzam La (Parahio) Formation. The detrital zircon (single grain) from the Batal Formation at Batal locality in Chandra Valley yielded an age of 524 ± 7 Ma [Myrow et al., 2010], suggesting that a part of the Batal Formation is Cambrian in age.

The rocks exposed in the Parahio Valley extend to the southeast in the Sumna Valley. Body fossils of trilobites, brachiopods and small shelly fossils (SSFs) are well known to exist in the Parahio Valley [Hayden, 1904, Reed, 1910, Jell and Hughes, 1997, Peng et al., 2009, Singh et al., 2014, 2015, 016a,b, 017a,b, 2019, Popov et al., 2015, Gilbert et al., 2016, Yin et al., 2018, Hughes et al., 2018, Srikantia and Bhargava, 2018, Kaur et al., 2019]. An angular unconformity separates the Kunzam La (Parahio) Formation from the overlying Ordovician Thango Formation [Hayden, 1904, Bhargava and Bassi, 1998, Myrow et al., 2006, 2010]; the latter was deposited after the Kurgiakh orogeny [Srikantia, 1977, Xu et al., 2014, Myrow et al., 2016, Singh et al., 2019].

The nomenclature of the Cambrian rocks in the Spiti region is currently a subject of debate [Myrow et al., 2006, Bhargava, 2008, 2011, Singh et al., 2014, 016a, Hughes et al., 2018, 2019, Srikantia and Bhargava, 2018]. In the present work, we follow Singh et al. [2014] and adopt the name Kunzam La (Parahio) Formation. The generalised lithostratigraphic scheme of the Spiti region is illustrated in Table 1.

3. Studied section

The Sumna Valley is a north–south-oriented subsidiary valley of the Parahio Valley. It lies between the Parahio (in the northwest) and Pin valleys (in the southeast) (Figure 1b). The studied section lies approximately 3.52 km southeast from the confluence of the Sumna and Parahio rivers. The section is exposed on the southwest facing slope on the bank of the Sumna River (GPS: N 32° 0.291′ and E 77° 57.308′) (Figures 1b and 2). The measured section is 49.5 m thick, and the base of the section lies close to the Sumna River. The section is lithologically divided into five lithounits, I–V (Figures 2 and 4). Lithounit-I, exposed at the base of the section, is 4.0 m of intercalated thin to thickly bedded (0.2–1.1 m) fine-grained, hummocky cross-bedded sandstone and minor shale beds (0.1–0.2 m). The interface of the shale and fine-grained sandstone beds shows little bioturbation (*Planolites*). Lithounit-II is a 13.8 m thick succession of medium- to coarse-grained sandstone. The sandstone exhibits reactivation surfaces, ripple tops and a few trough cross-laminations. The top 0.56 m of this lithounit is reddish, weathered coarse-grained ferruginous sandstone, which may indicate aerial exposure or a diastem (Figure 3). Lithounit-III is a 5.6 m thick succession composed of blackish to bluish shale (0.7 m), silty shale (0.1–0.3 m)

