Cambrian rocks and faunas of the Wachi La, Black Mountains, Bhutan

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Abstract – The Pele La Group in the Wachi La section in the Black Mountains of central Bhutan represents the easternmost exposure of Cambrian strata known in the Himalaya. The group contains a succession of siliciclastic rocks with minor amounts of carbonate, the uppermost unit of which, the Quartzite Formation, bears age-diagnostic trilobite body fossils that are approximately 493 Ma old. Trilobite species include *Kaolishania granulosa, Taipaikia glabra* and the new species *Lingyuanaspis sangae.* A billingsellid brachiopod, *Billingsella* cf. *tonkiniana,* is co-occurrent. This fauna is precisely correlated with that of a specific stratigraphic horizon within the upper part of the *Kaolishania* Zone, Stage 9 of the Cambrian System, Furongian Epoch of the North China block, and thus represents the youngest Cambrian sedimentary rocks yet known from the Himalaya. The faunal similarity suggests proximity between North China and the Himalayan margin at this time. This unit was deposited in a predominantly storm-influenced shelf and shoreface environment. U–Pb geochronological data from detrital zircon grains from the fossil-bearing beds of the Quartzite Formation and strata of the underlying Deshichiling Formation show grain age spectra consistent with those from Cambrian rocks of the Lesser and Tethyan Himalaya in Tibet, India and Pakistan. These data support continuity of the northern Gondwanan margin across the Himalaya. Prominent peaks of approximately 500 Ma zircons in both the Quartzite and Deshichiling formations are consistent with the Furongian (late Cambrian) age assignment for these strata. The presence of these relatively young zircon populations implies rapid post-cooling erosion of igneous bodies and subsequent deposition which may reflect the influence of a widespread Cambro-Ordovician orogenic event evident in the western Himalaya.

Keywords: Cambrian, detrital zircon, trilobite, Himalaya, palaeogeography.

1. Introduction

Understanding of the pre-collisional stratigraphic and erosional history of the Himalaya is critical for reconstruction of the structural, tectonic and depositional history of the Himalayan orogeny. The Cambrian System is of special importance in this regard because of its widespread distribution along and across the Himalaya (Hughes & Jell, 1999), and recent work provides the outline of a stratigraphic correlation for Neoproterozoic and Cambrian rocks that stretches from Pakistan to the Everest region of Nepal, and across strike onto the Indian craton (Bhargava, 1998; DiPietro & Pogue, 2004; Hughes *et al.* 2005; Myrow *et al.* 2009, 2010). These correlations have allowed for precise age determination of strata even in the absence of diagnostic fossils (Myrow *et al.* 2009),

and have permitted reinterpretation of the structural relationships across major Himalayan fault systems. They suggest that the entire Himalayan region was once blanketed in a thick Neoproterozoic to late middle Cambrian succession, most of which has since been eroded. In the northernmost of the Himalayan lithotectonic zones, the Tethyan Himalaya, syntectonic terrestrial and marine rocks of probable Early or Middle Ordovician age (see Torsvik *et al.* 2009) unconformably overlie Cambrian strata and are associated with a tectonic event known as the Kurgiakh (Srikantia, 1981) or Bhimphedian (Cawood, Johnson & Nemchin, 2007) orogeny.

Furongian (late Cambrian) rocks, which are absent in the central and western parts of the Himalaya, are present in Bhutan (see Section 4). Rocks of this age occur sporadically across much of southeastern Asia and extensively in China. Indeed, upper Cambrian deposits have been confirmed from western Yunnan, Myanmar,

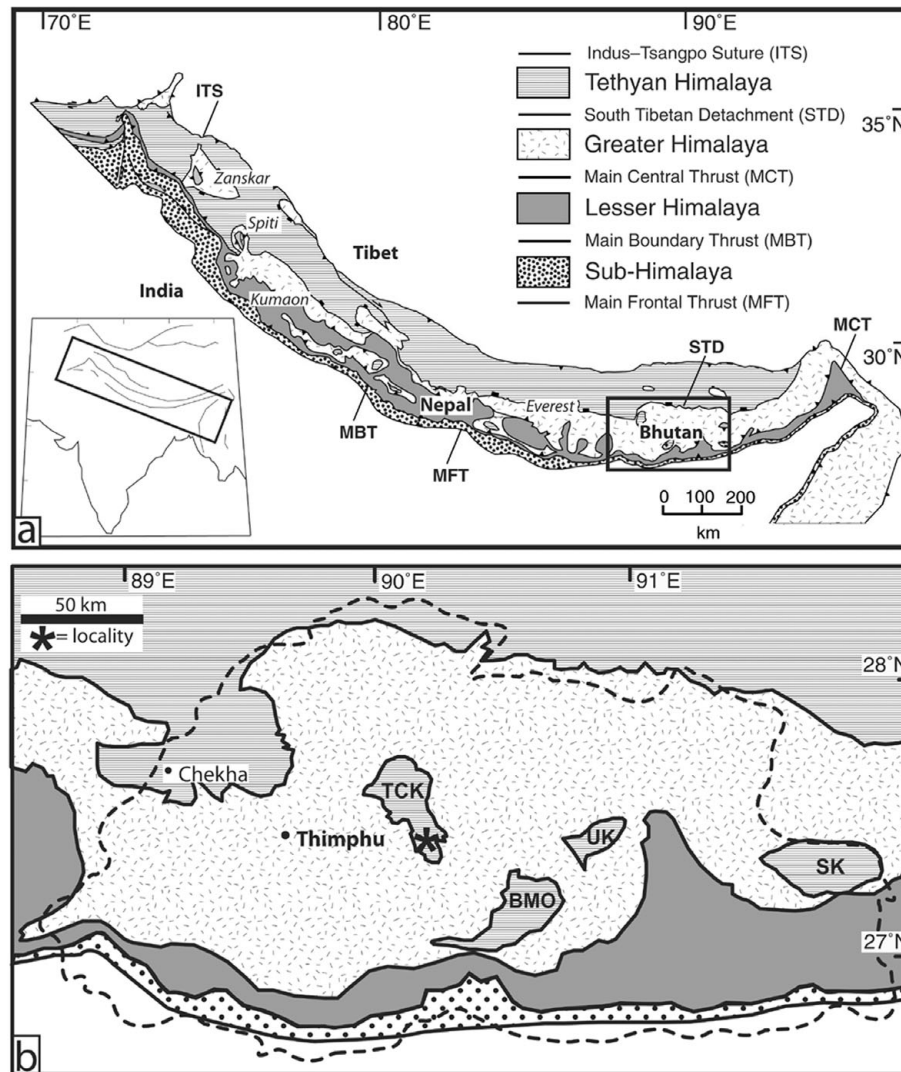†Author for correspondence: nigel.hughes@ucr.edu

Figure 1. (a) Simplified geological map of Himalayan orogenic system and lithotectonic divisions (modified from Yin, 2006). (b) Geological map of Bhutan: TCK – Tang Chu klippe, BMO – Black Mountain outlier, UK – Ura klippe, SK – Sakteng klippe (modified from Grujic, Hollister & Parrish, 2002).

Thailand and Vietnam (Zhang, 1988), whereas rocks of earlier Cambrian ages are poorly described or unknown from these regions. Thus, with regard to Cambrian geology, Bhutan serves as a potentially pivotal tie-point between the Himalayan region and the rest of SE Asia, as well as with parts of China. Comparisons of lithostratigraphic and biostratigraphic aspects of the Cambrian strata of Bhutan with those to the east provide a framework for the regional tectonostratigraphic affinities of the Himalayan margin. Here we provide sedimentological, stratigraphic, palaeontological and detrital zircon geochronological data with which to assess these relationships.

2. Geological setting and previous work

2.a. Geological context of the Wachi La succession

Between its western and eastern syntaxes two of the three northern Himalaya lithotectonic zones contain sedimentary rocks, namely the Lesser Himalaya and Tethyan Himalaya (Myrow *et al.* 2003). An intervening zone of high-grade metamorphic rock of igneous and sedimentary protolith, the Greater Himalaya, separates these zones (Fig. 1). The boundaries between these lithotectonic zones are important tectonic structures, such as the Main Central Thrust, which separates the Greater Himalaya and the Lesser Himalaya, and the South Tibetan Fault System, a top-to-the-north normal fault that separates the Greater Himalaya and Tethyan Himalaya.

Cambrian sedimentary rocks occur in both the Lesser Himalaya and the Tethyan Himalaya in the central and western sectors of the Himalaya, and as sedimentary protolith in the Greater Himalaya (Myrow *et al.* 2009). This distribution and the stratigraphic characteristics of these rocks suggest a passive margin during Cambrian deposition that progressively deepened to the north (Brookfield, 1993; Searle, 1996; Myrow *et al.* 2003; Hughes *et al.* 2005). In the western and central Himalaya, no Cambrian sedimentary rock younger than about 501 Ma is known (Peng *et al.* 2009).

Nautiyal et al., 1964	Jangpangi, 1978	Chaturvedi, Mishra & Mulay, 1983a,b		Tangri & Pande, 1995	Grujic, Hollister & Parrish, 2002
Tongchu Series	Tangchu Series	Black Mountain Group	Black Mountain Group	Tang Chu Group	Tethyan Sediments
Chekha Series	Thimpu-Chekha Group / Chekha Formation			Pele La Group	Chekha Formation
		Mao-Khola Group	Maokhola Group	Chekha Formation	

b Chaturvedi, Mishra & Mulay, 1983b			Bhargava, 1995; Tangri & Pande, 1995		This study
Age	Lithostratigraphy			Age	Age
Silurian	Black Mountain Group	Wachi La Formation	Tang Chu Group / Wachi La Formation	Devonian	Furongian (late Cambrian)
Middle to Late Ordovician		Mane-Ting Formation — Mbr H, Mbr G, Mbr F, Mbr E, Mbr D, Mbr C, Mbr B, Mbr A	Pele La Group / Quartzite Formation	Middle Cambrian	
			Maneting Formation	Early Cambrian	
Early Ordovician	Maokhola Group	Nake Chu Formation	Deshichiling Formation	Precambrian	

Figure 2. (a) General summary of nomenclature applied to lower Tethyan strata of the Bhutanese outliers. (b) Summary of nomenclature and chronostratigraphy of the Pele La Group, Wachi La section. Spellings are as given in the original references.

The succession in Bhutan differs in several ways. Although continuous lithotectonic belts of both Tethyan Himalayan and Lesser Himalayan strata are present in the northern and southern parts of the country, respectively, Bhutan also contains a series of outliers bearing sedimentary rocks that are situated within the Greater Himalayan lithotectonic belt (Gansser, 1983; Bhargava, 1995; Grujic, Hollister & Parrish, 2002) (Fig. 1a), although the number and boundaries of the outliers recognized differ among authors. The Pele La Group, which contains the material described herein, belongs to a region containing Palaeozoic rocks that has been termed the Tang Chu or Pele La klippe (Fig. 1b) (Gansser, 1983; Grujic et al. 2006). Several Bhutanese outliers, including the Tang Chu, are reportedly underlain by thrust faults and are thus klippen (Grujic et al. 2006; Kellett, Grujic & Erdman, 2009, but also see Long & McQuarrie, 2010). Details of the relationship between the rocks in the Bhutanese outliers and other parts of the Himalaya have not been investigated to date.

We show herein that the age of the dated Cambrian part of the Pele La Group sedimentary succession is younger than any Cambrian strata known in the western and central Tethyan Himalaya, or in the Lesser Himalaya. The succession is also important in that it is the only Himalayan Cambrian rock bearing body fossils yet known east of the Gori Valley of the Kumaon region of India, over 1000 km to the WNW (Fig. 1). The absence of intervening fossil-bearing Cambrian rocks in the Tethyan Himalaya of Nepal and Tibet is likely to be due to metamorphism, as rocks of this depositional age are present in these regions (Brookfield, 1993; Myrow et al. 2009).

2.b. The Chekha Formation and its stratigraphic relationship to low-grade sedimentary rocks in the Bhutanese outliers

In NW Bhutan, where Chekha (N 27.667°, E 089.217°) is located (Fig. 1b), a sequence of metasedimentary siliciclastic rocks with minor carbonates mapped as the Chekha Series was noted to be in fault contact with the high-grade gneisses of the Thimphu Series (Nautiyal et al. 1964). In the NW margin of this region Chekha Series rocks are mapped as in contact with Tethyan Himalayan rocks, and the Chekha Series is interpreted as the hanging wall of the South Tibetan Fault System (Chakungal et al. 2010, fig. 1a; Long & McQuarrie, 2010, fig. 1). According to this view, the Chekha Series is a Tethyan Himalayan stratigraphic unit. The high-grade Thimphu Series is considered part of the Greater Himalaya (Gansser, 1983; Golani, 1995). Both series were subsequently re-designated as the Thimphu-Chekha Group and divided into the Thimphu Formation and the Chekha Formation (Jangpangi, 1978) (Fig. 2a).

The Tethyan Himalayan succession of Bhutan has not been studied in detail, and so the relationship between the Chekha Formation at its type section

and the sedimentary rocks exposed within the outliers remains unclear. Nevertheless, the map of Nautiyal *et al.* (1964, fig. 1) shows the Chekha Series to be exposed in what has since been recognized as the area containing both the Tang Chu klippe and the Black Mountain outlier. This view has since been extended to include outcrops of the Chekha Formation in all the Bhutanese outliers and in the Tethyan Himalaya (Grujic, Hollister & Parrish, 2002; McQuarrie *et al.* 2008; Chakungal *et al.* 2010; Long & McQuarrie, 2010). In effect, the term 'Chekha Formation' has become the default stratigraphic name for all sedimentary rocks within the outliers unless they are distinguished by the presence of age-diagnostic fossils. The depositional age of the Chekha Formation in these various regions has yet to be constrained.

Nautiyal *et al.* (1964) noted that in the Tang Chu klippe, the Chekha Series was unconformably overlain by bryozoan-bearing limestones of the Tongchu Series. These fossiliferous rocks were referred to the Tethyan sequence by Gansser (1983). It has been suggested that the oldest fossiliferous rocks in any of the outliers are Devonian in age (Termier & Gansser, 1974), and found only in the Tang Chu klippe (Fig. 2a) (e.g. Grujic, Hollister & Parrish, 2002, p. 180).

Others have reported fossils from, and alternative stratigraphic nomenclatures for, older rocks in the Tang Chu klippe (Chaturvedi, Mishra & Mulay, 1983*a,b*; Bhargava, 1995; Tangri & Pande, 1995) (Fig. 2a, b). These schemes have included a stratigraphically re-stricted Chekha Formation that lies at the base of the sequence (Tangri & Pande, 1995). The stratigraphy of the Cambrian rocks that overlie the Chekha Formation (*sensu* Tangri & Pande, 1995) is discussed in the next section.

2.c. Cambrian stratigraphy of the Wachi La succession

This paper focuses on collections from the Pele La Group in the Wachi La region of the Tang Chu klippe which overlie rocks of the Chekha Formation (*sensu* Tangri & Pande, 1995) (Fig. 1b). Initial attempts at chronostratigraphy of these rocks were conducted by Chaturvedi, Mishra & Mulay (1983*a,b*) and revised by Bhargava (1995) and Tangri & Pande (1995) (Fig. 2b). We accept Bhargava's (1995) argument that Chaturvedi, Mishra & Mulay's (1983*a,b*) stratigraphic units were too poorly defined to be acceptable without extensive revision, and we therefore employ the revised scheme of Tangri & Pande (1995), which is based on described type sections (Fig. 2). The basal unit of the Pele La Group is reportedly the Singhi Formation, which consists of rhyolitic/dactic volcanic flows. This is overlain by the quartz sandstone of the Deshichiling Formation, followed by dark shales of the Maneting Formation. The latter is succeeded by the fossiliferous fine-grained siliciclastic Quartzite Formation, which also bears minor beds of white recrystallized limestone. The overlying Wachi La Formation marks the base of the subsequent Tang Chu Group (Tangri & Pande,

1995). The interval from the upper part of the Deshichiling Formation to above the recrystallized carbonate at the base of the Wachi La Formation is exposed in the Wachi La section and is the subject of this report. Stratigraphic heights mentioned below are in metres above the base of the Maneting Formation.