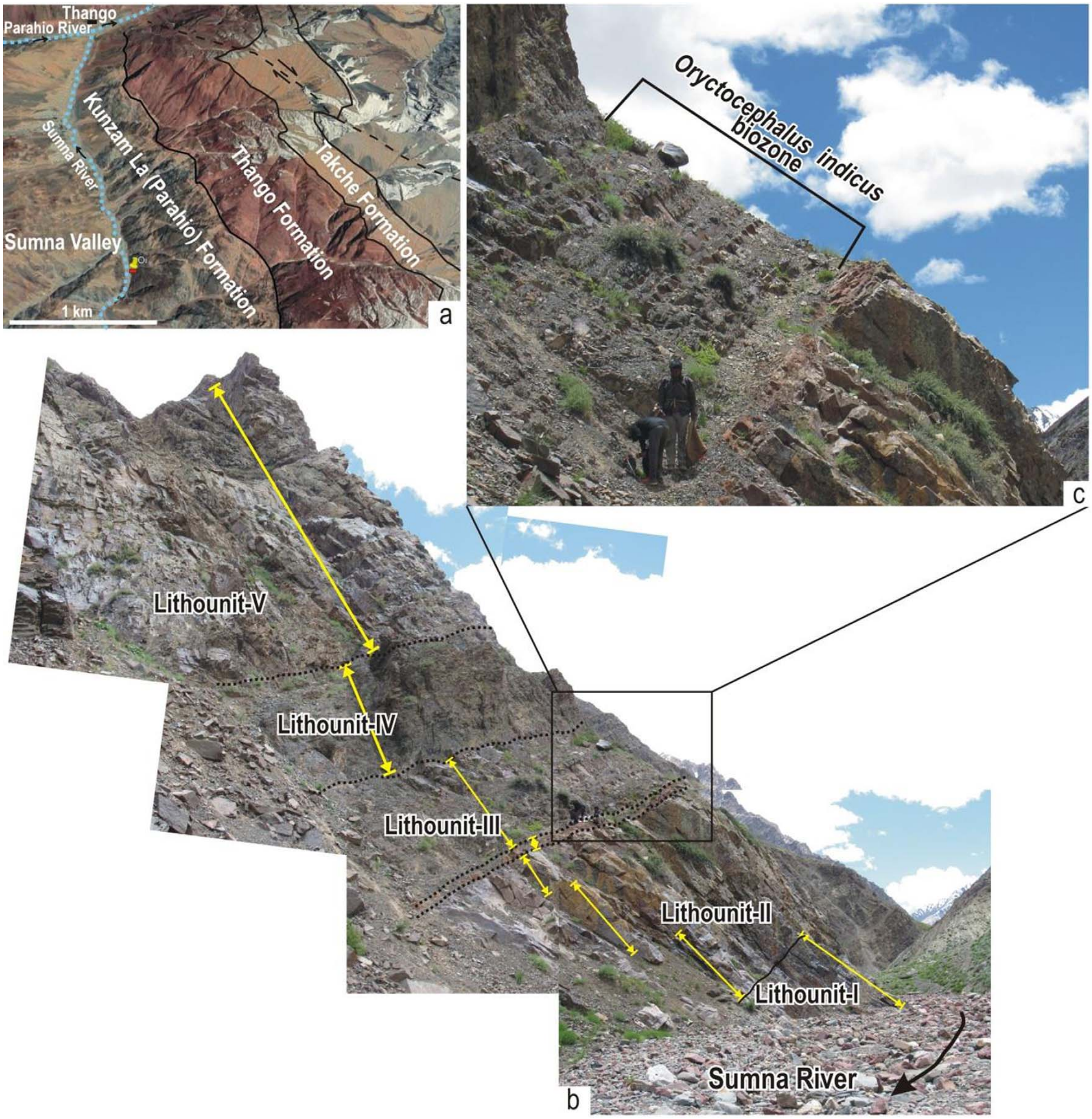

Figure 2. (a) Google Earth© image of the Sumna Valley showing the location of the studied section (yellow pin); (b) field photographs of the studied section in the Sumna Valley and its lithological subdivision (lithounits I–V); (c) inset showing the enlarged view of lithounit-III and *Oryctocephalus indicus* biozone.

and minor intercalated siltstone and sandstone (0.1–0.2 m). The blackish to bluish shale and silty shale contain the trilobites *Oryctocephalus indicus*, *Pagetia significans* and *Kunmingaspis pervulgata* (Figure 5). The *Oryctocephalus indicus* biozone is reported only from this unit. Lithounit-IV is a 5.8 m thick succession and consists of alternating silty shale–siltstone and thin beds of fine-grained sandstone. Thin beds of siltstone (0.1–0.3 m) and sandstone (0.1–0.2 m) exhibit ripple surfaces. The shale–siltstone beds contain *Pagetia significans* and *Kunmingaspis pervulgata*. *Oryctocephalus indicus* is not found within this lithounit. Lithounit-V is 20.3 m thick and is made up of medium- to coarse-grained, bedded to massive

Figure 3. Field photograph showing the contact of reddish-brown ferruginous, coarse-grained sandstone (top of lithounit-II) and black shale–silty shale (lithounit-III); lithounit-III yielded trilobite fossils of the *Oryctocephalus indicus* biozone (Sumna Valley, Spiti; stick as a scale =1 m).

sandstone (0.5–1.1 m) exhibiting trough cross-beds and ball and pillow structures. Well-preserved fossils have not been recorded from this lithounit though fragments of trilobite *Bhargavia prakritika* have been observed.

4. Materials and methods

Fossiliferous samples were collected from the Kunzam La (Parahio) Formation. Close systematic sampling was undertaken in order to establish the biostratigraphy of the studied interval. A total of 389 samples of trilobites were collected from the section. For photography, the fossil specimens were washed and dried and coated with magnesium oxide to enhance morphological features. The morphological features were examined under an Olympus SZX16 binocular microscope. The well-preserved selected specimens representing different taxa were photographed using an RSN-9 Stereo Zoom Light Microscope with an attached digital camera. The illustrated trilobites (Figure 5) were deposited in the repository of the Department of Geology, Panjab University under the label CAS/2017/SV.

5. Biostratigraphy

The studied part of the Kunzam La (Parahio) Formation in the Sumna Valley is significant as it bears the *Oryctocephalus indicus* biozone (~509 Ma), which demarcates the base of the Miaolingian Series [e.g. Zhao et al., 2019, Singh et al., 016a].

5.1. *Oryctocephalus indicus biozone*

Along the studied section, the FAD of *Oryctocephalus indicus* is recorded in blackish to bluish shale, silty shale, siltstone and sandstone intercalations at 17.8 m from the base of the measured section (Section C, Figure 1b and Figure 4). The last appearance datum is recorded at 23.4 m from the base of the section. The *Oryctocephalus indicus* biozone in the Sumna Valley is 5.3 m thick. Besides the eponymous species, the other trilobite fossils recorded include *Pagetia significans* and *Kunmingaspis pervulgata* (Figure 5). Along this section, a thin horizon of argillaceous limestone or nodular limestone, common in the Parahio Valley sections, is absent (see Sections A and B in Figure 1b). This missing limestone