3. Sedimentology

3.a. Description

The Deshichiling Formation consists primarily of white vitreous and grey carbonate-cemented quartz-rich fine sandstone (Fig. 3). Beds are 5–30 cm thick and make up bed sets up to 70 cm thick that are separated by thin shale drapes. There are a few widely spaced, highly cleaved shale beds up to 40 cm thick, but most shale consists of millimetre-thick laminae. Simple bedding-parallel burrows are abundant and exist on most bedding planes. Most of the quartzite is massive, although some weathering surfaces show trough cross-bed sets up to 95 cm thick. Additional sedimentary structures include sporadic shale intraclasts, polygonal desiccation cracks, and small symmetrical ripple marks, which confirm that the section is right-way-up.

The Maneting Formation is poorly exposed along the ridge leading to the Wachi La pass. The lower, poorly exposed part of the formation is approximately 60 m thick and consists of dark shale mostly exposed in float. The remainder of the formation was measured from the first exposures of interbedded shale and sandstone. The lower part consists of dark grey shale with tan weathering, very fine and fine sandstone beds (Fig. 4a). The sandstone beds average 3 cm in thickness and a small percentage of beds are greater than 10 cm thick. These beds have slightly irregular bases and contain abundant parallel lamination and small-scale hummocky cross-stratification. A single bed in float consists of 43 cm of trough cross-bedded fine sandstone.

The Quartzite Formation begins at 147.95 m, at the base of a 68 cm thick unit with three amalgamated hummocky cross-stratified beds. The lower part of the member, from 147.95 m to 201.3 m, consists primarily of variably exposed thin to medium beds (5–15 cm thick) of grey, fine sandstone and minor (< 20 % of thickness) shale. Sandstone beds are massive, parallel laminated and hummocky cross-stratified. From 201.3 m to 263.7 m the member consists of very poorly exposed, amalgamated, fine sandstone with large-scale hummocky cross-stratification throughout.

The interval from 263.7 m to 273.44 m in the formation consists of stacked, very thin- to thin-bedded (1–7 cm thick), grey, fine sandstone with abundant red-weathering siderite spots (weathered carbonate cement). This is interbedded with minor amounts (< 10 %) of green-grey bioturbated shale with thin laminae of very fine sandstone. The laminated sandstone
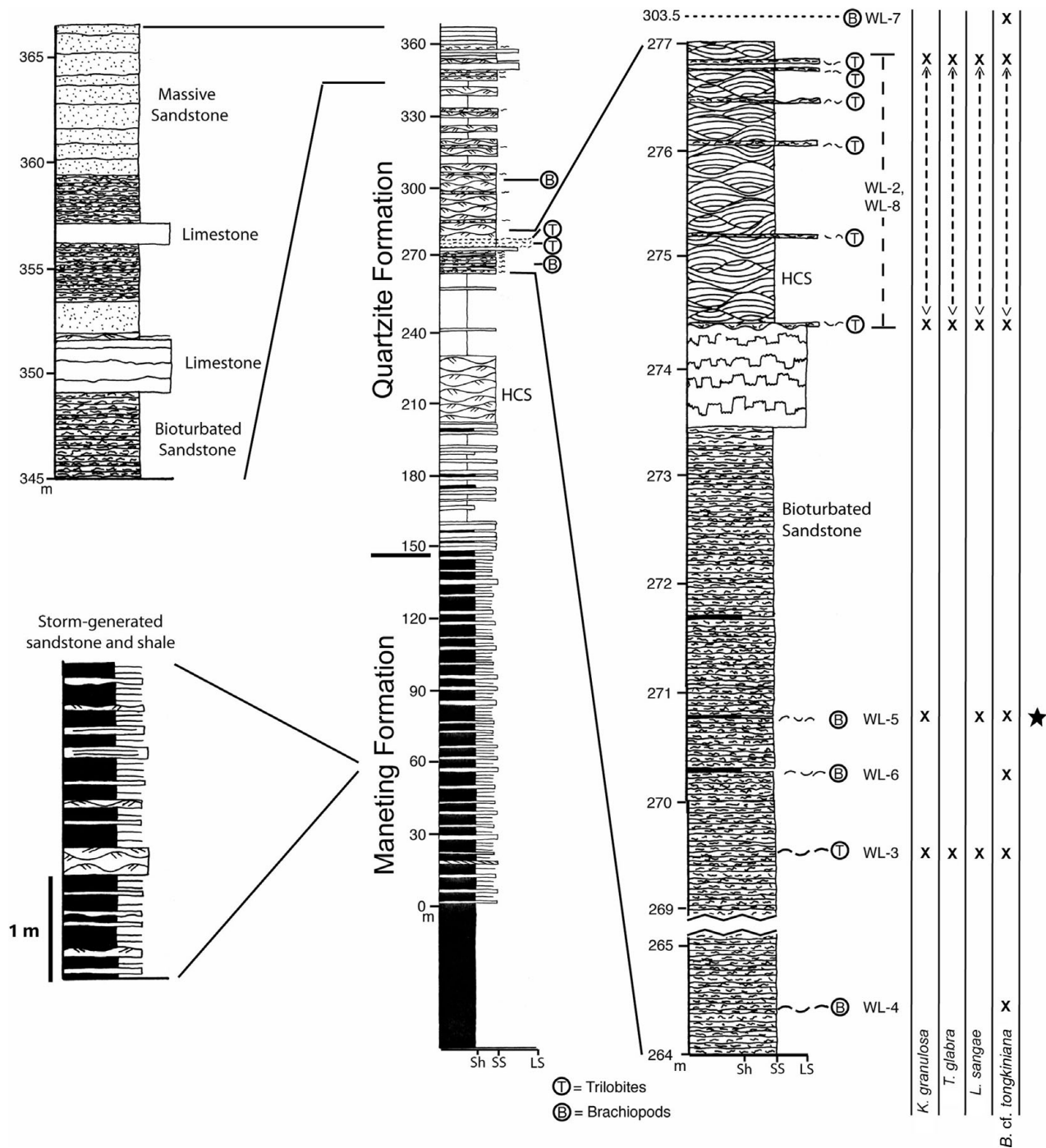
Figure 3. Stratigraphic section for the Maneting and Quartzite formations measured along the Wachi La ridge. Fossiliferous horizons are indicated by T (trilobites) and B (brachiopods). Representatives of both phyla were found in each horizon, but taxon abundance varied with the dominant form in each bed indicated by T or B. The solid star indicates the stratigraphic position of the detrital zircon sample analysed from the Quartzite Formation. The Deshichiling Formation sample was collected below the base of this section.

contains abundant rhynchonelliform brachiopods and some trilobite fossils. Nearly all bedding planes exhibit abundant trace fossils.

A prominent 96 cm thick bed of white-weathering limestone exists at 273.44 m (Fig. 4c). This bed consists of extremely pure, homogeneous, recrystallized limestone with abundant stylolites spaced 1–5 cm apart. Directly above this limestone bed are thick amalgamated beds showing large-scale hummocky cross-stratification (Fig. 4b). The lower two metres

of these strata contain very thin (1–4 cm thick) brachiopod and trilobite coquinites (Fig. 4b, d). A 5 cm thick intraclast conglomerate with abundant trilobite fossils sits within a shallow scour directly on top of the limestone bed (Fig. 4e). The thick amalgamated hummocky cross-stratified deposits are interbedded with units up to 60 cm thick of 1–3 cm thick, burrowed, fine sandstone beds similar in character to those below the prominent limestone bed at 273.44 m. This facies becomes more abundant up-section to 349.05 m.
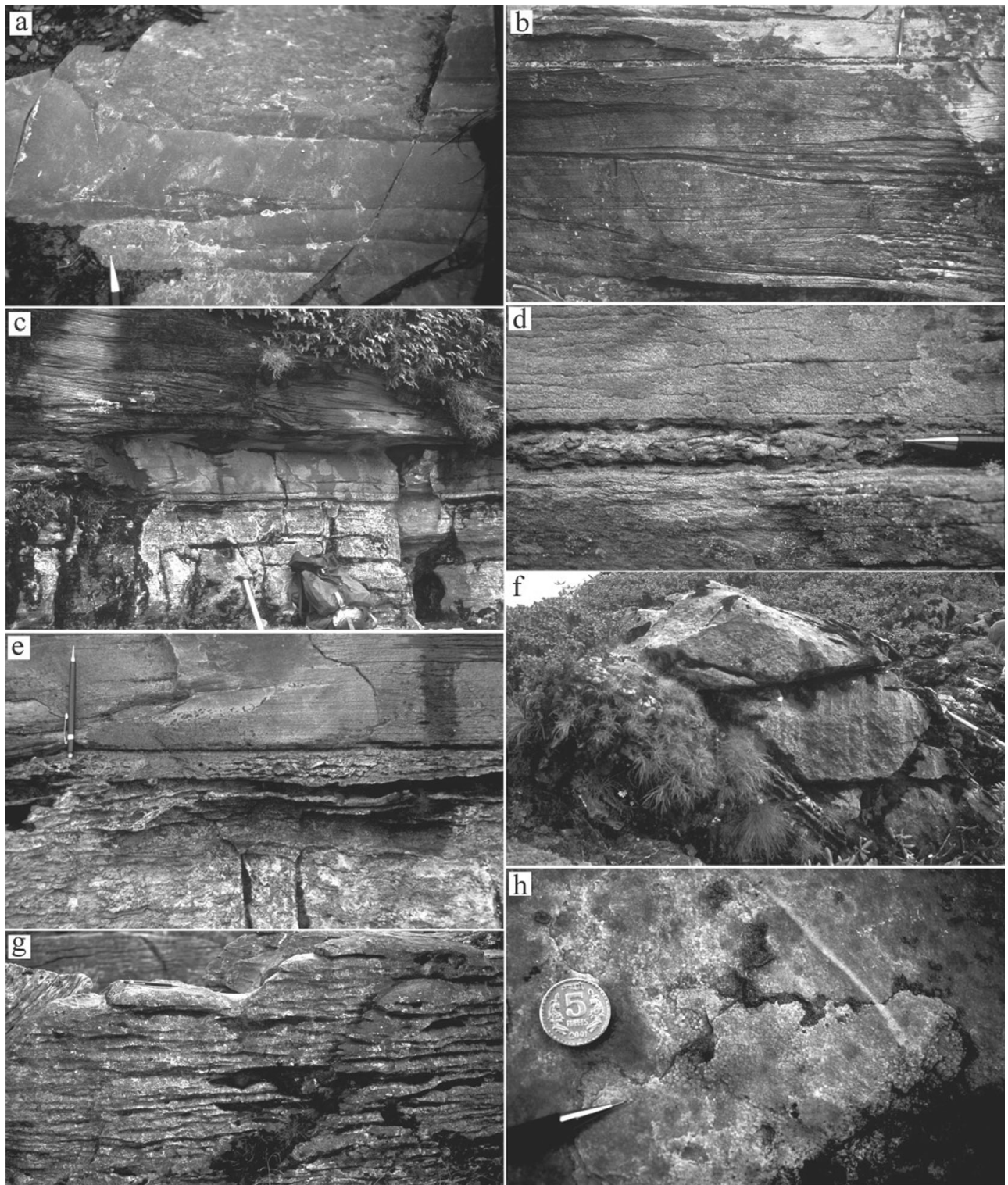
Figure 4. (a) Interbedded graded sandstone and shale from 50 m level in the Maneting Formation, tip of pencil 2 cm long. (b) Well-developed hummocky cross-stratification at ∼ 275 m level in the Quartzite Formation. Note thin trilobite hash bed at base of pencil which is 14 cm long (see d). (c) Thick (96 cm) white weathering recrystallized limestone bed at 273.44 m, and overlying amalgamated hummocky cross-stratified sandstone; hammer about 34 cm long. (d) Two centimetre thick trilobite hash layer within amalgamated hummocky cross-stratified sandstone at 275.2 m; tip of pencil 2 cm long. (e) Thin bed of flat-pebble conglomerate at 274.4 m that rests directly on the white limestone bed in (c); pencil 14 cm long. (f) Bed of blue-grey weathering limestone, 87 cm thick, at 356.2 m; pencil 14 cm long. (g) White limestone above top of Quartzite Formation; pencil 14 cm long. (h) Coral-bearing surface at the top of a limestone bed above the Quartzite Formation, in the Wachi La Formation; tip of pencil 2 cm long; Indian five rupee coin 2.3 cm in diameter.

A second limestone bed exists at 349.05 m and consists of 2.55 m of tan to grey weathering, massive, mottled limestone. Up to 18 cm of brown weathering hummocky cross-stratified fine sandstone and white limestone are interbedded on a cm scale directly above the thick limestone bed. The white limestone beds are
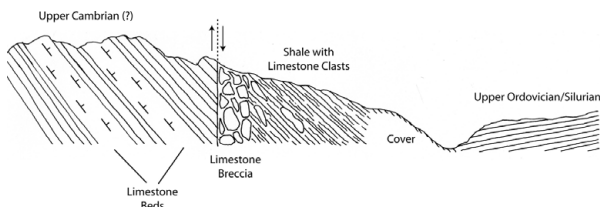
Figure 5. Sketch of the inferred geology of the upper part of the Wachi La section (above about 340 m; see Fig. 3) showing the top of the measured section, a fault with associated fault breccia, and overlying apparently Ordovician carbonate strata with different strike and dip. The fault itself is poorly exposed. The sketch is approximately orientated east–west, with east on the right.

up to 3 cm thick. This is overlain by brown, siderite-mottled, very thin- to thin-bedded (1–7 cm), burrowed fine sandstone, the lower 1.7 m of which contains varying minor amounts of carbonate. At 356.2 m is a 3.27 m thick white, blue-grey weathering limestone bed (Fig. 4f). The lower 87 cm has biohermal mounds with what may be an encrusting stromatoporoid. The rest of the section, up to 366.57 m consists of burrowed, thin-bedded fine sandstone.

The top of the section is defined by a prominent fault that is followed by a series of deformed shale and minor limestone beds and then a covered zone (Fig. 5). Beyond this covered zone are hundreds of metres of reefal limestone (Fig. 4g) deposits with well-preserved corals (Fig. 4h). Time limitations did not allow for a careful study of the younger limestone deposits. The nature of these deposits (colour, texture) is very similar to the thick limestone units at the top of the Quartzite Formation described above.

3.b. Interpretation

Although internal sedimentary structures are not abundant in the Deshichiling Formation, the suite of preserved sedimentary and biogenic structures is consistent with deposition within high-energy shallow marine environments. Symmetrical wave ripples with small wavelengths and desiccation cracks indicate very shallow depths, and the latter episodic subaerial exposure. The paucity of shale indicates that most deposition was above fair weather wave base, that is, metres to a few tens of metres water depth (Komar, 1976).

The lower part of the Maneting Formation, from the base of the shale member to 263.7 m in the measured section, is a large-scale coarsening-up succession. The dominance of parallel lamination and hummocky cross-stratification indicates that the shoreline was subjected to powerful storm events (Dott & Bourgeois, 1982; Brenchley, 1985; Myrow & Southard, 1996). The upward-coarsening stratigraphic trend from shale to interbedded sandstone and shale to amalgamated sandstone reflects shoaling. The facies trends and the thickness of the succession are typical of prograding storm-dominated shoreline deposits (Walker, 1984;

Myrow *et al.* 2006*b*). The loss of shale and transition into amalgamated hummocky cross-stratified beds records shallowing into a shoreface environment (Hamblin & Walker, 1979; Walker, 1984).

The transition into the first occurrence of the burrowed, thin-bedded sandstone facies is difficult to interpret. The presence of marine fauna and abundant trace fossils indicates deposition in a marine environment. The presence of a small number of thin shale beds within this sandstone-rich facies suggests deposition in the lower shoreface transition zone (Midtgaard, 1996). This environment is also consistent with the abundance of burrows (Pemberton & MacEachern, 1995). A shift to a lower shoreface setting would reflect a minor transgression relative to amalgamated, thicker-bedded hummocky cross-stratification. The sudden introduction of abundant burrows and the thinner bedding may reflect a decrease in sedimentation rate and/or intensity of storms, both of which may have accompanied relative sea level rise. The sharp transition into pure limestone certainly reflects a dramatic decrease in the influx of siliciclastic sediment. Unfortunately, the processes of deposition for any of the limestone beds are difficult to interpret because of the near total lack of preservation of physical and biogenic features, with the exception of small bioherms at 356.2 m. The rapid transition into amalgamated hummocky cross-stratified beds above the first limestone bed is a rather unusual facies transition that indicates a shift back to a storm-dominated shoreface environment. The very thin to thin beds of trilobite and brachiopod coquinas above the limestone bed at 263.7 m represent thin fossil lags produced by fair-weather waves or storm waves (Brenner & Davies, 1973; Kidwell, 1991), and may represent concentration along minor transgressive surfaces of erosion or ravinement surfaces (Myrow, 1998).

The thicker limestone beds at the top of the section are interbedded with the burrowed, thin-bedded sandstone facies. The prominent mound shapes and the presence of reef-building marine fossils indicate that these are boundstone deposits. Once again, the shift to relatively pure carbonate deposits reflects a sharp decrease in siliciclastic deposition. As with the bed at 263.7 m, the change from shoreface sandstone to pure limestone is an unusual facies transition. Limestone beds of older Cambrian age exposed along strike in the Spiti Valley of northern India occur at the top of upward-coarsening and -shoaling deltaic cycles as a result of the sudden reduction of sediment input during fluvial avulsion events (Myrow *et al.* 2006*a,b*). Sandstone dominated shoreface deposits are almost invariably associated with shaly nearshore deposits (that is, below fair-weather wave base). Thus, the sharp upper and lower stratigraphic transitions with sandstone of possible lower shoreface origin suggests that the carbonate formed and disappeared as a facies, instead of existing long-term as a facies belt that migrated as a result of changes in relative sea level.

4. Systematic palaeontology

We describe a new trilobite and rhynchonelliform brachiopod fauna collected from horizons within a 40 metre stratigraphic interval within the Quartzite Formation along the Wachi La ridge (Fig. 3) in September 2002. The fossils described herein were all collected from red weathering fine-grained sandstone. Each collection was distinguished by the collection number WL-no., the number corresponding to the section height in metres, Global Positioning System coordinates and approximate altitude: WL-2, at 274.40–276.05 m, N 27°24.100′, E 090°17.575′, 4133 m altitude; WL-3, at 269.54 m, N 27°24.090′, E 090°17.617′, 4136 m altitude; WL-5, at 270.75 m, N 27°24.153′, E 090°17.525′, 4132 m altitude; and WL-8, at 274.40–276.05 m, N 27°24.035′, E 090°17.593′, 4111 m altitude. Chaturvedi, Mishra & Mulay (1983*a*,*b*, fig. 1 in both publications) provided a basic geological map for the region. The trilobite taxonomy is by Ryan McKenzie and Nigel Hughes and the new taxon should be attributed to those authors. The brachiopod taxonomy is by David Harper and Ryan McKenzie. Specimens are housed in the type collection of the Royal Bhutan Department of Geology and Mines/Geological Survey of Bhutan (GSB).

Phylum ARTHROPODA
Class TRILOBITA
Order CORYNEXOCHIDA Kobayashi, 1935
Suborder LEIOSTEGIINA Fortey, 1997
Superfamily LEIOSTEGIOIDEA Bradley, 1925
Family KAOLISHANIDAE Kobayashi, 1935

This family of leiostegiinid trilobites bears a single pair of prominent pygidial spines associated with the posterior band of the anteriormost pleural segment of the holaspid pygidium (Kobayashi, 1956, p. 12).

Genus *Kaolishania* Sun, 1924

Type species. *Kaolishania pustulosa* Sun, 1924 (p. 52, pl. 3, fig. 8a–h); from the *Kaolishania* Zone, Changshan Formation, Haolishan, Taian, Shandong province, China.

Species assigned. *Kaolishania granulosa* Kobayashi, 1933 (p. 104, pl. 11, figs 15, 16) from *Kaolishania* Zone, Paichiashan, Liaoning Province, China; *Kaolishania yunnanensis* Sun & Xiang, 1979 (p. 7, pl. 1, figs 1, 2) from the upper Cambrian Liushui Formation, Lijiasi, Baoshan, Yunnan; *Parakaolishania brevica* Sun & Xiang, 1979, (p. 8, pl. 1, figs 4–9) from the upper Cambrian Liushui Formation, Huajiaosi, Pupiao, Baoshan, Yunnan. Other species currently assigned to the genus are discussed below.

Diagnosis. Trapezoidal cranidium of high relief with pustulose ornament. Glabella trapezoidal with four pairs of lateral furrows, terminating in firmly incised anterior border furrow behind long (sag.), upturned anterior border. Fixigenae broad (tr.). Librigena with long (exsag.) genal spines diverging abaxially toward posterior. Librigenal lateral border furrow not confluent with posterior border furrow. Pygidium semi-elliptical with five or more axial rings with prominent relief, firmly incised pleural furrows, and a pair of large macropleural spines associated with the posterior band of the anteriormost pleurae.

Kaolishania granulosa Kobayashi, 1933
Figures 6a–j, 7a–h, 12a

1933 *Kaolishania?* granulosa Kobayashi, pp. 103–5, pl. 11, figs 19, 20.
1935 *Kaolishania granulata* Kobayashi, pp. 175–7, pl. 8, figs 9–11; pl. 9, figs 14, 15 (*nomen dubium*).

1935 *Kaolishania obsolata* Kobayashi, pp. 177–8, pl. 9, fig. 16.
1937 *Paramansuyella granulosa* Endo *in* Endo & Resser, p. 359, pl. 70, figs 1–9.
1956 *Kaolishania granulosa* Kobayashi; Kobayashi, p. 13.
1960 *Kaolishania granulosa* Kobayashi; Kobayashi, pp. 355–6; pl. 20, figs 8–12, pl. 21, fig. 14.
1960 *Kaolishania*? *latiura* Kobayashi, p. 356, pl. 21, fig. 19.
1965 *Kaolishania granulosa* Kobayashi; Lu *et al.*, p. 422, pl. 81, figs 5, 6.
1980 *Kaolishania granulosa* Kobayashi; Nan, p. 506, pl. 207, figs 2–5.
1983*a* ?*Prosopiscus* sp. or ?*Annamitella* sp.; Chaturvedi, Misra & Mulay, p. 236, pl. 2, figs 1, 3, *non* fig. 2.
1983*b* ?*Prosopiscus*; Chaturvedi, Misra & Mulay, p. 236, pl. 2, figs 1, 3, *non* fig. 2.
1994 *Kaolishania granulosa* Kobayashi; Qian, p. 119.
1995 Trilobite remains; Tangri & Pande, p. 134, figs 3.10.37–40.
1995 Kaolishaniids/pagodiids; Bhargava, p. 187, figs 5.2.9, 5.2.11.
2002 *Prochuangia;* Hughes, Peng & Luo, p. 714 (discusses figured material of Bhargava, and Tangri & Pande).
2005 *Kaolishania granulosa* Kobayashi; Duan *et al.*, p. 27.

Type material. Holotype fragmentary cranidium, Kobayashi (1933, pl. 11, figs 19, 20), *Kaolishania* Zone, Paichiashan, Liaoning Province, China.

Bhutanese material. Twelve cranidia from WL-2 (GSB46, GSB47), WL-3 (GSB45) and WL-8 (GSB12, GSB13, GSB14, GSB15, GSB16, GSB17, GSB18, GSB48, GSB49); four librigenae from WL-2 (GSB19, GSB51), WL-3 (GSB20) and WL-8 (GSB50); and fourteen pygidia from WL-2 (GSB23, GSB52, GSB53, GSB54, GSB58, GSB59), WL-3 (GSB21) and WL-8 (GSB22, GSB24, GSB25, GSB26, GSB55, GSB56, GSB57) from the Quartzite Formation, Wachi La section, Black Mountains, Bhutan.

Diagnosis. *Kaolishania* with pygidium semi-elliptical bearing five well-defined axial rings and terminal piece, pleural furrows firmly impressed with four pleural ribs and a pair of long (exsag.), posteriorly divergent marginal spines.

Description. Pustulose cranidium with length (sag.) approximately 50 % of width (tr.) at posterior border. Glabellar length (sag., including occipital ring) about 80 % of total cranidial length (sag.), tapering gently anteriorly, with rounded anterolateral corners and transverse anterior margin. Axial furrow firmly incised, shallowing slightly anteriorly, confluent with four pairs of lateral glabellar furrows. SO long (sag.), transverse, deeply incised abaxially, shallower medially, confluent with axial furrow. S1 deeply incised abaxially, obsolete in medial glabellar third, oblique rearward at approximately 45° angle to sagittal axis, bifurcate in adaxial most portion in some specimens; S2 transverse or oblique posteriorly at low angle (tr.), shorter (exsag.) than S1, crossing one third of glabellar width; S3 faint, transverse, crossing one quarter of glabellar width. L1 subtriangular abaxially. LO width (tr.) of similar width to posterior of L1 (tr.), bearing tiny medial node. Anterior margin of LO bowed slightly forward medially. Preglabellar furrow long (sag.). Anterior border about 15 % of cranidial length (sag.), convex dorsally, with steep posterior margin,
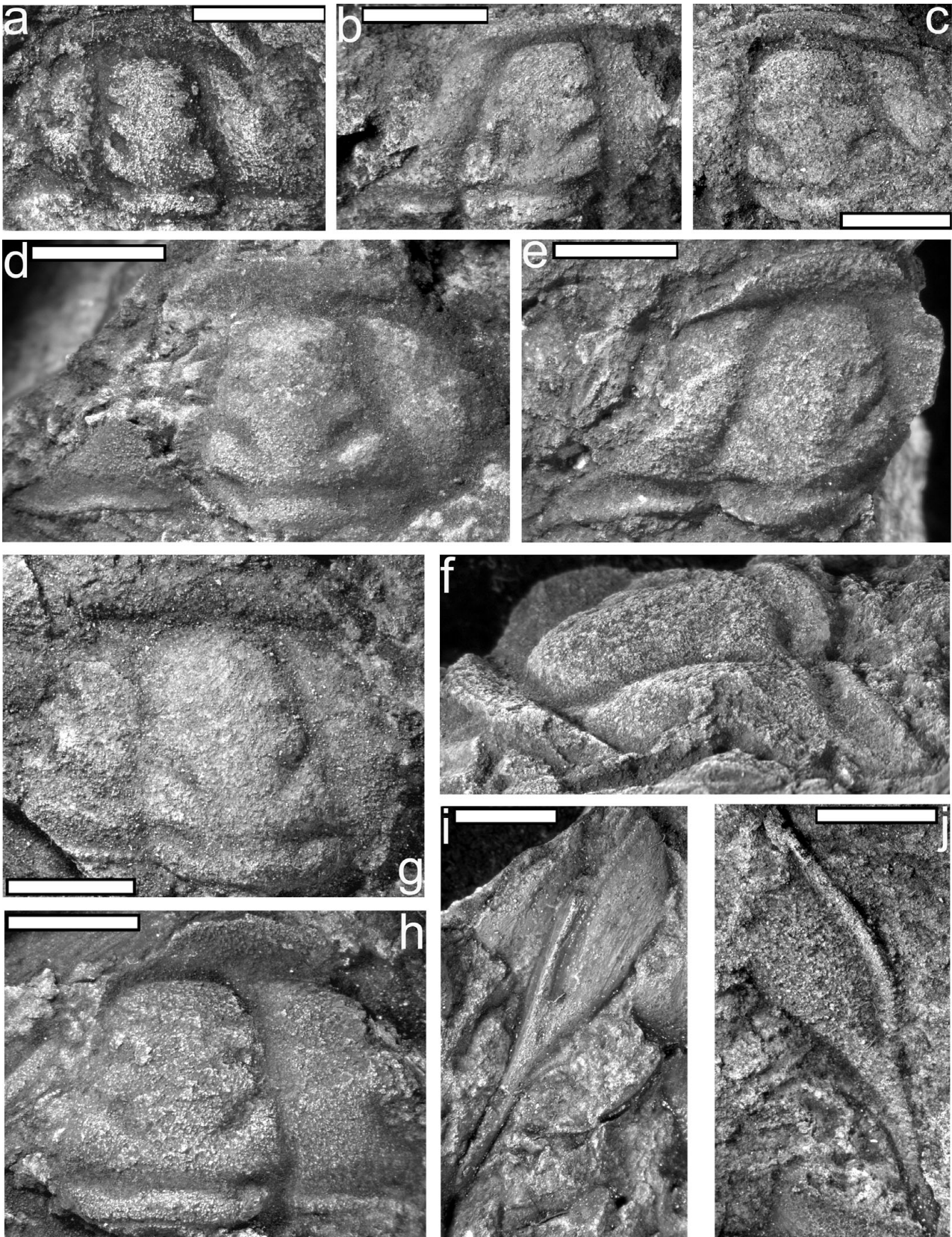
Figure 6. Cephalic sclerites of *Kaolishania granulosa* Kobayashi from the Quartzite Formation, Wachi La section, Bhutan. All specimens are coated with ammonium chloride sublimate prior to digital photography, specimens are internal surfaces of moulds unless otherwise stated. White scale bar is 5 mm long. (a) GSB12, partial cranidium. (b) GSB13, partial cranidium. (c) GSB14, partial cranidium. (d) GSB15, partial cranidium. (e, f) GSB16, partial cranidium; (e) dorsal view; (f) oblique view. (g) GSB17, partial cranidium. (h) GSB18, partial cranidium. (i) GSB19, librigena. (j) GSB20, librigena.
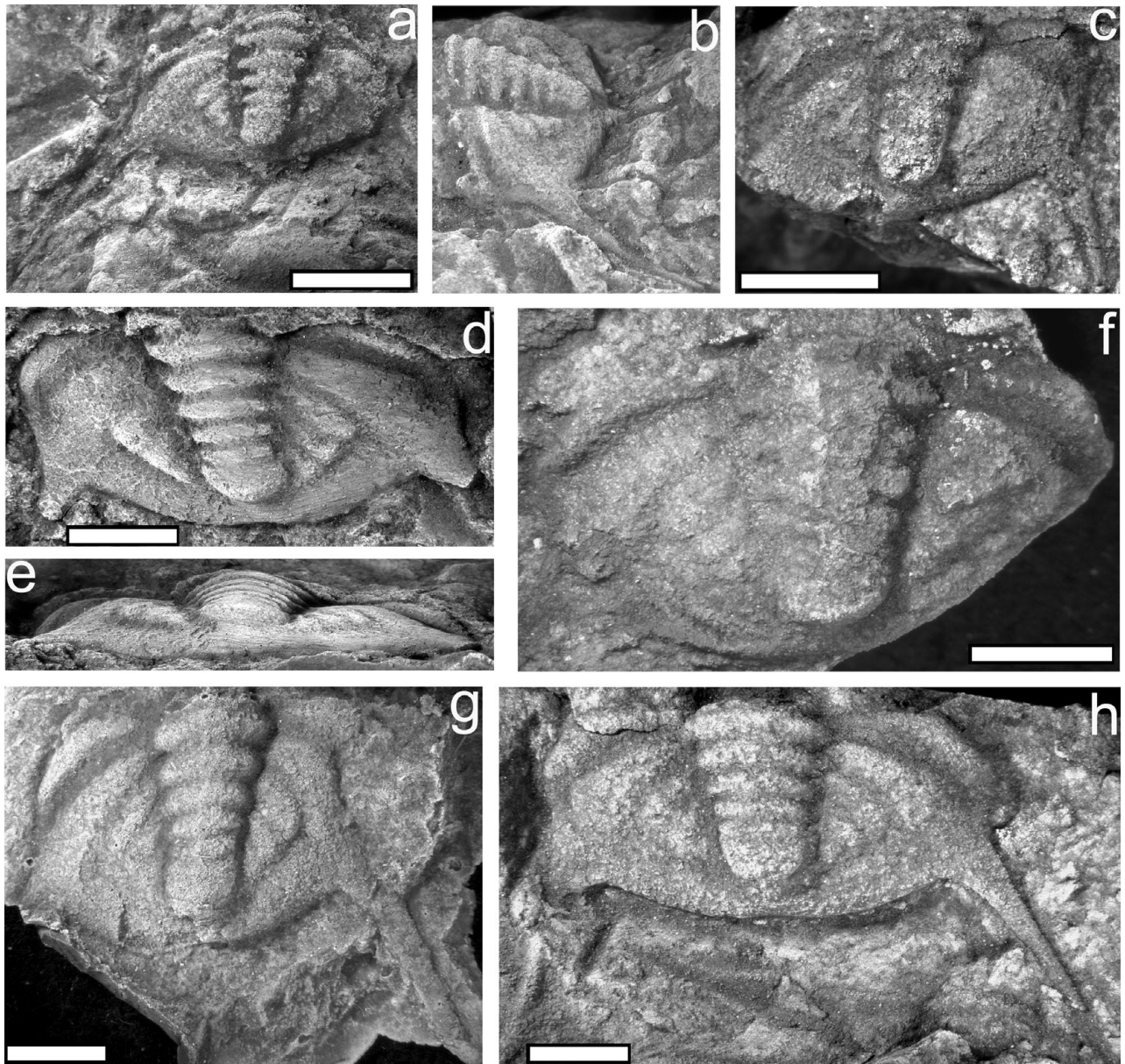
Figure 7. Pygidia of *Kaolishania granulosa* Kobayashi from the Quartzite Formation, Wachi La section, Bhutan. All specimens coated with ammonium chloride sublimate prior to digital photography, specimens are internal surfaces of moulds unless otherwise stated. White scale bar is 5 mm long. (a, b) GSB21; (a) dorsal view, (b) lateral-oblique view. (c) GSB22. (d, e) GSB23; (d) dorsal view, (e) posterior view. (f) GSB24. (g) GSB25, latex cast. (h) GSB26.

lengthening (sag.) medially. Ocular ridge oriented oblique rearward and outwards at about 20° angle to transverse axis, originating approximately opposite anterior of S3. Palpebral lobe small, about 20 % of glabellar length, elevated, with anterior opposite S2 and posterior opposite S1. Palpebral fixigenal width (tr.) 50 % of glabellar width at palpebral area midlength. Preocular fixigenae widest opposite L3, truncated sharply by anterior border furrow. Posterior lateral border furrow firmly incised, lengthening (exsag.) abaxially. Preocular dorsal suture diverges slightly (exsag.) immediately anterior of palpebral lobe, then converges gently forward; postocular suture defines triangular posterior border.