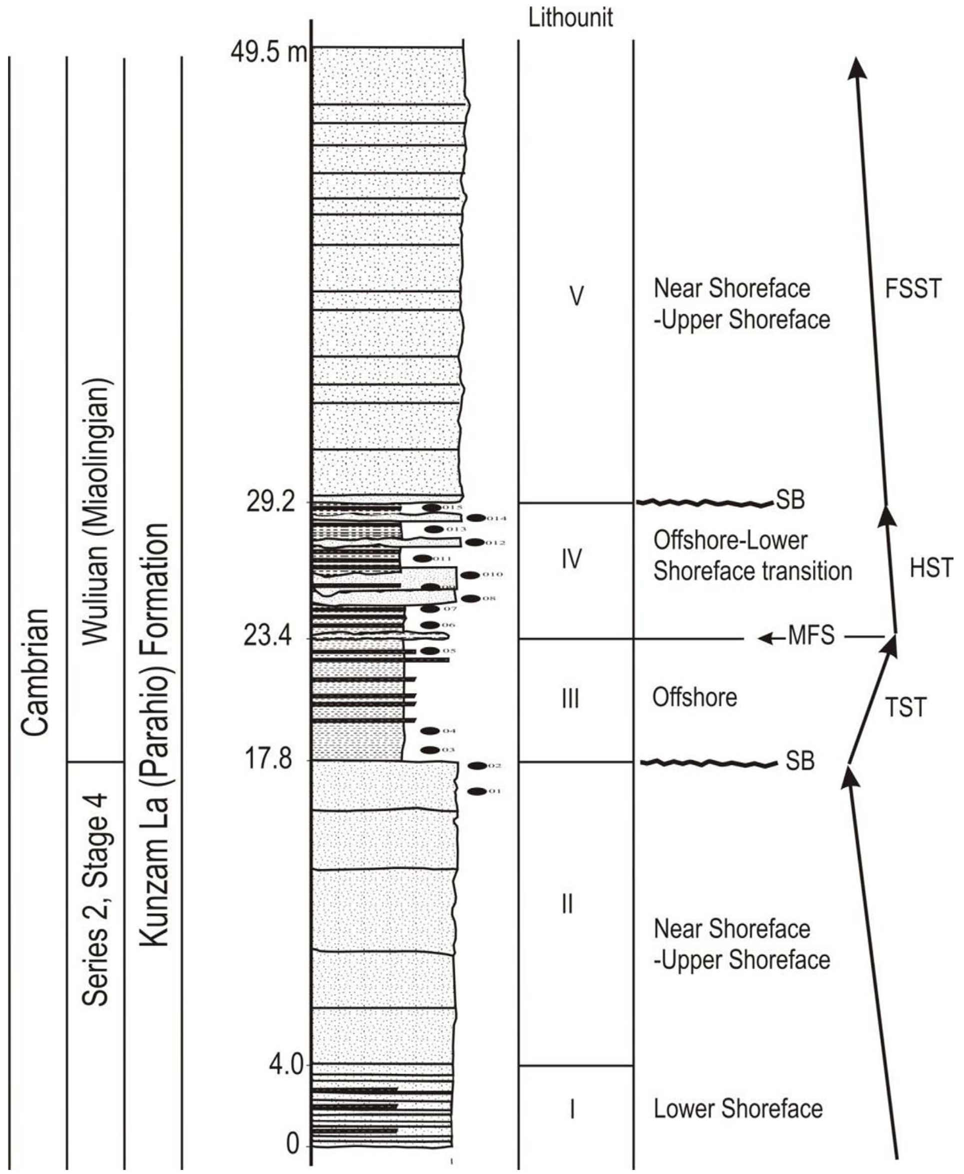

Figure 4. Lithocolumn of the measured section on the right bank of the Sumna River in the Sumna Valley, showing the distribution of lithounits (I–V) and their respective inferred depositional environment and sequence stratigraphic framework.

horizon contains the *Pagetia–Kunmingaspis* level [Singh et al., 016a, 017b]. Above the *Oryctocephalus indicus* biozone, *Pagetia significans* and *Kunmingaspis pervulgata* are also recorded from 23.4 m to 29.2 m in the section. Poorly preserved fragments of *Bhargavia prakritika* are recorded in overlying sediments at 29.2 to 49.5 m of the succession.

6. Depositional environment and implication on Cambrian series 2–Miaolingian evolution in Sumna Valley

Based on sedimentological and sequence stratigraphic analysis of the 49.5 m thick successions of the Kunzam La (Parahio) Formation, five lithounits (I–V) are recognised (Figure 4). Lithounits I and II

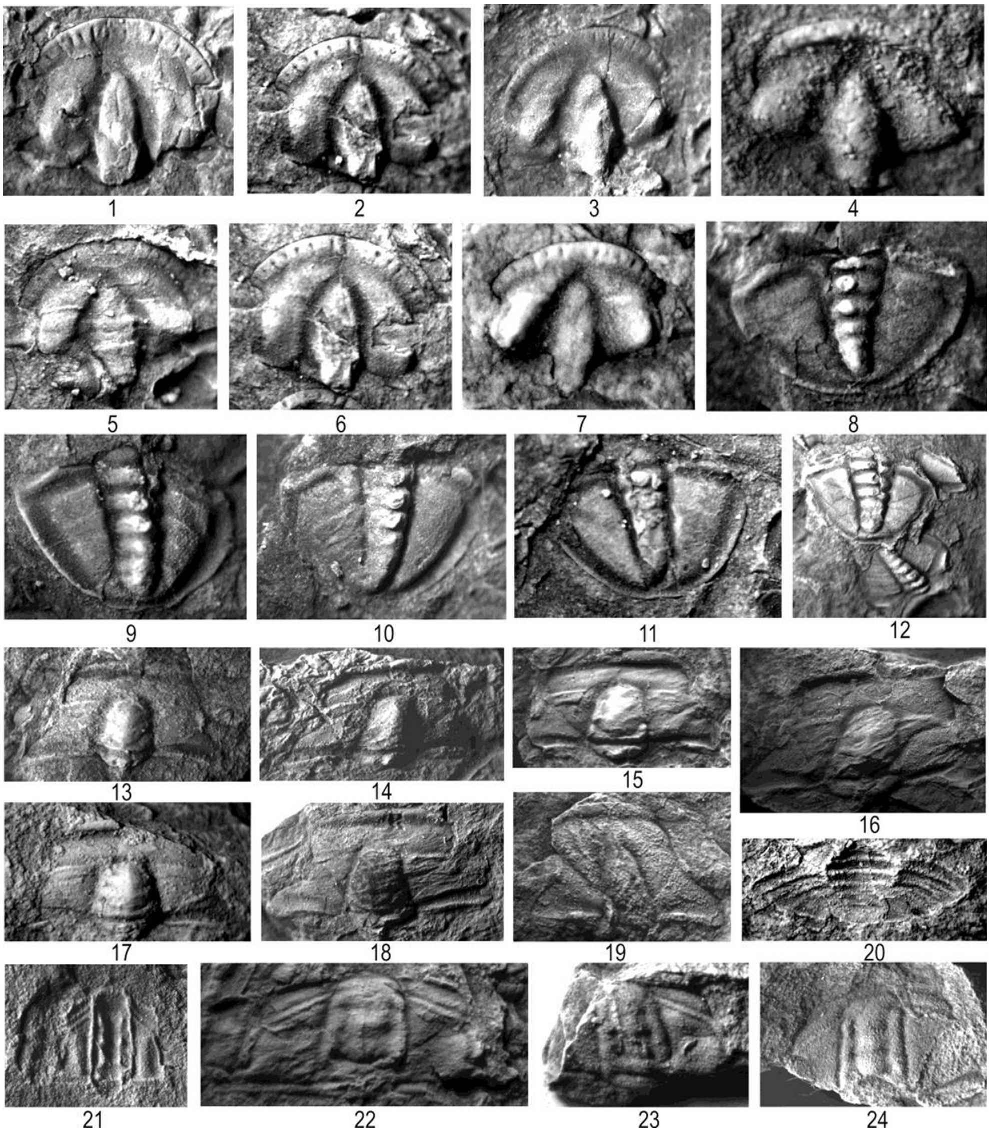

Figure 5. Representative trilobites from the *Oryctocephalus indicus* biozone in the Sumna Valley, Spiti region, Himalaya. (1–12): *Pagetia significans* [Etheridge Jr., 1902], 1–7: cranidium (1: CAS/2017/SV-1003, 22x; 2: CAS/2017/SV-1007, 22x; 3: CAS/2017/SV-1008, 21x; 4: CAS/2017/SV-1009, 23x; 5: CAS/2017/SV-1017, 22x; 6: CAS/2017/SV-1025, 22x; 7: CAS/2017/SV-1029, 45x); 8–12: pygidium (8: CAS/2017/SV-1005, 30x; 9: CAS/2017/SV-1011, 22x; 10: CAS/2017/SV-1019, 22x; 11: CAS/2017/SV-1036, 22x; 12: CAS/2017/SV-1030, 21x); (13–20): *Kunmingaspis pervulgata* [Reed, 1910], 13–19: cranidium (13: CAS/2017/SV-1035, 9x; 14: CAS/2017/SV-1048, 10x; 15: CAS/2017/SV-1053, 14x; 16: CAS/2017/SV-1056, 16x; 17: CAS/2017/SV-1061, 10x; 18: CAS/2017/SV-1063, 11x; 19: CAS/2017/SV-1037, 10x); 20: pygidium, CAS/2017/SV-1037, 14x; (21–24): *Oryctocephalus indicus* [Reed, 1910], cranidium (21: CAS/2017/SV-1002, 10x; 22: CAS/2017/SV-1023, 10x; 23: CAS/2017/SV-1004, 11x; 24: CAS/2017/SV-1006, 10x).