Librigenal field slopes down into firmly incised lateral border furrow that is isolated from posterior border furrow by convex, ridge-like extension of librigenal field that extends from anterior portion of genal spine base. Lateral border inflated, rim-like. Posterior border short (exsag.), with firmly incised posterior border furrow that tapers into posterior of genal spine base. Genal spine broad (tr.) and straight sided, divergent from sagittal axis posteriorly, slightly less than length of the remainder of the librigena (exsag.).

Pygidium semi-elliptical with length (sag.) about 50 % of maximum width (tr.), excluding spines. Axis tapers gently posteriorly with anterior width (tr.) about 30 % of maximum pygidial width (tr.) and five firmly incised axial rings plus a bulbous terminal piece with possible additional ring furrow evident in some specimens. Articulating half ring short (sag.). Terminal piece longer (sag.) than anteriormost ring, with round posterior margin. Anterior band of anteriormost pleural segment short (exsag.), lengthening abaxially beyond distinct fulcrum. Anteriormost pleural furrow wide (tr.) and long (exsag.) with steep margins, long (exsag.) almost reaching pygidial margin. Posterior band of first pleural segment inflated abaxially, extending into long, posteriorly and abaxially directed, straight sided, marginal spines. In

smaller specimens spine length (exsag.) roughly equal to pygidial width (tr.), and in larger specimens spine length is roughly equal to one half of pygidial width (tr.). Pleural field of subsequent segments crosses about half of pleural width, and traversed by four obliquely directed pleural furrows. Pleural field terminates at sharp, steep, break of slope separating pleural platform from flat border. Edge of pleural platform intersects terminal piece margin. Pygidial margin with slight emargination postaxially.

Discussion. Specimens from Wachi La have been subject to tectonic deformation, with specimens whose sagittal axis was at low angles to the principal extension direction becoming relatively elongated (Figs 6a, 7g), while those with sagittal axes at high angles to the principal extension direction have become tectonically shortened (Figs 6d, 7h). This deformation notwithstanding, species-specific characteristics are evident from this material. The reconstruction of the species (Fig. 12a) is based on a consideration of type and other non-Bhutanese material assigned to the species, in addition to our new specimens.

Several specimens previously illustrated from the Wachi La belong to this species. One cranidium and one partial thoracopygon from the Wachi La section may belong to this species, but they are poorly illustrated and their assignment is uncertain (Chaturvedi, Mishra & Mulay, 1983a,b, pl. 2, figs 1, 3). Better-illustrated material that certainly belongs to this taxon has also been figured (Bhargava, 1995; Tangri & Pande, 1995).

Kaolishania granulosa can be assigned to the genus with confidence, but other assignments are less secure. This is because either the material differs markedly from the forms of *K. pustulosa* and *K. granulosa*, or because the material is poorly preserved. The type material of *Kaolishania granulosa* is distinguished from *Kaolishania pustulosa* by its possession of larger pustules (Kobayashi, 1933, p. 104). While the holotype is poorly preserved, subsequent work by Kobayashi (1935, 1956, 1960) expanded documentation of the species and added further illustrations, and our assignment of the Bhutanese material to *K. granulosa* is based on comparison with Kobayashi's additional material from North China and Korea.

The difference in pustule size of *K. pustulosa* and *K. granulosa*, while apparent in well-preserved material, is not a reliable character for species identification in all cases. The relatively coarse grain size of the Bhutanese specimens prohibits preservation of surficial ornament. Secondly, variation in pustule size or presence can be ontogenetic in some trilobites (e.g. Hughes, 1994). Other characters more useful for differentiating *K. granulosa* from *K. pustulosa* are the more semicircular pygidium of *K. pustulosa* with more firmly incised pleural furrows, which show five pleural ribs and six or seven axial rings in well-preserved specimens with a terminal piece, whereas *K. granulosa* exhibits only four pleural ribs and five axial rings with an undivided terminal piece. The pygidial spines in *K. pustulosa* run sub-parallel to the axis, whereas the pygidial spines in *K. granulosa* are more strongly abaxially divergent posteriorly. Abaxial expansion of the posterior border furrow is more pronounced in *K. granulosa* than in *K. pustulosa*.

Kobayashi (1933, pl. 11, figs 15, 16) erected *Kaolishania obsolata* based on a fragmented cranidium and pygidium. Neither of these sclerites possesses characters diagnostic of *Kaolishania*, as both cranidium and pygidium are effaced, the cranidium has a narrow fixed cheek, and the pygidium bears only three axial rings. Kobayashi (1935, pl. 9, figs 16–18) illustrated three additional fragmentary cranidia that he assigned to *K. obsolata*, but it is difficult to identify character

states from the poor quality of the illustrations. The specimen figured as Kobayashi's (1935, pl. 9, fig. 16) is pustulated with a trapezoidal glabella with three furrows and an anterior border comparable to *K. granulosa*, whereas specimens in his plate 9, figures 17 and 18 have weakly impressed furrows or lack them entirely, narrow fixigenae, and longer, more pointed anterior borders that differ from the condition in *Kaolishania*.

Kaolishania latiura (Kobayashi, 1960) was defined by a single pygidium that we consider similar to that of *K. granulosa*, and we treat *K. latiura* as a junior synonym of *K. granulosa*. Kobayashi (1960) assigned *Teinistion* sp. indet. Walcott (1913, pl. 9, fig. 4) to *K. granulosa*. Subsequently, Zhang & Jell (1987) reassigned that specimen to *Mansuyia* without discussion of Kobayashi's (1960) reassignment. We concur that this specimen does not belong within *Kaolishania* due to the elliptical shape of the pygidium.

Resser (1942) distinguished the new species *Kaolishania hopeiensis* from a suite of specimens that Sun (1935, pl. 2, figs 25–29) had assigned to *K. pustulosa*. The two cranidia that Sun (1935) figured do not show differences of likely taxonomic import, and the single pygidium illustrated shows as many as seven axial rings, five pleural ribs and rather weakly divergent pygidial spines, all of which suggest *K. pustulosa*. In our opinion the slight variation in cranidial length and pygidial width noted by Resser (1942) does not warrant recognition of a new species, especially when the small sample size is considered. Thus we concur with the opinion of Lu *et al.* (1965, p. 422) that *Kaolishania hopeiensis* is a synonym of *K. pustulosa.*

Zhang & Wang (1985) established three new species, *K. yanshanensis*, *K. pingquanensis* and *K. dongyushanensis*, all from fragmentary material. *Kaolishania pingquanensis* was based on a single poorly preserved pygidium that might belong to one of several kaolishaniid genera. *Kaolishania dongyushanensis* was based on deformed material with a single cranidium weakly resembling *Kaolishania*. However, the pygidia figured contain eight axial rings plus a terminal piece, six pleural furrows and no preserved pygidial spines, all features that differ from other species of *Kaolishania*. Without clear evidence of pygidial spines we consider assignment to *Kaolishania* to be unconfirmed.

The pygidium of *K. yanshanensis* is nearly identical to that of *K. pustulosa*, whereas the figured cranidium (Zhang & Wang, 1985, pl. 140, fig. 5) is similar to that in *Kaolishania cylindrica,* a species previously established by Guo & Duan (1978). Duan *et al.* (2005) erected a new species also called *Kaolishania yanshanensis* that is broadly similar to *K. yanshanensis* Zhang & Wang 1985, although the Duan *et al.* (2005) species is largely effaced with weakly incised glabellar furrows and large pustules. *Kaolishania yanshanensis* Duan is a junior homonym of *K. yanshanensis* Zhang & Wang, but it is unclear whether it is also its junior synonym. All three of these species, *K. cylindrica* Guo & Duan, *K. yanshanensis* Zhang & Wang, *K. yanshanensis* Duan, have highly convex cranidia with short anterior borders and parallel-sided glabellae, and these features differ from the condition in typical *Kaolishania*. Both *K. cylindrica* and *K. yanshanensis* Duan also possess larger palpebral lobes than those of other *Kaolishania* species, and *K. cylindrica* contains particularly deeply incised bifurcate S1 glabellar furrows. All these features resemble *Eokaolishania* (Wittke, 1984; Zhu & Wittke, 1989). Duan *et al.* (2005, p. 34) listed another new species, *Kaolishania funingensis*, in a stratigraphic column but provided no description or illustrations of this species, which is thus *nomen nudum*.

Kaolishania laevigata was erected based on a single quite poorly preserved pygidium that is kaolishaniid (Qian, 1994).

It has only four axial rings, but we do not think that this single specimen warrants the recognition of a new species. Rather we restrict this name to this specimen pending the recovery of more material.

The species *Kaolishania megaspina* has been recognized from South China (Zhou *et al.* 1977) and was based on a single thoracopygon. This specimen differs from species of *Kaolishania* by having extremely long pygidial spines. Although the form of the pygidium is kaolishaniid, the lack of an associated cranidium precludes confident assignment of this species to *Kaolishania*.

Two other species have been described from western Yunnan by Sun & Xiang (1979), and these are *Kaolishania yunnanensis* and *Parakaolishania brevica*, which was reassigned to *Kaolishania* by Shergold, Laurie & Shergold (2007). Effacement of the glabellar furrows in *K. yunnanensis* and *K. brevica* distinguish these species from *K. pustulosa* and *K. granulosa*, and in this respect they resemble the cranidia of *Peichishania* species, but both species are poorly known.

Shergold (1972) erected *Kaolishania australis* from the Gola Beds of western Queensland. Cranidia of this species differ from those of *Kaolishania granulosa* and *K. pustulosa* by possessing two pairs of isolated glabellar furrows and in having a very short anterior border. Shergold (1972, p. 51) acknowledged that the pygidia assigned to this species may not be correctly associated with the cranidia, and while the 'meraspid' pygidia figured (Shergold, 1972, pl. 21, figs 1, 3, 4) are generally similar to those of kaolishaniids except in the smaller number of axial rings, the single illustrated holaspid pygidium (Shergold, 1972, pl. 21, fig. 2) apparently has spines with a wider base than typical of other *Kaolishania* species. The cranidia of *Kaolishania clarkensis* Shergold, Laurie & Shergold, 2007 from the Clark Sandstone of the Bonaparte Basin in NW Australia differ from the generic concept of *Kaolishania* by having a conical glabella with a rounded anterior end, a largely effaced cranidium with only faint S1, and a short, narrow anterior border. If it belongs within *Kaolishania,* it is quite different from the typical species *K. pustulosa* and *K. granulosa*.

In summary, two species *K. pustulosa* and *K. granulosa* can be assigned with confidence to the genus. Other putative members of the genus for which reasonably well-preserved material is available, such as *K. clarkensis, K. australis* and *K. cylindrica,* are distinctly different. Most other putative species are either likely synonyms of either *K. pustulosa* and *K. granulosa* or are too poorly know to be further evaluated.

Family TSINANIIDAE Kobayashi, 1935

Taipaikia has consistently been placed within this family of large, effaced trilobites (Kobayashi, 1960; Jell & Adrain, 2003; Zhu, 2008). Although recent discussions have varied greatly in their assessment of tsinaniid affinities, we now consider the group to comprise large, effaced leiostegiinid trilobites with an extended preglabellar field (Zhu, Hughes & Peng, 2010). Fortey (1997) placed Tsinaniidae in Illaenina based on the presence of the lunettes, and this may be appropriate if the tsinaniid bacculae are indeed homologous with lunettes. Zhu, Hughes & Peng (2007) noted that *Taipaikia* differed from other tsinaniids in the more abaxial position at which the facial suture intersects the anterior margin. In other respects *Taipaikia* closely resemble other tsinaniids.

Genus *Taipaikia* Kobayashi, 1960

1960 *Taipaikia* Kobayashi, p. 398.
1965 *Taipaikia* Kobayashi; Lu *et al.,* p. 344.

1980 *Taipaikia* Kobayashi; Nan, p. 501.
2003 *Taipaikia* Kobayashi; Jell & Adrain, p. 450.
2005 *Taipaikia* Kobayashi; Duan *et al.*, p. 171.
2007 *Taipaikia* Kobayashi; Zhu, Hughes & Peng, p. 248.
2008 *Taipaikia* Kobayashi; Zhu, pp. 140, 160, table 6.1.

Type species. Paramansuyella glabra Endo *in* Endo & Resser, 1937, Changshan Formation, China.

Diagnosis. Effaced cranidium with long (sag.), concave frontal area with anterior branch of facial suture running abaxially anterior of the palpebral lobe, then sweeping adaxially in open curve to intersect anterior margin in front of fixigena. Glabellar conical with weakly incised anterior margin. Posterior border furrow and SO firmly incised. Posterior lateral margin of LO pit-like. Isopygous with convex, semicircular pygidium with distinct pleural facet, axis tapering posteriorly, border broad, flattened with broad doublure.

Taipaikia glabra (Endo *in* Endo & Resser, 1937)
Figures 8a–h, 9a–g, 10a–d, 12b

1937 *Paramansuyella glabra* Endo *in* Endo & Resser, p. 358, pl. 69, fig. 21, *non* 22 (= ?*Kaolishania*).
1952 *Mansuyia? glabra* (Endo); Kobayashi, p. 148, pl. 20, fig. 18.
1960 *Taipaikia glabra* (Endo); Kobayashi, p. 398, pl. 20, fig. 18, pl. 21, figs 20, 21.
1965 *Taipaikia glabra* (Endo); Lu *et al.,* p. 344, pl. 64, fig. 14.
1980 *Taipaikia glabra* (Endo); Nan, p. 501, pl. 25, figs 5–8, 25.
?1995 Trilobite remains Tangri & Pande, p. 134, fig. 3.10.6.
2005 *Shergoldia yanshanensis* Duan *in* Duan *et al.*, p. 170, pl. 34, figs 12, 13.
2005 *Taipaikia glabra* (Endo); Duan *et al.*, p. 171, pl. 34, figs 4–8, pl. 53, fig. 9.
2008 *Taipaikia glabra* (Endo); Zhu, p. 160.

Type material. Holotype cranidium Endo *in* Endo & Resser, 1937, pl. 69, fig. 21, Changshan Formation, *Kaolishania* Zone, Paichiashan, Liaoning Province, China.

Bhutanese material. Five cranidia from WL-2 (GSB27, GSB28, GSB60, GSB62), WL-8 (GSB61); four librigena from WL-2 (GSB29, GSB31), WL-3 (GSB63), WL-8 (GSB30); and six pygidia from WL-2 (GSB33, GSB36) and WL-8 (GSB32, GSB34, GSB35, GSB37) from the Quartzite Formation, Wachi La section, Black Mountains, Bhutan.