are deposited under the falling stage systems tract (FSST), and they indicate a forced regressive event due to a shift from lower shoreface (lithounit-I) to near shoreface–upper shoreface (lithounit-II) successions (Figure 4). The sequence boundary (SB) lies on the top part of lithounit-II, and it is characterised by a break in sedimentation (a diastem) reflected by the reddish-brown ferruginous, coarse-grained sandstone at the top of lithounit-II (Figure 3). The bluish-black pyritised shale of lithounit-III indicates deposition in a reducing environment during transgression (transgressive systems tract (TST)) of the deeper offshore facies. The maximum flooding surface (MFS) is marked at the contact of the offshore shale (lithounit-III) with an overlying alternation of thin shale–siltstone–sandstone (lithounit-IV). The latter is considered to represent an early stage of the highstand systems tract (HST). The intercalated thin shale–siltstone–sandstone interval is inferred to be formed in an offshore–lower shoreface transition environment. The HST deposits are not very thick, and they represent only the early stage of the HST. Upwards, these are followed by medium- to coarse-grained sandstone (lithounit-V) containing ball and pillow structures and interpreted to be deposited in a near shoreface–upper shoreface environment in an FSST. An SB is recognised in between lithounits IV and V—the recognition is based on the sudden change in depositional environments from offshore–lower shoreface to near shoreface–upper shoreface deposits. Overall, the studied section exhibits dynamic changes in the depositional energy reflected by the presence of two regressive events and one transgressive event within a 49.5 m interval of the Kunzam La (Parahio) Formation, spanning the Cambrian Series 2–Wuliuan (Miaolingian) boundary interval in the Sumna Valley (Figure 4).

To study the lithological variation and depositional environment across the Cambrian Series 2–Wuliuan (Miaolingian) boundary interval in the southeastern part of the Spiti region, detailed sedimentological studies were carried out along two sections previously described from the Parahio Valley (Sections A and B, Figure 1) [Singh et al., 2015, 016a, 017b] and one section (Section C, Figure 1) from the Sumna Valley (Figure 6). Figure 6 depicts a comparison of the lithological variation across the Cambrian Series 2–Wuliuan (Miaolingian) boundary interval in the Parahio and Sumna valleys from the northwest to the southeast direction in the southeastern part of the Spiti region. In the Parahio Valley, the Cambrian Series 2–Wuliuan (Miaolingian) boundary interval is marked based on the *Oryctocephalus indicus* biozone along two sections, that is, in Section B of the Parahio Valley [Singh et al., 016a, 017a] and in Section A of the Kaltarbo locality [Singh et al., 2015, Yin et al., 2018, Kaur et al., 2019]. In the Kaltarbo section (Section A, Figure 1) of the Parahio Valley, the *O. indicus* biozone is 5.8 m thick (section range 345.7 m–351.5 m). Below this biozone, a horizon of more or less isolated limestone nodules (15–24 cm diameter) occurs encased in shale [Singh et al., 2015]; they were probably formed by diagenetic pressure solution (compaction and dewatering of clay) [cf. Markello and Read, 1981]. In Section B of the Parahio Valley, the *O. indicus* biozone is 6.8 m thick (section range 7.74–4.6 m) [Singh et al., 016a]. Below this biozone, a thin horizon of argillaceous limestone (7.38–7.74 m) exists [Singh et al., 016a, 017a]. However, in the Sumna Valley (Section C, Figure 1), the *O. indicus* biozone is 5.6 m thick (section range 17.8–23.4 m). It directly rests over the reddish-brown ferruginous, medium- to coarse-grained sandstone (Figure 3) and lacks nodular limestone or argillaceous limestone rocks (Figure 6). The thin nodular limestone and argillaceous limestone horizon in the Parahio Valley yield *Pagetia, Kunmingaspis* and SSFs. Thus, in the southeastern part of the Spiti region in the three sections studied (from northwest to southeast, i.e. Section A, Section B and Sumna Valley Section C; Figure 1), the reddish-brown ferruginous, medium- to coarse-grained sandstone forms the uppermost part of the thick medium- to coarse-grained sandstone (lithounit-II). Compared to Sections A and B (of the Parahio Valley), the absence of carbonates indicates that the Sumna Valley was locally aerially exposed becasue of local topographic high during the Wuliuan (Miaolingian) transgression (Figure 4). The early transgression with argillaceous limestones and nodular limestones filled the lower topography of the Parahio Valley. The subsequent offshore shale bearing the *O. indicus* and associated trilobites transgressed all over the basin. This implies that the depositional basin topography was not uniform throughout the southeastern part of the Spiti during the Wuliuan (Miaolingian) transgression or the eustatic sea-level change at the basal part of Wuliuan (Miaolingian) [e.g. Zhu et al., 1999, Wang et al., 2006, Gaines et al., 2011]. In the Spiti region, it seems that the Wuliuan (Miaolingian) deposits rest on an undulatory surface formed due to a break in sedimentation or aerial exposure of the rocks of Cambrian

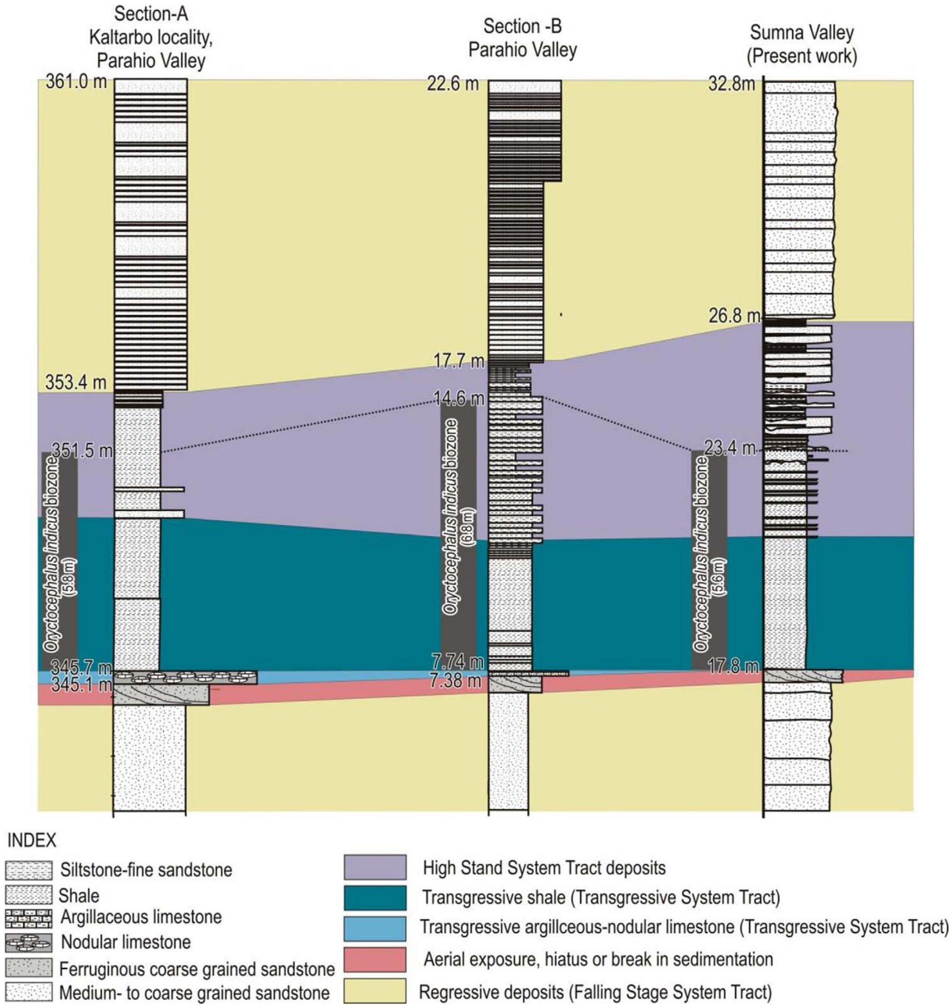

Figure 6. Correlation of lithologies, *O. indicus* biozone and depositional settings from Sections A and B (of the Parahio Valley) and Section C (of the Sumna Valley) (refer to Figure 1 for position of Sections A and B). Note the uniform aerial exposure, hiatus or break in sedimentation below the base of the *O. indicus* biozone or Miaolingian transgression. For Section A, refer to Singh et al. [016a,b, 017a] and for Section B, refer to Singh et al. [2015] and Yin et al. [2018].

Series 2 prior to the Wuliuan (Miaolingian) transgression (Figure 6). The reddish-brown ferruginous, medium- to coarse-grained sandstone of lithounit-II represents a break in sedimentation. It is notable that in the Lesser Himalayan Zone, the Cambrian sedimentation ceased in the late part of Cambrian Series 2/Stage 4 just above the *Redlichia noetlingi* biozone (~512 Ma) [Singh et al., 2019]. In the Spiti region (Tethyan Himalayan Zone (THZ)), although the *Redlichia noetlingi* (~512 Ma) is known from a float in the Pin Valley [Hayden, 1904, Reed, 1910, Jell and Hughes, 1997], the exact stratigraphic position with respect to the *Haydenaspis parvatya* level (~510 Ma) and the *O. indicus* biozone (~509 Ma) is unknown. Recently, Kaur et al. [2019] have established a stratigraphic distance of approximately 183.4 m between the *O. indicus* biozone (509 Ma) and the *Haydenaspis parvatya* level (~510 Ma) in the Spiti region. Finding the in situ occurrence of *Redlichia noetlingi* in the Spiti region will be helpful in understanding the exact stratigraphic position of the *Redlichia noetlingi* bearing level with respect to the *O. indicus* biozone or the *H. parvatya* level. However, here we propose that in the Spiti region (THZ), the Cambrian Series 2/Stage 4 regressive event affected the region after the deposition of rocks from the *Haydenaspis parvatya* level (~510 Ma). In addition, a break in sedimentation (diastem) is recognised preceding the Wuliuan (Miaolingian) transgression.

7. Conclusions

The *Oryctocephalus indicus* biozone is widely recognised in the southeastern part of the Spiti region, which includes Parahio, Sumna and Pin valleys. This biozone is globally used to demarcate the base of the Miaolingian Series (traditional Middle Cambrian). In the Parahio and Sumna valleys of the Spiti region, this biozone is 5.6 to 6.8 m thick. The uppermost part of the Cambrian Series 2 deposits (immediately below the *O. indicus* biozone) in the southeastern part of the Spiti region bears a reddish-brown ferruginous, very coarse grained sandstone unit, which indicates a diastem or a break in sedimentation prior to the Wuliuan (Miaolingian) transgression.

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References

Bhargava, O. N. (2008). An updated introduction to the Spiti geology. *J. Palaeontol. Soc. India*, 53:113–129.

Bhargava, O. N. (2011). Early Palaeozoic paleogeography, basin configuration, paleo-climate and tectonics in the Indian Plate. *Mem. Geol. Soc. India*, 78:69–99.

Bhargava, O. N. and Bassi, U. K. (1998). Geology of Spiti-Kinnaur Himachal Himalaya. *Mem. Geol. Surv. India*, 124:1–210.