Diagnosis. As for genus, monotypic.

Description. Effaced cranidium of moderate relief, length (sag.) about 75 % of width (tr.) at posterior border. Glabella conical, low relief, tapering slightly and evenly anteriorly, about 75 % of cranidial length (sag.). SO entire, firmly incised, shallowing abaxially but confluent with axial furrow and of even length (sag.), preoccipital glabellar furrows absent. Axial furrow moderately incised posteriorly, shallow anteriorly, preglabellar furrow absent, with anterior end of glabella sloping into concave frontal area. Posterior border furrow moderately well incised. Posterior of LO meets axial furrow in depressed, pit-like node. Ocular ridge straight, short (exsag.), extending from glabellar anterior lateral margin to the anterior of palpebral lobe at an angle of about 45° to transverse axis. Palpebral lobe approximately 20 % of cranidial length (sag.), oriented at about 30° to sagittal axis with rearward divergence, posteriorly positioned
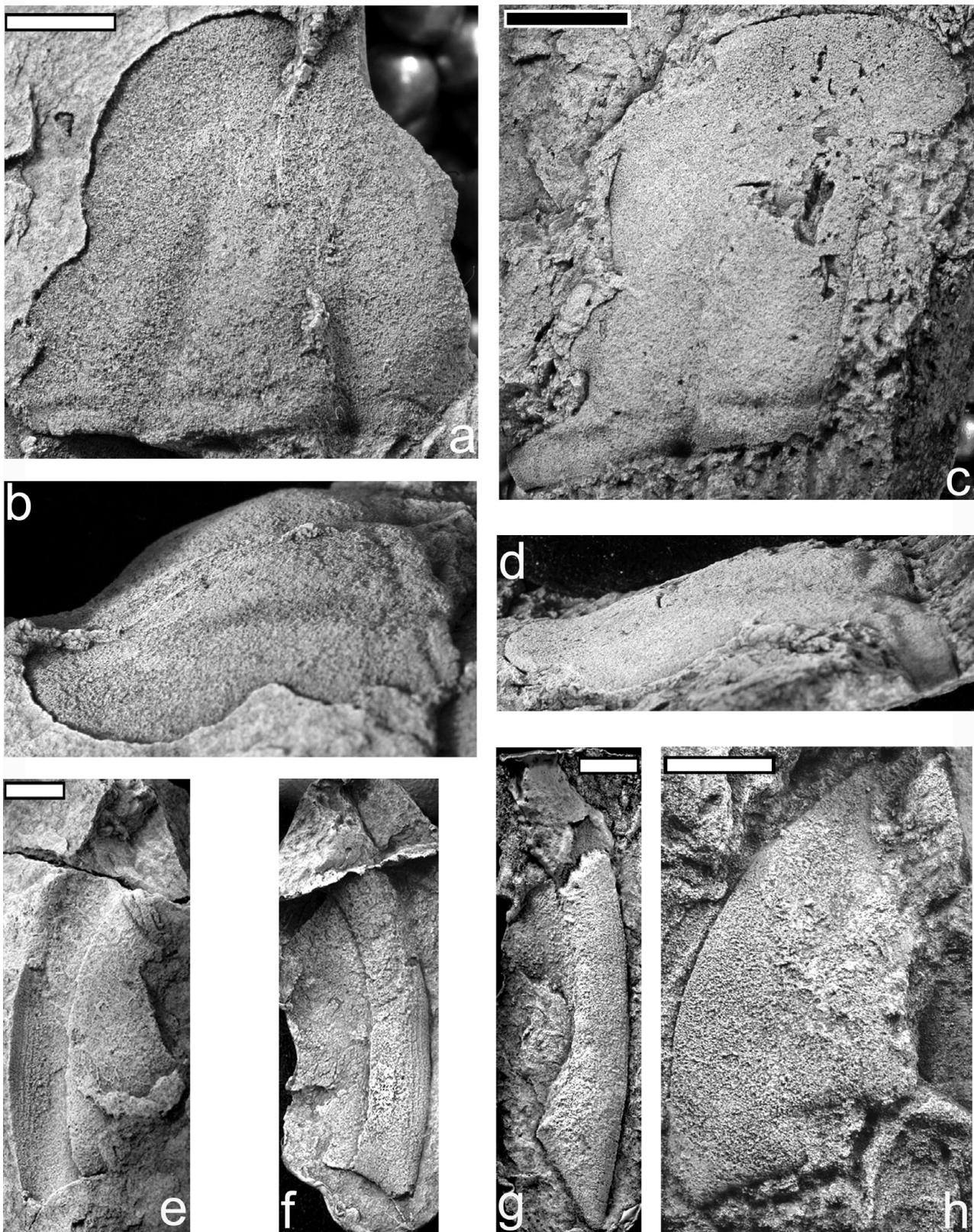
Figure 8. Cephalic sclerites of *Taipaikia glabra* (Endo) from the Quartzite Formation, Wachi La section, Bhutan. All specimens are coated with ammonium chloride sublimate prior to digital photography, specimens are internal surfaces of moulds unless otherwise stated. White scale bar is 5 mm long, black scale bar is 10 mm long. (a, b) GSB27, partial cranidium; (a) dorsal view; (b) oblique view. (c, d) GSB28, partial cranidium; (c) dorsal view; (d) lateral view. (e, f) GSB29, ventral doublure of librigena; (e) external mould; (f) latex cast. (g) GSB30, ventral doublure, latex cast. (h) GSB31, librigena.
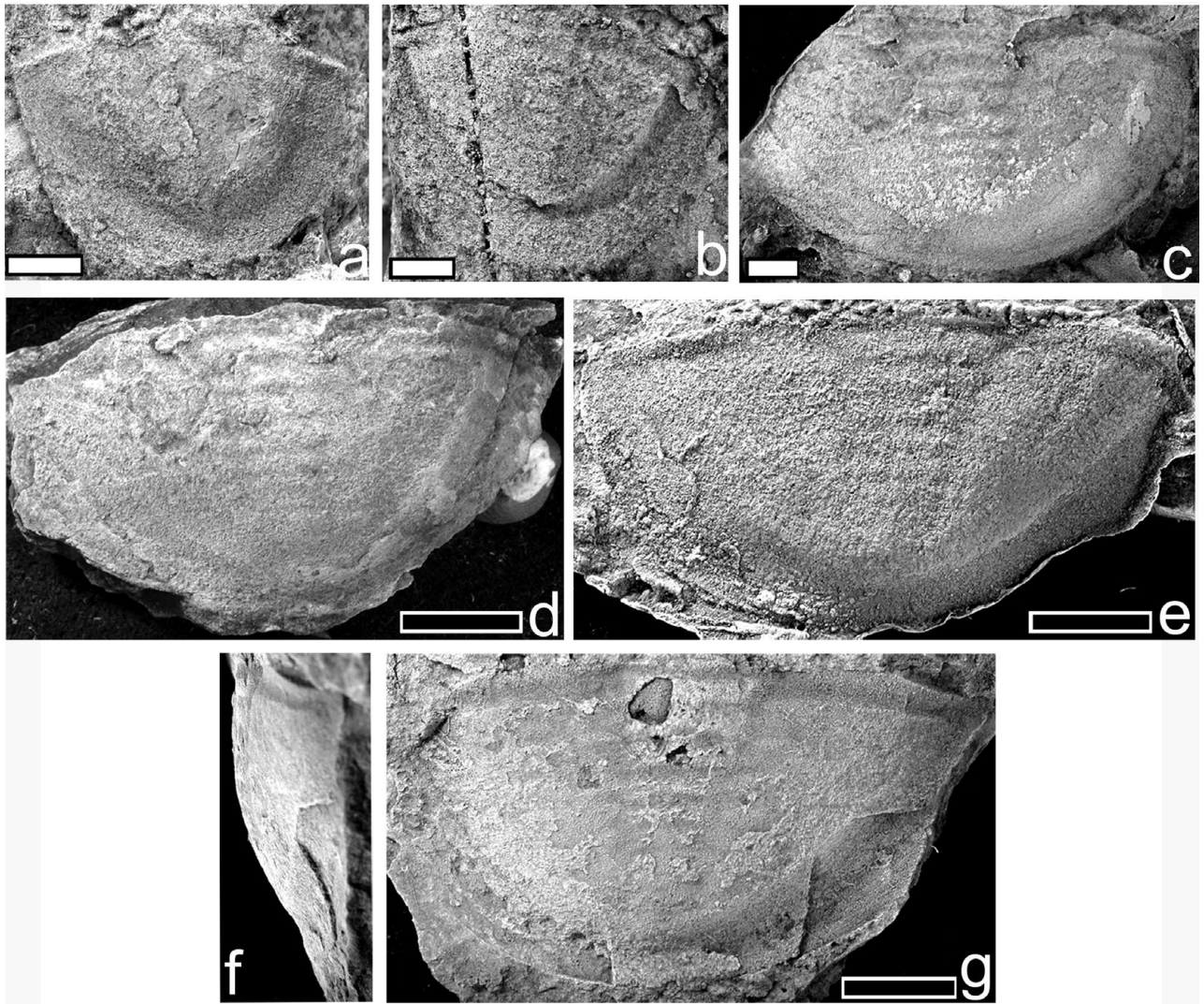
Figure 9. Pygidia of *Taipaikia glabra* (Endo) from the Quartzite Formation, Wachi La section, Bhutan. All specimens are coated with ammonium chloride sublimate prior to digital photography, specimens are internal surfaces of moulds unless otherwise stated. White scale bar is 5 mm long, black scale bar is 10 mm long. (a) GSB32. (b) GSB33. (c) GSB34, latex cast. (d) GSB35, (e) GSB36, latex cast. (f, g) GSB37; (f) lateral view; (g) dorsal view.

with anterior opposite glabellar midpoint. Palpebral furrow weakly incised. Interocular fixigenal width (tr.) equal to glabellar width (tr.) at palpebral area midlength. Prepalpebral fixigena about 80 % of glabellar length at widest. Facial suture weakly divergent anterior to palpebral lobe, then curving gently and evenly toward anterior margin, which it intersects in front of fixigena. Posterior branch runs posteriorly for short distance behind palpebral lobe, then curves abruptly abaxially to define long, spatulate posterior border that obliquely truncates posterior border furrow. Posterior margin subtransverse adaxially, flexed posteriorly beyond weak fulcrum.

Librigenal border furrow effaced. Doublure wide, strongly convex ventrally, almost half of fixigenal width with prominent straight-crested terrace ridges on ventral surface at density of about 2 ridges/mm. Genal spine short (exsag.) and narrow (tr.), posteriorly directed. Librigenal length approximately twice width, suggesting cephalic width to length ratio of about 2:1.

Pygidium semicircular, of moderately high relief, sloping evenly and gently to posterior margin. Axis weakly inflated, straight-sided, decreasing in width (tr.) posteriorly, with up to 7 poorly defined axial rings in large specimens. Axis occupies about 75 % of pygidial length (sag.). Articulating facet distinctly defined on abaxial portion of anterior border. Convex pleural platform slopes evenly into concave border, with slope inflection approximately coincident with weakly incised paradoublural line. Anteriormost pleural furrow evenly long (exsag.) and firmly incised, other pleural and interpleural furrows weakly incised near axis, effaced abaxially. Pygidial border broad, flat to slightly concave, extending across about one third of anterior pygidial width in small specimens and about one quarter of anterior pygidial width (tr.) in large specimens. Doublure with straight crested terrace lines approximately 3 ridges/mm, convex ventrally extending across about one third of pygidial width.

Discussion. The Bhutanese specimens assigned to this species have been tectonically deformed, and we have been able to retrodeform a cranidium that experienced simple oblique shear (see below). The pygidia show little oblique shear (Fig. 9), but it is notable that smaller specimens are relatively long and narrow (Fig. 9a, b) and larger pygidia relatively wide and short (Fig. 9c–g). These differences may result from deformation, in which the sagittal axes of the smaller specimens paralleled the principal extension
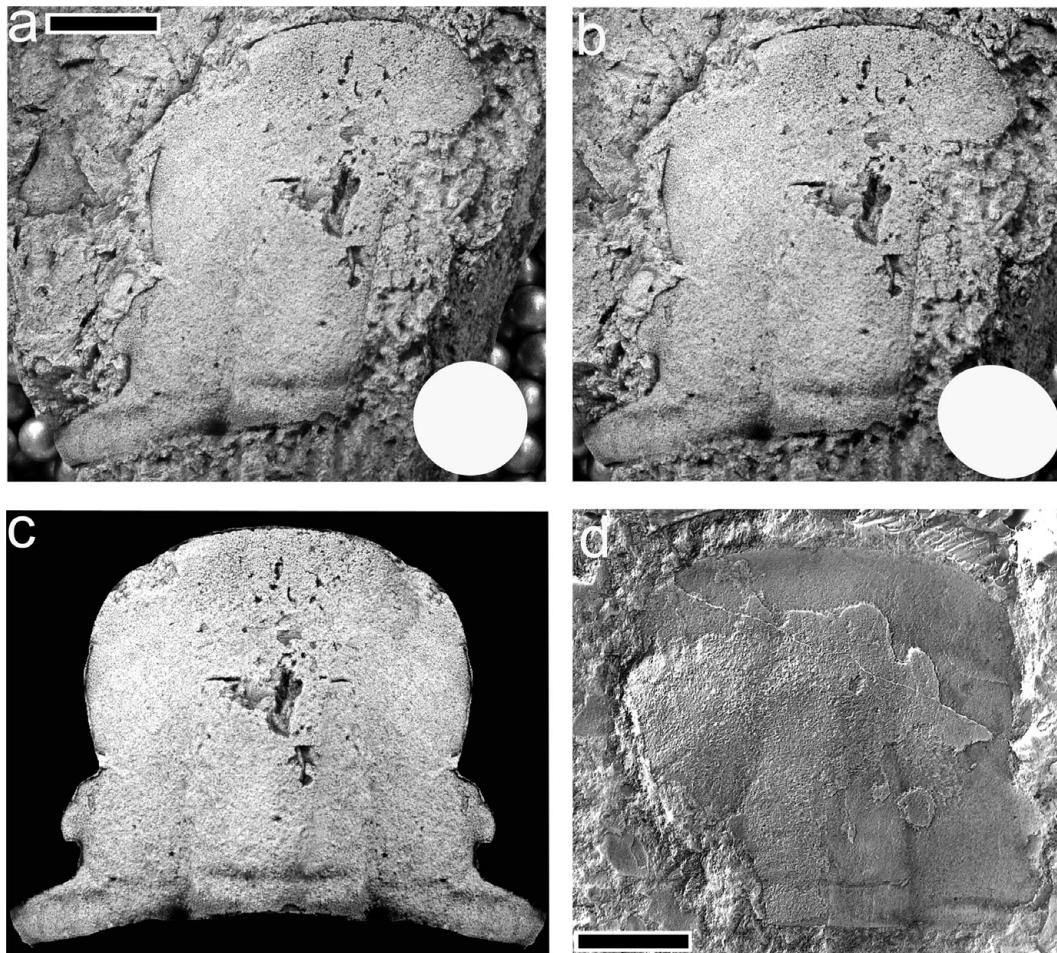
Figure 10. Comparison of retrodeformed Bhutanese specimen of *Taipaikia glabra* with Korean *T. glabra*. Black scale bar is 10 mm long. (a–c) GSB28 partial cranidium from the Quartzite Formation; (a) cranidium as recovered; (b) retrodeformation of (a) with strain ellipse (10 % pure shear); (c) composite image of single retrodeformed partial cranidium, reflected and digitally merged illustrating our concept of the form of the complete cranidium; (d) partial cranidium of *T. glabra* collected about 3 km northeast of the summit Mt Taebaek, *Kaolishania* zone, Taebaeksan Basin, Korea (counterpart of Kobayashi, 1960, p. 248, pl. 21, fig. 20) with pixels digitally inverted to create an image with positive relief, PA2481, University Museum, University of Tokyo.

direction, and those of the larger specimens were orthogonal to it. Further collecting will be needed to confirm whether this explanation or others, such as size-related shape change, are preferable.