Burchfiel, B. C., Zhiliang, C., Hodges, K. V., Yuping, L., Royden, L. H., Changrong, D., and Jiene, X. (1992). The South Tibetan detachment system, Himalayan orogen: extension contemporaneous with and parallel to shortening in a collisional mountain belt. Geol. Soc. America Bulletin, Special Papers, 269.

Etheridge Jr., R. (1902). Evidence of further Cambrian trilobites. *Contrib. Palaeontol. South of Australia*, 13:3–4.

Gaines, R. R., Mering, J. A., Zhao, Y., and Peng, J. (2011). Stratigraphic and microfacies analysis of the Kaili Formation, a candidate GSSP for the Cambrian Series 2–Series 3 boundary. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 311:171–183.

Gilbert, I. R., Hughes, N. C., and Myrow, P. M. (2016). Cambrian microfossils from the Tethyan Himalaya. *J. Paleontol.*, 90:10–30.

Hayden, H. H. (1904). The Geology of Spiti with parts of Bashahr and Rupshu. *Mem. Geol. Surv. India*, 36:1–121.

Hodges, K. V., Parrish, R. R., Housh, T. B., Lux, D. R., Burchfiel, B. C., Royden, L. H., and Chen, Z. (1992). Simultaneous Miocene extension and shortening in the Himalayan orogen. *Science*, 258:1466–1470.

Hughes, N. C. (2016a). The Cambrian palaeontological record of the Indian subcontinent. *Earth-Sci. Rev.*, 159:428–461.

Hughes, N. C. (2016b). Soft-bodied fossil preservation in the Cambrian Parahio Formation of Spiti. *Curr. Sci.*, 110(5):774–775.

Hughes, N. C., Myrow, P. M., Peng, S., and Banerjee, D. M. (2018). The Parahio Formation of the Tethyan Himalaya: The Type Section, Thickness, Lithostratigraphy and Biostratigraphy of the best characterised Cambrian Succession in the Indian Subcontinent. *J. Palaeontol. Soc. India*, 63:1–18.

Hughes, N. C., Myrow, P. M., Peng, S., and Banerjee, D. M. (2019). The Parahio Formation of the Tethyan Himalaya: further consideration of a case history in lithostratigraphy. *J. Palaeontol. Soc. India*, 64:275–282.

Jell, P. A. and Hughes, N. C. (1997). Himalayan Cambrian trilobites. *Spec. Pap. Palaeontol.*, 58:1–113.

Kaur, R., Singh, B. P., Bhargava, O. N., Singla, G., and Stopden, S. (2019). Cambrian trilobite fauna of the *Haydenaspis parvatya* level (Series 2, Stage

4): Its stratigraphic position with respect to the *Oryctocephalus indicus* Biozone (Miaolingian Series, Wuliuan Stage) in the Spiti Himalaya, India. *C. R. Palev.*, 18:298–305.

Kellett, D. A. and Grujic, D. (2012). New insight into the South Tibetan detachment system: not a single progressive deformation. *Tectonics*, 31. doi:10.1029/2011TC002957.

Leloup, P. H., Liu, X., Mahèo, G., Paquette, J. L., Arnaud, N., Aubray, A., and Liu, X. (2015). New constraints on the timing of partial melting and deformation along the Nyalam section (central Himalaya): implications for extrusion models. In Mukherjee, S., Carosi, R., Vanderbeek, P. A., Mukherjee, B. K., and Robinson, D. M., editors, *Tectonics of the Himalaya*, pages 131–175. Geol. Soc. London, Special Publications.

Lui, Z.-C., Wu, F.-Y., Qiu, Z.-L., Wang, J.-G., Liu, X.-C., Ji, W.-Q., and Liu, C.-Z. (2017). Leucogranite geochronological constraints on the termination of the South Tibetan Detachment in eastern Himalaya. *Tectonophysics*, 721:106–122.

Markello, J. R. and Read, J. F. (1981). Carbonate ramp-to-deeper shale shelf transitions of an Upper Cambrian intrashelf basin, Nolichucky Formation, Southwest Virginia Appalachians. *Sedimentology*, 28:573–597.

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. *Geol. Soc. Am. Bull.*, 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. *Geol. Soc. Am. Bull.*, 128:1679–1695.

Myrow, P. M., Hughes, N. C., Paulsen, T. S., Williams, I. S., Parcha, S. K., Thompson, K. R., Bowring, S. A., Peng, S. C., and Ahluwalia, A. D. (2003). Integrated tectonostratigraphic reconstruction of the Himalaya and implications for its tectonic reconstruction. *Earth Planet. Sci. Lett.*, 212:433–441.

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. *Geol. Soc. Am. Bull.*, 120:323–332.

Myrow, P. M., Thompson, K. R., Hughes, N. C., Paulsen, T. S., Sell, B. K., and Parcha, S. K. (2006). Cambrian stratigraphy and depositional history of the northern Indian Himalaya, Spiti Valley, north-central India. *Geol. Soc. Am. Bull.*, 118:491–510.

Peng, S. C., Hughes, N. C., Heim, N. A., Sell, B. K., Zhu, X., Myrow, P. M., and Parcha, S. K. (2009). Cambrian trilobites from the Parahio and Zanskar Valleys, Indian Himalaya. *Mem. Paleontol. Soc.*, 71:1–95.

Popov, L. E., Holmer, L. E., Hughes, N. C., Ghobadi, P. M., and Myrow, P. M. (2015). Himalayan Cambrian brachiopods. *Pap. Palaeontol.*, 1:345–399. https://doi.org/10.1002/spp2.1017.

Reed, F. R. C. (1910). The Cambrian fossils of Spiti. *Palaeontol. Indica*, 15:1–70.

Sahni, A. K. and Sudan, C. S. (1996). Agnostid Fauna from the Cambrian of Spiti. *J. Geol. Soc. India*, 48(6):653–662.

Searle, M. P. and Treloar, P. J. (1993). Himalayan Tectonics - an Introduction. In Treloar, P. J. and Searle, M. P., editors, *Himalayan Tectonics*, volume 74, pages 1–7. Geol. Soc. London Special Publication.

Shah, S. K., Parcha, S. K., and Raina, A. K. (1991). Late Cambrian trilobites from Himalaya. *J. Geol. Soc. India*, 36:89–107.

Shah, S. K. and Paul, S. (1987). Oryctocephalid fauna from the Cambrian of Spiti. *J. Geol. Soc. India*, 30:187–193.

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. *J. Palaeontol. Soc. 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 (Parahio) Formation, Parahio valley, Spiti region (Tethyan Himalaya), India. *Curr. Sci.*, 109:2191–2195.

Singh, B. P., Bhargava, O. N., Mikuláš, R., Prasad, S. K., Morrison, S., Chaubey, R. S., and Kishore, N. (2019). Discovery of Ordovician trace fossils from the Lesser Himalaya, India: its stratigraphic, tectonic and palaeogeographic implications. *J. Palaeontol. Soc. India*, 64(2):283–303.

Singh, B. P., Bhargava, O. N., Negi, R. S., Zhao, Y.-L., Yin, L., and Sharma, C. A. (2017a). Additional trilobite fauna from the basal part of the Cambrian Series 3, Stage 5, Kunzam La (Parahio) Formation, Parahio Valley, Spiti (Northwest Himalaya), India and its biostratigraphic significance. *Ann. Paléontol.*, 103:271–281.

Singh, B. P., Chaubey, R. S., Bhargava, O. N., Prasad, S. K., and Negi, R. S. (2017b). The Cambrian trilobite fauna from the Shian (Saybang) section, Pin Valley (Spiti) and its biostratigraphic significance. *Palaeoworld*, 26:25–36.

Singh, B. P., Virmani, N., Bhargava, O. N., and Gill, A. (2016b). Revision of diagnostic features of the trilobite genus *Bhargavia* (Ellipsocephaliodea) from the Parahio valley (Spiti), Northwest Himalaya, India. *J. Palaeontol. Soc. India*, 61:9–14.

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. *J. Palaeontol. Soc. India*, 59:81–88.

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

Singla, G., Singh, B. P., Bhargava, O. N., Kaur, R., and Stopden, S. (in press). Trilobites of medial Wuliuan (Miaolingian) age from the Kunzam La (Parahio) Formation, Sumna river section, Spiti region and its biostratigraphic significance. *Int. J. Stratigraphic Geol. Correlation.*

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 Scientifique*, 268:395–408.

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

Srikantia, S. V. and Bhargava, O. N. (2018). Stratigraphic nomenclature of early Palaeozoic in the Spiti Himalaya: cobwebs cleared. *J. Palaeontol. Soc. India*, 63:233–241.

Wang, Y., Yu, Y. Y., Peng, J., and Wang, P. L. (2006). Discussion on the sequence stratigraphy and sea-level changes of the Kaili Formation at Balang, Taijiang, Guizhou. *J. Stratigraphy*, 30:34–41.

Webb, A. A. G., Yin, A., Harrison, T. M., Cèlèrier, J., and Burgess, W. P. (2007). The leading edge of the Greater Himalayan Crystalline complex revealed in the NW Indian Himalaya: implications for the evolution of the Himalayan orogen. *Geology*, 35:955–958.

Xu, Y. J., Cawood, P. A., Du, Y. S., Huang, H. W., and Wang, X. Y. (2014). Early Paleozoic orogenesis along Gondwana's northern margin constrained by provenance data from South China. *Tectonophysics*, 636:40–51.

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. *Paleoworld*, 27:30–41. 10.1016/j.palwor.2017.05.004.

Zhao, Y.-L., Yuan, J.-L., Babcock, L. E., Guo, Q., Peng, J., Yin, L., Yang, X., Peng, S. C., Wang, C., Gaines, R. R., Esteve, J., Tai, T., Yang, R., Wang, Y., Sun, H., and Yang, Y. (2019). Global Standard Stratotype-Section and Point (GSSP) for the conterminous base of the Miaolingian Series and Wuliuan Stage (Cambrian) at Balang, Jianhe, Guizhou, China. *Episodes*, 42:165–184.

Zhu, M. Y., Erdtmann, B. D., and Zhao, Y.-L. (1999). Taphonomy and Paleoecology of the early Middle Cambrian Kaili Lagerstätte in Guizhou, China (in Chinese). *Acta Palaeontol. Sin.*, 38:28–57.