Taipaikia glabra (Endo *in* Endo & Resser, 1937) is known from various outcrops of the Changshan Formation in North China (Duan *et al.* 2005), and from a single locality in the Taebaeksan basin of South Korea (Kobayashi, 1960). Subtle differences exist between the Bhutanese and east Asian specimens of *T. glabra*. The Bhutanese specimens lack a well-defined medial ridge on a glabella that is slightly wider than in the type material, has a more spatulate posterior border of the cranidium, and bear one less distinctive ring on the pygidial axis. As these characteristics may reflect preservational differences between the tectonically deformed fine- to medium-grained siliciclastic material of Bhutan and the carbonate east Asian material, or minor intraspecific variation, we do not consider them to be of taxonomic significance.

The Bhutanese cranidia are fragmentary and tectonically deformed. As individual slabs preserve no more than a single cranidium or single pygidium of *T. glabra*, retrodeformation and reconstruction of a complete cranidium has been attempted (Fig. 10) by attempting to restore original approximate bilateral symmetry. The retrodeformation was achieved by compression of the digital image along the inferred principal extension direction and matching extension along axis orthogonal to principal extension (Hughes, 1999). The restoration of symmetry was judged using the outline of the anterior border. The portion of the specimen missing on the right hand side was copied, reflected and combined with the original image such that the anterior border was entire, thus creating an artificial image of a complete retrodeformed cranidium. This cranidium can be compared with the counterpart of an undeformed Korean specimen of this species preserved in limestone and figured by Kobayashi (1960, pl. 21, fig. 20). Digital inversion of the image of the unfigured original counterpart better illustrates features not preserved in the figured cast. The Korean specimen is similar to the retrodeformed Bhutanese specimen, notably in the shape of the anterior border, the location of the palpebral lobe, and proportion of the glabellar width and length relative to cranidial length and width. There is a slight difference in the depth and width of SO. The glabella in the Korean specimen is slightly more conical, although subtle variation is seen in this feature among other figured material preserved in limestone from a single locality (Duan *et al.* 2005, pl. 34, figs 4, 5). Accordingly, we do not consider that the Bhutanese material warrants a new species.

Pygidia of *T. glabra* are similar to those of *Shergoldia*, but cranidia of *Taipaikia* are distinguished by small, more posteriorly situated palpebral lobes, and a more evenly rounded profile of the frontal area. In *Shergoldia* the facial suture cuts the anterior border in front of the glabella, defining a more pointed or 'spade'-shaped frontal area (e.g. Zhu, Hughes & Peng, 2007, fig. 2F). *Taipaikia* also lacks the glabellar furrows seen in *Shergoldia*. Furthermore, no pygidia of *Taipaikia* have been found bearing the spines seen in pre-mature pygidia of *Shergoldia* (Zhu, Hughes & Peng, 2007). Duan *et al.* (2005) erected the species *Shergoldia yanshanensis* based on material from a single locality from the Changshan Formation in Liaoning, North China, where the species co-occurs with *Kaolishania granulosa* and *Lingyuanaspis lingyuanensis*. The figures of the two pygidia of *Shergoldia yanshanensis,* one of which is holotype (Duan *et al.* 2005, pl. 34, figs 12, 13), are nearly identical to the pygidia of *Taipaikia*. *Taipaikia* appears to have been restricted the *Kaolishania* Zone which is stratigraphically below the base of the *Ptychaspis–Tsinania* Zone, in which other species of *Shergoldia* have been recovered.

Order PTYCHOPARIIDA Swinnerton, 1915
Family SOLENOPLEURIDAE Angelin, 1854

Members of this 'ptychoparioid' family are grouped according to the possession of an inflated, sub-triangular glabella, and relatively narrow fixigena (Kobayashi, 1935). *Lingyuanaspis* was assigned to Solenopleuridae by Guo & Duan (1978), an opinion maintained by Jell & Adrain (2003) and Zhu (2008). We note that that *Lingyuanaspis* and *Phylacterus* are characterized by a similar sagittal preglabellar furrow that could denote shared ancestry, but until more is known we maintain *Lingyuanaspis* within Solenopleuridae.

Genus *Lingyuanaspis* Guo & Duan, 1978

1978 *Lingyuanaspis* Guo & Duan, p. 450.
2003 *Lingyuanaspis* Guo & Duan; Jell & Adrain, p. 398.
2005 *Lingyuanaspis* Guo & Duan; Duan *et al.*, pp. 27, 39.
2008 *Lingyuanaspis* Guo & Duan; Zhu, pp. 140, 160, table 6.1

Type species. *Lingyuanaspis lingyuanensis* Guo & Duan, 1978 (p. 450, pl. 2, figs 24–27) from the Changshan Formation, Laozhuanghu section, Lingyuan County, Liaoning Province, China.

Species assigned. In addition to the type species, *Lingyuanaspis sangae* sp. nov. is described herein.

Diagnosis. Cranidium of moderate to high relief, roughly triangular in outline, axial furrow deeply incised, inflated fixigena curve steeply into preglabellar field, meeting in depressed, anteriorly expanding (tr.) sagittal preglabellar furrow. Posterior margin of anterior border expanded posteriorly along sagittal axis. Pygidium trapezoidal, with deeply incised axial furrow and well-defined axial rings, and two short, posteriorly directed spines originating from pygidial margin just abaxial to axial furrow.

Discussion. This genus bears some resemblance to the middle Cambrian solenopleuriid genera *Changqingia* Lu & Zhu *in* Qiu *et al.* 1983 and *Eilura* Resser & Endo *in* Kobayashi 1935. We accept *Austrosinia* Zhang & Jell, 1987 to be a junior synonym of *Changqingia* Lu & Zhu *in* Qiu *et al.* 1983, as suggested by several authors (see Peng *et al.* 2009, p. 79). Zhang & Jell (1987) acknowledged the similarity between *Changqingia* and *Eilura*, but noted differences

in their pygidial outline and concavity. The cranidium of *Lingyuanaspis* is comparable to that of *Changqingia* in glabellar shape and the presence of a shallow sagittal preglabellar furrow, but the pygidium of *Lingyuanaspis* is more similar in outline to that of *Eilura*. *Lingyuanaspis* is distinguished from both these taxa by the presence of short posterior pygidial spines, a feature lacking in both *Eilura* and *Changqingia*.

Another comparable form is *Phylacterus vermontanus* (Raymond, 1937), which is known from Laurentian cranidia that are stratigraphically slightly above the level bearing *Lingyuanaspis*. The Laurentian species bore a comparable sagittal preglabellar furrow, but has wider fixigenae, a distinct ocular ridge (Ludvigsen, 1982, fig. 53A–D), and lacks marked posterior sagittal inflection of the anterior border. *Phylacterus vermontanus* also appears to be more strongly inflated than any *Lingyuanaspis*. Although the pygidium of *P. vermontanus* is unknown, the generic type species *P. saylesi* Raymond, 1924 has a triangular pygidium that contains multiple segments and is broadly comparable to that of *Lingyuanaspis* but differs in having more axial rings, an axis that extends almost of the posterior margin, and in lacking marginal spines (see Ludvigsen, Westrop & Kindle, 1989, pl. 43).

Lingyuanaspis sangae sp. nov.
Figures 11a–p, 12c

Name. In honour of Her Royal Highness Ashi Sangay Choden Wangchuck, Queen of Bhutan, in recognition of her interest in the natural and human heritage of her country, and for her efforts in its conservation.

Holotype. Cranidium (Fig. 11e, f), GSB5 from the WL-8 collection, Wachi La section, Quartzite Formation in the Black Mountain region, Bhutan.

Other material. Nine cranidia from WL-3 (GSB1, GSB2, GSB3, GSB4, GSB6, GSB7, GSB38), WL-5 (GSB39, GSB40); 10 pygidia from WL-2 (GSB11) WL-3 (GSB6, GSB7, GSB8, GSB9, GSB41, GSB42) and WL-5 (GSB10, GSB43, GSB44), Quartzite Formation, Wachi La section, Black Mountains, Bhutan.

Diagnosis. *Lingyuanaspis* with glabellar furrows absent or weakly incised. Pygidial pleural furrows absent or weakly incised.

Description. Cranidium of moderate relief with length (sag.) approximately 50 % of width (tr.) at posterior border. Glabella conical, gently tapering and rounded anteriorly with preoccipital glabellar furrows absent or weakly incised, S1 pit-like, isolated where present. Occipital ring slightly narrower than glabellar width at posterior of L1, with firmly incised SO. Axial furrows deeply incised, preglabellar furrow slightly shallower. Preglabellar field short, about 15 % of cranidial length (sag.) with prominent preglabellar furrow expanding anteriorly into broad (tr.) anterior border furrow. Anterior border narrow (tr.) with posterior margin slightly elongated sagittally. Anterior border about 15 % of cranidial length. Palpebral lobe small, forward, inclined at 25° angle to sagittal axis with anterior end adaxial, about 20 % of cranidial length (sag.), interocular palpebral width 50 % of glabellar width (tr.) at palpebral fixigenal midlength. Anterior branch of facial suture runs forwards and inwards. Posterior branch curves gently abaxially posterior to eye, then sweeps posteriorly. Posterior border slopes steeply into posterior border furrow in abaxial portion. Posterior border furrow long (exsag.), firmly incised.

Pygidium convex, length (sag.) about 60 % of maximum width (tr.), trapezoidal in outline, width between abaxial
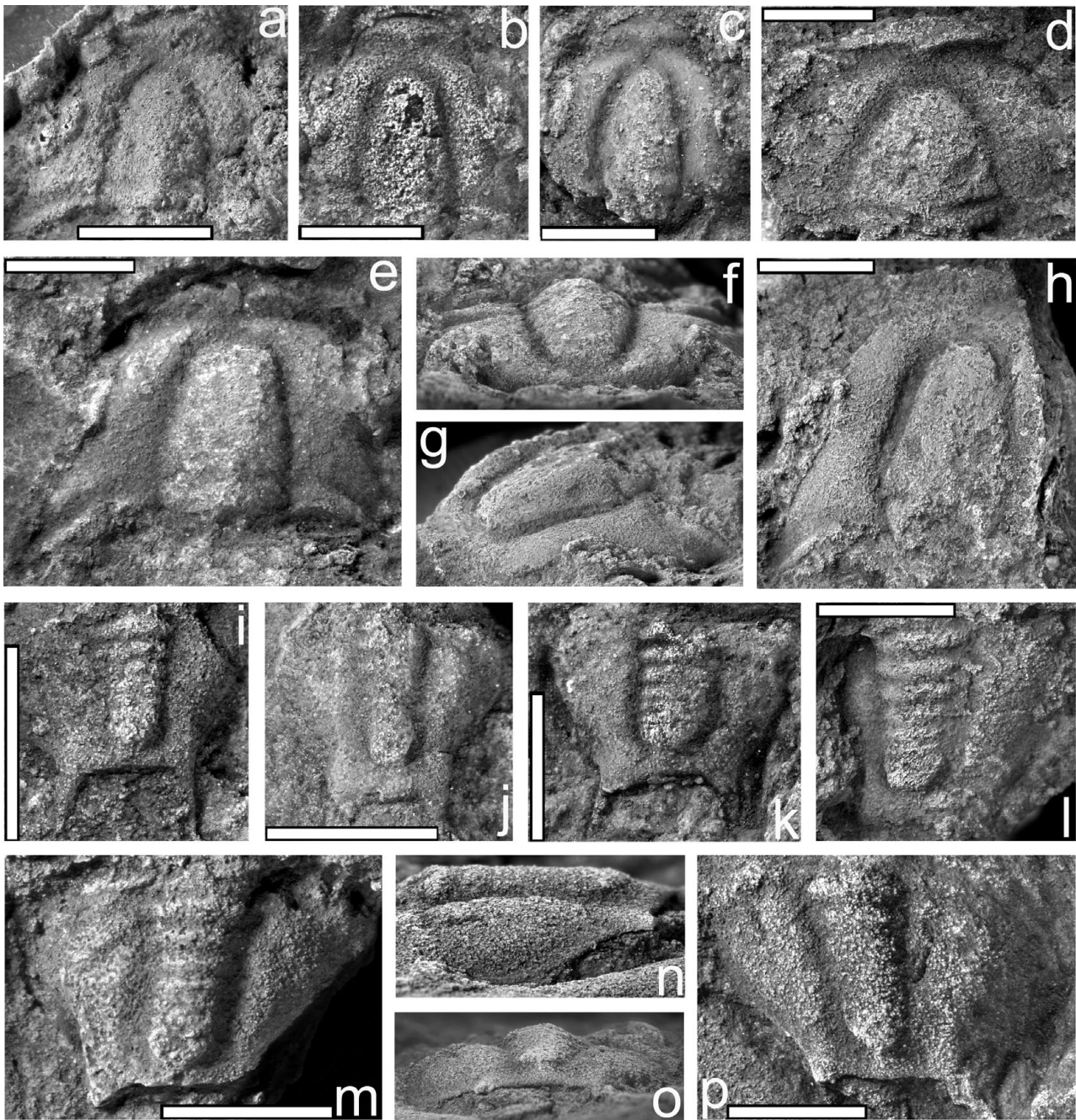
Figure 11. *Lingyuanaspis sangae* sp. nov. from the Quartzite Formation, Wachi La section, Bhutan. All specimens coated with ammonium chloride sublimate prior to digital photography, specimens are internal surfaces of moulds unless otherwise stated. White scale bar is 5 mm long in all figures. (a) GSB1, latex cast of partial cranidium. (b) GSB2, partial cranidium. (c) GSB3, partial cranidium. (d) GSB4, partial cranidium. (e, f) GSB5, cranidium, holotype; (e) dorsal view; (f) anterior view. (g, h) GSB38, partial cranidium; (g) oblique view; (h) dorsal view. (i) GSB6, partial pygidium. (j) GSB7, partial pygidium. (k) GSB8, pygidium. (l) GSB9, partial pygidium. (m) GSB10, partial pygidium. (n–p) GSB11, partial pygidium; (n) lateral view; (o) posterior view; (p) dorsal view.

pygidial spine base (tr.) 60 % of maximum width (tr.). Posterior marginal spine pair straight sided, diverge abaxially at slight angle to sagittal axis. Spine base approximately 40 % of anteriormost axial ring width (tr.). Spine up to approximately 40 % of pygidial length. Posterior border between spines transverse or slightly emarginated sagittally. Axis occupies about 75 % of pygidial length (sag.), strongly inflated, axial rings evenly decrease in width (tr.) posteriorly. Six or more axial rings plus terminal piece with bulbous, rounded end. Axial furrow firmly incised, axial ring furrows short (sag.), evenly incised, shallower posteriorly. Pleural field highly convex, sloping convexly downward from inflated pleural platform, effaced with one or rarely two furrows apparent anteriorly in some specimens.

Discussion. All specimens of *L. sangae* have experienced mild to moderate tectonic deformation. Those forms orthogonal to the axis of principal extension have become markedly shortened (Fig. 11d), while those parallel to that axis have been elongated (Fig. 11h). Accordingly, we have attempted a reconstruction (Fig. 12c) that approximates our view of the undeformed morphology.

The type species *Lingyuanaspis lingyuanensis* (Guo & Duan, 1978) is only known from the Changshan Formation
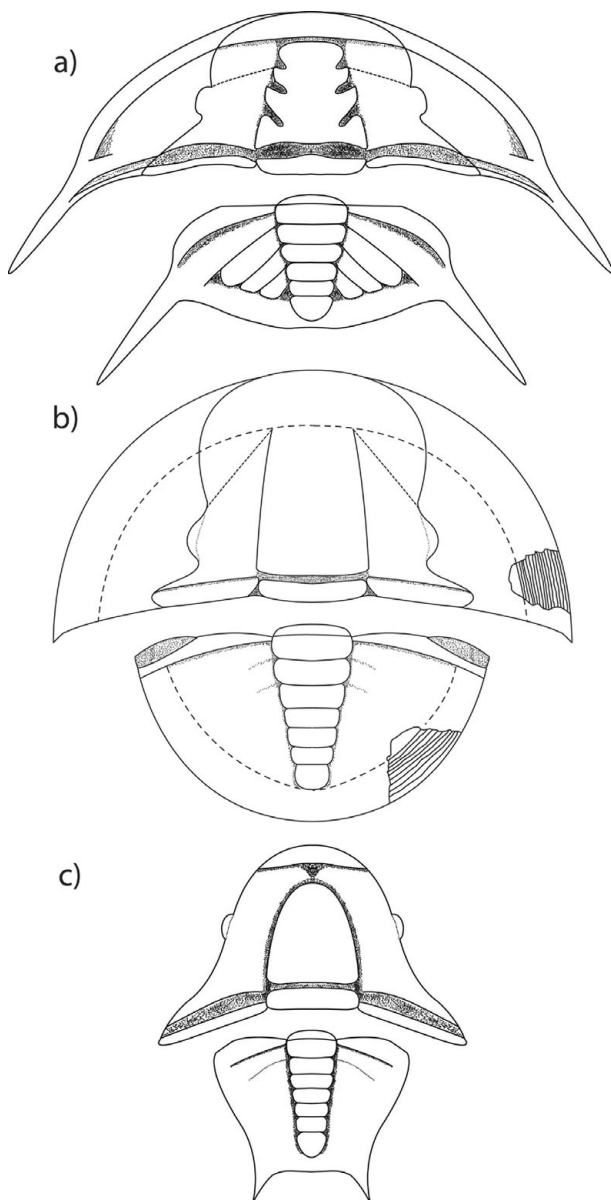
Figure 12. Schematic reconstructions of the Wachi La trilobite species. (a) *Kaolishania granulosa;* (b) *Taipaikia glabra*; (c) *Lingyuanaspis sangae.*

in the Laozhuanghu section in Lingyuan County and from the Yuanshishan section in Jinxi County of the Liaoning Province, North China (Duan *et al.* 2005). The presence of firmly incised lateral glabellar furrows distinguishes *L. lingyuanensis* from *L. sangae*. There is also a difference in glabellar shape, with the glabella of *L. lingyuanensis* tapering anteriorly to yield a more triangular form than that of *L. sangae*, which has a more gently tapered, conical glabella. The pygidia also differ with *L. lingyuanensis* displaying multiple well-defined pleural furrows, whereas the pleurae of *L. sangae* are effaced with no more than two faint furrows.

Phylum BRACHIOPODA
Class RHYNCHONELLIFORMA
Order BILLINGSELLIDA Schuchert, 1893
Suborder BILLINGSELLIDINA Schuchert, 1893
Superfamily BILLINGSELLOIDEA Schuchert, 1893
Family BILLINGSELLIDAE Schuchert, 1893

The billingsellids are a distinctive group of strophomenate brachiopods that have many features in common with the orthide brachiopods where until recently they were placed. Nevertheless, the presence of a pseudodeltidium and a chilidium together with transverse flat-lying socket plates and in particular a secondary shell layer consisting of cross-bladed laminae, has required a reassignment of the group to the Strophomenida (Williams & Harper, 2000). The family ranges from the middle Cambrian to the Lower Ordovician (Floian) and currently includes some six genera.

Genus *Billingsella* Hall & Clarke, 1892

Type species. Orthis pepina Hall, 1863, p. 134, pl. 6, figs 23–27.

Billingsella is generally ventribiconvex with variable cardinal extremities, a strong pseudodeltidium and convex chilidium together with an apical foramen. The dental plates are widely divergent and the ventral muscle scars are commonly impressed on a long, tongue-like callus; a subperipheral rim is occasional developed. The other members of the family conform to the *Billingsella* model but have minor differences, mainly in overall shape and features of the ventral interior. *Billingsella* ranges from the middle Cambrian to the Lower Ordovician (Tremadocian) and has a cosmopolitan distribution. The majority of its some 20 reported species are known from the Furongian.

Billingsella cf. *tonkiniana* Mansuy, 1915
Figure 13a–k

cf. 1915 *Billingsella tonkiniana* Mansuy, p. 7, pl. I, fig. 2a–q.
cf. 1916 *Billingsella tonkiniana* Mansuy; Mansuy, p. 13, pl. I, fig. 12a–g.
  1983*a Rafinesquina* sp. Chaturvedi, Mishra & Mulay, pl. 1, figs 1–4, 6.
  1983*a Orthis* sp. ? Chaturvedi, Mishra & Mulay, pl. 1, figs 5, 7.
  1983*a* Chaturvedi, Mishra & Mulay, pl. 1, figs 8, 9.
  1983*a* Strophomenidae sp. Chaturvedi, Mishra & Mulay, pl. 1, fig. 11.
 ?1983*a* ?*Sowerbyites* sp. Chaturvedi, Mishra & Mulay, pl. 1, fig. 14.
  1983*b Rafinesquina cratera* Salter; Chaturvedi, Mishra & Mulay, pl. 1, figs 1–4, 6.
  1983*b Orthis* cf. *dalmenella* Chaturvedi, Mishra & Mulay, pl. 1, figs 5–7, 9.
  1983*b* ?*Strophomena* sp. indet. Chaturvedi, Mishra & Mulay, pl. 1, fig. 11.
 ?1983*b* ?*Sowerbyites* sp. indet. Chaturvedi, Mishra & Mulay, pl. 1, fig. 14.
  1995 Brachiopod impression Tangri & Pande, p. 134, fig. 3.10.41.

Material. Two dorsal conjoined exteriors and ventral inter-areas from WL-5 (GSB64, GSB69); one ventral exterior (GSB65) from WL-5 and one (GSB66) from WL-6; two dorsal interiors (GSB68, GSB70) from WL-5; one ventral interior (GSB67) from WL-5. The species also occurred in the following collections: WL-2, WL-7 and WL-8, Quartzite Formation, Wachi La section, Black Mountains, Bhutan.

Description. Exterior. Unequal, usually dorsibiconvex valves of transverse to subquadrate outline with maximum width commonly at or just anterior to hingeline; cardinal extremities rectangular or slightly obtuse. Anterior commissure slightly to markedly sulcate. Ventral valve feebly convex with low, flat median fold and planar to slightly concave
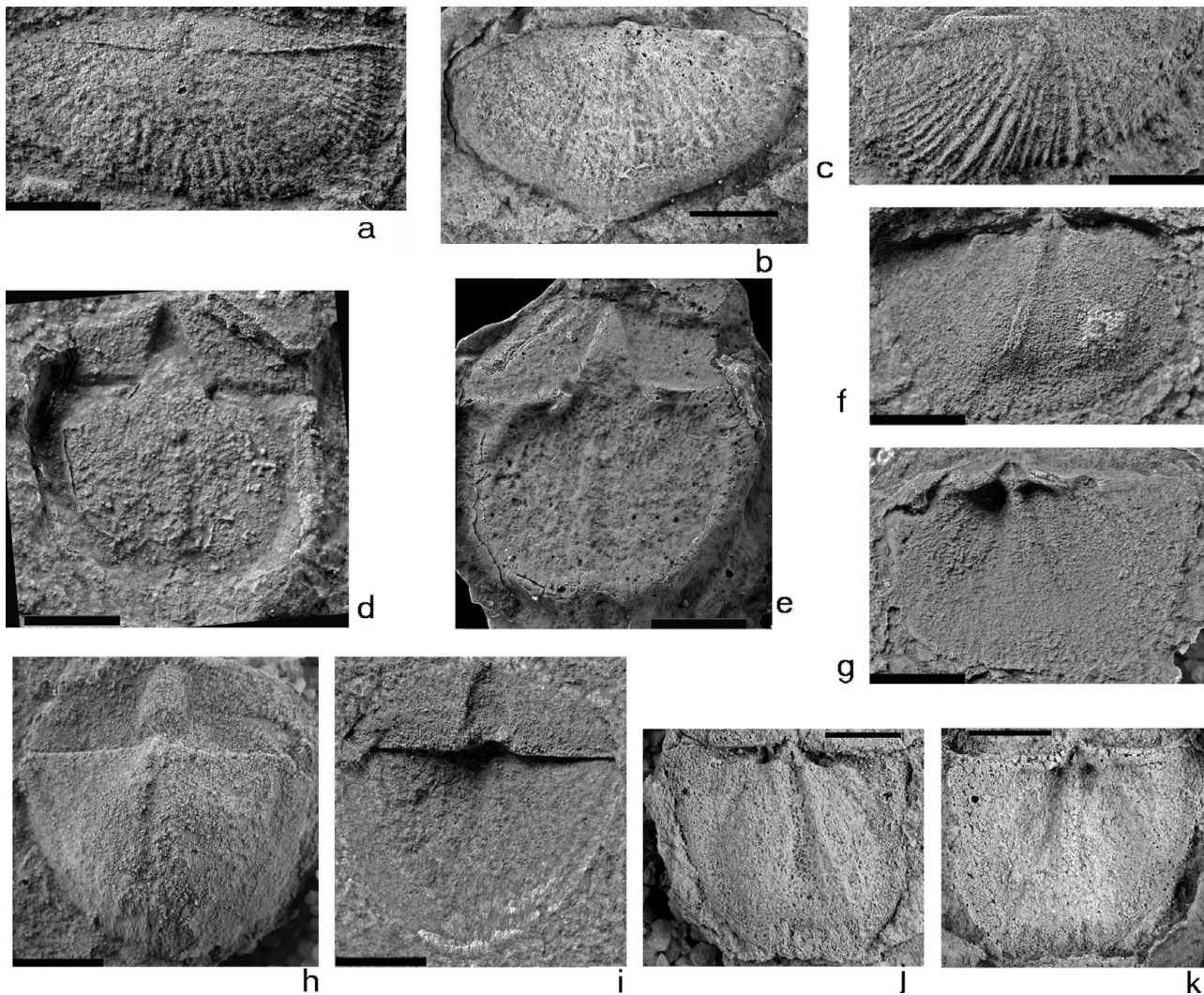
Figure 13. *Billingsella* cf. *tonkiniana* Mansuy, 1915, from the Quartzite Formation, Wachi La section, Black Mountain outlier, Bhutan. (a) GSB64, latex replica of conjoined valves showing dorsal exterior and the ventral interarea. (b) GSB65, latex replica of ventral exterior; (c) GSB66, latex replica of dorsal exterior. (d, e) GSB67, internal mould of ventral valve and latex replica. (f, g) GSB68, internal mould of dorsal valve and latex replica. (h, i) GSB69, external mould and latex replica of conjoined pair showing dorsal exterior and ventral interarea. (j, k) GSB70, dorsal interior and latex replica of dorsal valve. Scale bar 5 mm.

flanks. Ventral interarea high, flat with strongly convex pseudodeltidium, occupying about two-thirds of deltidium and with slight trace of minute, apical pedicle foramen. Dorsal valve convex with transverse outline; marked sulcus with steep sides arising at or near umbo, deepening and widening anteriorly; commonly flanked by two strong ribs and with curved base. Dorsal interarea relatively short, flat; chilidium relatively small, convex occupying the apical part of the notothyrium. Ornament of strong costae and costellae, with sharp profiles and flat interspaces; arising by both branching and intercalation; concentric growth lines variably developed, accentuated at and near anterior commissure; up to ten ribs developed per 5 mm at about 5 mm from dorsal umbo, with commonly five in the sulcus.

Ventral interior. Muscle scars not clearly discernible. Teeth, relatively large and robust, forming knoblike, divergent projections extending outwards from the anterolateral margins of the delthyrium.

Dorsal interior. Well-developed, high notothyrial platform with simple, bladelike cardinal process flanked by pair of suboval depressions, marking the site of the diductor scars;

platform extended anteriorly as ridge, that broadens and fades within the posterior third of the valve length. Notothyrial platform flanked by flat-lying socket ridges that extend laterally, subparallel to hingeline, thickening slightly, distally. Posterior pair of adductor scars, oval, faintly impressed lateral to median ridge. Vascular media impressed and diverge anteriorly.

Discussion. This is a large, subquadrate to tranverse, dorsibiconvex *Billingsella* species with normally coarse costae and costellae, arising by branching and intercalation; the cardinal process is simple, situated on a high notothyrial platform with widely divergent socket ridges, subparallel to the hingeline; the large convex pseusodeltidium is perforated by minute apical foramen.

Several previous figured brachiopod specimens from the Quartzite Formation of the Wachi La section evidently belong to this species. Specimens assigned to *Rafinesquina cratera* are internal moulds of the ventral valve, whereas external moulds were generally assigned to *Orthis* cf. *dalmenella* (Chaturvedi, Mishra & Mulay, 1983*b*). Our new material is also preserved as moulds and is variably deformed. The material exhibits a wide degree of morphological variation

due partly to tectonic strain but in common with many other late Cambrian taxa, there is probably also a significant degree of biologically related morphological variation. Nevertheless, the biconvex, costellate shells with long interareas, and a large, convex pseudodeltidium perforated by an apical foramen and flat-lying socket ridges subparallel to the hingeline confirm an assignment to *Billingsella*. Approximately 20 species have been placed within *Billingsella* and many of those that have not already been reassigned to other genera, such as *Oligomys* and *Wimanella*, are in need of revision. Many species of *Billingsella* show wide variation in shell shape and ornament (Bell, 1941; Freeman & Stitt, 1996), and are thus difficult to characterize. The Bhutanese material is most similar to a group of species centred around *B. perfecta* Ulrich & Cooper, 1938 but which also includes *B. coloradoensis* (Shumard, 1861) and *B. texana* Bell & Ellinwood, 1962. This group has transverse dorsal and subquadrate ventral valves, a large pseudodeltidium and relatively coarse radial ornament. The Bhutanese species differs in having a high notothyrial platform, simple socket ridges developed virtually parallel to the hingeline and a lack of ridges in the dorsal interior, together with a raised muscle platform in the ventral valves.

A number of species of *Billingsella* have been reported from Shandong and Liaoning provinces of North China (Kobayashi, 1933; Endo & Resser, 1937). *Billingsella pumpellyi* Walcott is reported and figured from the Furongian Changshan Formation of Shandong (Endo, 1939, pl. 1, fig. 9). The key characters of the species are its strongly convex ventral valve, a projecting ventral apex, a faintly-defined median fold and sharp, radiating ribs. Endo (1939), however, only figured a dorsal exterior. The Shandong material is apparently broken and poorly preserved, and although having sharp ribs and a sulcate anterior commissure, the Bhutanese material lacks a strongly-projected ventral apex, apparently typical of this form. Three new species were assigned by Endo & Resser (1937) to *Billingsella*. *Billingsella aojii* is similar to *B. pumpellyi* but possesses less convex and wider valves. *Billingsella simplex* is characterized by a subcircular ventral valve, which is more convex and with finer ribs than the two latter species. *Billingsella willisi*, however, is subquadrate, moderately convex with fine ribs. All three are only briefly described and inadequately illustrated for comparison with the Bhutanese material.

Two new species were reported from the Liaoning Province (Kobayashi, 1933). *Billingsella goettschei* is similar to *B. pumpellyi* but is less convex and displays vascula media that are more narrowly divergent, whereas *B. hsishunenesis* is characterized by costellae that increase by intercalation and strong concentric growth lines. Both species are based on inadequate sample sizes and thus it is not possible to judge if these, and indeed the other species from China, are indeed recognizable species or merely part of a single, more variable species.

Mansuy (1915, 1916) described and illustrated two named species of *Billingsella* from Haut-Tonkin, which is part of the South China block. *Billingsella loungeoensis* Mansuy, 1916 is based on a transverse, ventral valve with a relatively fine ornament. It apparently lacks the high ventral interarea typical of *Billingsella*, and significantly Mansuy (1916) compared his species with *Billingsella exporrecta* Linnarsson, a Swedish species now assigned to *Oligomys*. *Billingsella tonkiniana* Mansuy, 1915 is adequately illustrated (Mansuy, 1915, 1916) and displays many of the features typical of *Billingsella*. Mansuy (1915) in fact compared his new species with *B. coloradoensis* (Shumard, 1861), and it is thus similar to both the American species and the new material described here (see above). The Haut-Tonkin material is

similar in overall shape, particularly in the development of a dorsal sulcus and apparently has a similar density of ribbing. The Bhutan material has generally a more transverse outline and a higher ventral interarea; detailed comparisons with the interiors of Mansuy's species are not possible. Both species are tectonically deformed, making precise morphological comparisons difficult, but both are clearly similar. On this assumption and to avoid further proliferation of specific names, the Bhutanese material is compared with *B. tonkiniana*. Pending revision of Mansuy's species, the Bhutanese taxon may be included in that species, or its distinctive characteristics could form the basis for a new species.

The *Billingsella* Association (Bassett, Popov & Holmer, 2002) was a low-diversity assemblage, dominated by the eponymous genus itself or closely related forms such as *Cymbithyris*. Many of these assemblages were limited in spatial distribution but formed high-density, high-dominance clusters in thin, locally extensive horizons commonly within nearshore facies. These distributional patterns suggest that *Billingsella* pursued an opportunist life strategy, forming thick near-monospecific shell beds in the middle and upper Cambrian rocks of Iran and the Furongian strata of north-central Kazakhstan (Bassett, Popov & Holmer, 2002). In the Wachi La section *Billingsella* occur throughout the fossiliferous interval and dominate some, but not all, beds in which they occur (Fig. 3).

5. Age, biostratigraphy and biogeography of the Pele La Group

5.a. New stratigraphic constraints from the fossils described herein

Our collections from the Quartzite Formation spanned about a 40 m stratigraphic interval, although the majority of the material is within 12 m of the base of this interval (Fig. 3). Individual beds contain different relative abundances, with the WL-5 and WL-6 collections dominated by *B.* cf. *tonkiniana,* whereas the WL-2, WL-3 and WL-8 collections were trilobite-dominated. As all three trilobite taxa occur throughout the section there is no indication of biozones within the section (Fig. 3).

The trilobite assemblage described here from the Quartzite Formation is unique, with all three of the Bhutanese trilobite genera known to be restricted to a narrow stratigraphic interval in North China (Sino-Korean block). *Kaolishania granulosa* occurs quite commonly in the *Kaolishania pustulosa* Zone of North China (the top zone of the Changshanian Stage in the traditional Chinese stage nomenclature), which is correlative to the *Eolotagnostus decoratus–Kaolishaniella* Zone of South China (Peng, 1992; Geyer & Shergold, 2000; Choi & Kim, 2006) (that is, within the lower portion of the Taoyuanian Stage in the slope-facies stages of China). It belongs to Stage 9 of the Furongian Epoch, and the age of this zone is estimated to be about 493 Ma (Peng & Babcock, 2008). This significantly modifies the middle Cambrian or Ordovician age estimate for the Quartzite Formation of the Pele La Group (Chaturvedi, Mishra & Mulay, 1983*a,b*; Bhargava, 1995; Tangri

& Pande, 1995; Hughes, Peng & Luo, 2002; Tangri, Bhargava & Pande, 2003; Long & McQuarrie, 2010). On the other hand, billingsellid brachiopod taxa have long stratigraphic ranges with the genus *Billingsella* extending from the middle Cambrian through the Early Ordovician (Tremadocian). The taxon also shows cosmopolitan distribution (Williams & Harper, 2000). This, coupled with the lack of modern descriptions of many billingsellid taxa hinders their further use as biostratigraphic and biogeographic indicators.

The genus *Kaolishania* is well represented in North China by *Kaolishania pustulosa* and *K. granulosa*. Possible congeners also occur on the South China block (Yangtze platform), in Western Yunnan and in Australia, but those forms differ from the typical North Chinese species. The occurrence of *K. granulosa* in Bhutan thus suggests a specific link between Bhutan and North China. Furthermore, *Taipaikia* and *Lingyuanspis* are rare genera and are only known from North China. *Taipaikia glabra* has been collected from outcrops in the Changshan Formation in Liaoning, Hebei and Shandong provinces of North China (Duan *et al.* 2005) and the Sesong Formation of the Taebaeksan Basin in South Korea (Kobayashi, 1960). In both of these locations it co-occurs with *Kaolishania granulosa* (Endo & Resser, 1937; Kobayashi, 1960; Duan *et al.* 2005). The only other species of *Lingyuanaspis*, *L. lingyuanensis*, is known only from a stratigraphically thin interval of the Changshan Formation at two localities in the Liaoning Province, North China, where it co-occurs with *Taipaikia glabra* and *Kaolishania granulosa* (Duan *et al.* 2005). Thus the co-occurrence of these three species in both Bhutan and North China allows both precise stratigraphic constraints to be placed on the age of the Bhutanese fauna, and a specific faunal association with North China to be advanced. These taxa have not been recovered from other areas bearing rock of similar age despite quite intensive studies of rocks of this age in South China and Australia.

In North China *K. granulosa*, *T. glabra* and *Lingyuanaspis lingyuanensis* occur in shallow water carbonate deposits as part of a mixed siliciclastic–carbonate succession (Duan *et al.* 2005; Kwon *et al.* 2006), whereas in Bhutan these taxa are found in nearshore, very fine- to medium-grained sandstone facies. Although both settings represent shallow shelfal conditions, the specific lithofacies were different, and occurrence of these taxa evidently was not exclusive to a single lithofacies. Hence there is no indication that this fauna occupied a particularly specialized physical habitat. Thus, proximity between North China and Bhutan, rather than specific environmental similarity, is a more likely explanation for the co-occurrence in both regions.

The Cambrian palaeogeographic position of India is well constrained as an element of core Gondwanaland (e.g. Scotese & McKerrow, 1990; Veevers, 2000, 2004) and, assuming that the Cambrian Himalayan margin was continuous along strike and that Bhutan was part of it, as the stratigraphic and detrital zircon analyses suggest, this faunal association described herein would favour placement of the outboard North China block in relatively close proximity. This contrasts with other models in which North China is placed adjacent to eastern Australia or even further around the Gondwanan margin, adjacent to the Ross Sea margin of Antarctica (Huang *et al.* 2000; Li & Powell, 2001).

Although the trilobite species allow specific stratigraphic and geographic correlation, the assemblage is of low diversity, as is quite common in Cambrian trilobite assemblages from nearshore sandstone facies. Sclerites of each of the three Bhutanese species have homeomorphs among co-occurrent trilobite species from other settings. For example, the pygidium of *K. granulosa* is grossly similar to that of species of *Crepicephalus*, the pygidium of *L. sangae* is similar to that of *Uncaspis discrepans*, and the overall size and form of both cranidia and pygidia of *T. glabra* resemble those of *Coosia grandis* from the Laurentian *Crepicephalus* Zone shale/limestone succession of central Montana (Lochman & Duncan, 1944). This distantly related Laurentian fauna is significantly older, more diverse and from a different lithofacies than that of the Quartzite Formation. Nevertheless, similarity in aspects of the ecological structure of these disparate faunas is suggested by these resemblances.

5.b. Implications for previous age estimates and correlations of the Pele La Group

The fauna from the Quartzite Formation analysed in this paper suggest stratigraphic equivalence of the formation to members G and H of the Maneting Formation of Chaturvedi, Mishra & Mulay (1983*a*,*b*) (Fig. 2). Those authors collected trilobites from several localities in their Member H of the Maneting Formation at Wachi La, and also in the Kha-Khola/Gongkhola area of the southern Black Mountains. On the basis of those fossils they considered the entire Maneting Formation to be Middle to Upper Ordovician, and the Deshichiling Formation (their Nake-Chu Formation) to be Lower Ordovician. Chaturvedi, Mishra & Mulay's (1983*a*,*b*) figured specimens are difficult to identify from the photographs provided in their papers, and the original specimens have been lost. Several of the forms from the Wachi La section that they illustrate can be assigned to species we describe herein (see synonymies above). Other forms that they illustrated are likely different taxa. For example, their (Chaturvedi, Mishra & Mulay, 1983*a*,*b*) plate 2, figures 10 and 11 might be a saukiid trilobite, a clade that we have not recovered in our own collections. Such a trilobite could have been collected from beds a little higher stratigraphically than those we collected. However, nothing illustrated from the Quartzite Formation in the Chaturvedi, Mishra & Mulay (1983*a*,*b*) papers is suggestive of an Ordovician age.

Specimens illustrated by Tangri & Pande (1995) and by Bhargava (1995) are from the WL-2 locality.

Bhargava (1995, p. 178) suggested a middle to late Cambrian age for the Quartzite Member based on the specimens that these authors illustrated from WL-2, and based on the suggestion by J. H. Shergold that the trilobites were either kaolishaniids or pagodiids. On the basis of this identification Bhargava (1995) proposed a middle Cambrian age for this horizon. This was prompted by the supposedly earliest Cambrian age of the underlying Maneting Formation (Tangri, Bhargava & Pande, 2003). Bhargava (1995) and Tangri, Bhargava & Pande (2003) argued that the contrast between strata bearing simple trace fossils such as *Planolites* in the Deshichiling Formation and lowest parts of the Maneting Formation, and the occurrence of *Treptichnus pedum* (*sensu* Jensen, 1997) in the lower part of the Maneting Formation, suggested that this interval spanned the Precambrian–Cambrian boundary. However, none of the trace fossils illustrated by these authors are diagnostic of an early Cambrian age. *Treptichnus pedum* ranges from the base of the Cambrian into the Ordovician (Geyer & Uchman, 1995), and rocks bearing this form are potentially of any age within that interval, although those on the Wachi La must be older than the trilobites described herein. Here we revise the age interpretation based on the new trilobite species identification, and this view is confirmed by the ages of detrital zircon grains from the Deshichiling Formation (see below). Our investigation shows that the leiostegiinid trilobite present is *K. granulosa*, not *Prochuangia* (see Hughes, Peng & Luo, 2002). This taxonomic revision and the other species identifications suggest that the assemblage is younger than the age suggested previously by Hughes, Peng & Luo (2002).

6. Detrital zircon geochronology

Two sandstone samples were taken from the Wachi La section for detrital zircon U–Pb age analysis. WL-1 is from the upper part of the Deshichiling Formation at N 27°25.014′, E 090°16.609′, at ∼ 3942 m altitude, and WL270.75 is from the WL-5 locality of the Quartzite Formation at a level from which *K. granulosa, L. sangae* and *B.* cf. *tonkiniana* were collected.

The detrital zircons were placed on mounts and polished, and then analysed using a sensitive high-resolution ion microprobe (SHRIMP) at the Research School of Earth Sciences, Australian National University. Procedures used are those of Williams (1998). Photomicrographs were prepared for the grains using both reflected and transmitted light, as well as separate cathodoluminescence (CL) scanning electron microscope images. The latter were used to determine the internal structures of the grains, and to allow us to aim the ∼ 20 μm diameter SHRIMP beam such that only the youngest single age component (the rims) was analysed within chosen grains. We initially analysed 60 grains for each sample (see online Appendix at http://journals.cambridge.org/geo), and then reanalysed the youngest grains (WL-1 n = 5; WL-
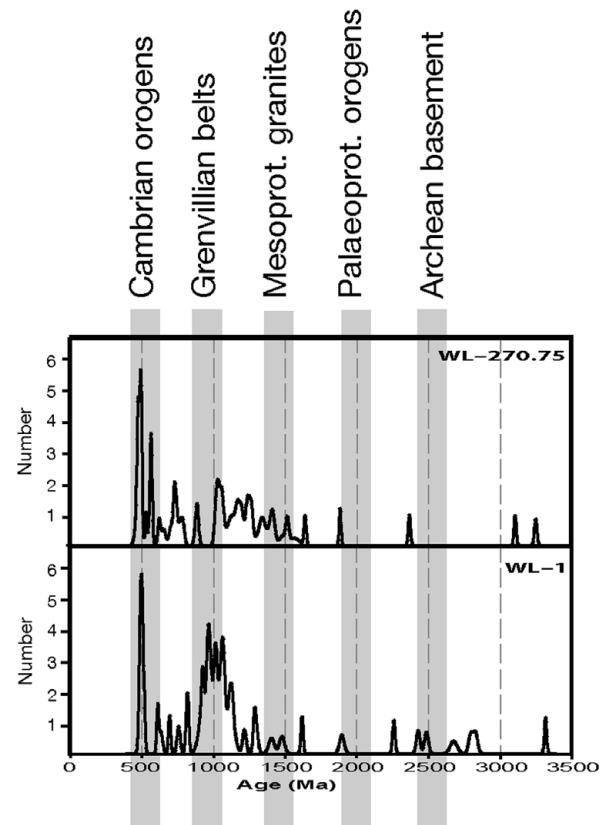

Figure 14. Detrital zircon age spectra from Cambrian and Ordovician strata from the WL-2 locality (WL-270.75), Quartzite Formation (n = 54), and from the Deshichiling Formation (WL-1) (n = 56), Wachi La section, Bhutan.

270.75 n = 4) for higher precision. The data were processed using the SQUID Excel macro of Ludwig (2001). U/Pb ratios were normalized relative to a value of 0.0668 for the Temora reference zircon, equivalent to an age of 417 Ma (Black *et al.* 2003). Uncertainties given for individual analyses (ratios and ages) are at the one-sigma level (see online Appendix at http://journals.cambridge.org/geo). Correction for common Pb was either made using the measured $^{204}Pb/^{206}Pb$ ratio in the normal manner, or for grains younger than *c.* 800 Ma (or those low in U and thus radiogenic Pb) the ^{207}Pb correction method was used (Williams, 1998). When the ^{207}Pb correction is applied it is not possible to determine radiogenic $^{207}Pb/^{206}Pb$ ratios or ages. In general for grains younger than *c.* 800 Ma, the radiogenic $^{206}Pb/^{238}U$ age was used for the relative probability plots; the $^{206}Pb/^{238}U$ age is also used for grains that are notably low in U, and therefore radiogenic Pb. The $^{207}Pb/^{206}Pb$ age is used for grains older than *c.* 800 Ma, or for those enriched in U. For these older grains, those > 15 % discordant have not been included in the relative probability plots.

The probability–density plot for sample WL-1 shows scattered Archaean, Palaeoproterozoic and Mesoproterozoic peaks (Fig. 14). Many of these peaks are found in rocks of roughly coeval depositional age from across the Himalaya (Myrow *et al.* 2010) and the Indian craton (Malone *et al.* 2008). A very large peak spans from approximately 800 Ma to 1300 Ma,

just as in other Himalayan samples. The rest of the profile consists of scattered prominent younger Neoproterozoic peaks and one large peak centered at about 500 Ma. The youngest grain in the sample is 489 ± 8 Ma, and 13 grains have probable Cambrian age ranging up to 523 ± 8 Ma. These data show that the Deshichiling Formation was almost certainly deposited in the late Cambrian, not earlier as was suggested by Tangri, Bhargava & Pande (2003).

Sample WL-270.75 contains a broadly similar profile to that of WL-1. It contains two Archaean grains, scattered Palaeoproterozoic peaks, and a prominent cluster of latest Archean and Mesoproterozic peaks that span the interval from 1000 Ma to 1700 Ma. Younger Neoproterozoic ages are abundant through *c.* 850 Ma, and include peaks at 600 and 750 Ma. There are nine grains with ages between 487 and 516 ± 5 Ma. The youngest grain is 487 ± 8 Ma. The depositional age of this sample is precisely constrained biostratigraphically by the trilobite fauna, which suggest a depositional age of about 493 Ma. Thus, as for early Palaeozoic samples in other parts of the Himalayan margin, the time lag between zircon crystallization in the magma and its deposition in the sediment was very short, on the order of a few million years or less.

The spectra from our samples are similar to each other, and to other spectra from Bhutan that are inferred to be of approximately similar depositional age (see samples NBH-18, NBH-5 of McQuarrie *et al.* 2008). This reflects the pattern common to all Cambrian samples from the Himalaya and cratonic India (Malone *et al.* 2008; Myrow *et al.* 2010). The common signature suggests a high degree of sediment mixing along the Himalayan margin (Myrow *et al.* 2010), and a wide variety of source material ages. The Archaean grains may have origins within India or in other parts of Gondwanaland (see Myrow *et al.* 2010). Palaeoproterozoic and Mesoproterozoic grains in our samples could have originated from a wide variety of sources within core Gondwanaland, but the prominent peaks of late Mesoproterozoic to early Neoproterozoic age, approximately 900 to 1300 Ma, were likely derived from orogenic belts produced by the assembly of Rodinia (Rivers, 1997; Fitzsimons, 2000*a*,*b*). These 'Grenville'-age orogens surrounded the Indian continent within Gondwanaland and include provinces from east Antarctica (Boger *et al.* 2000; Harley & Kelly, 2007), south-central Africa (Cahen *et al.* 1984) and Sri Lanka/south India (Fitzsimons, 2000*a*,*b*). Local potential sources for grains of these ages include magmatic rocks in various tectonic units of Bhutan, Arunachal Pradesh and the Shillong plateau (Daniel *et al.* 2003; Richards *et al.* 2006; Chakungal *et al.* 2010; Yin *et al.* 2010*a*,*b*).

As with other Himalayan Cambrian detrital zircon spectra, we interpret the majority of Neoproterozoic grains to have been derived from the East African Mozambique orogenic belt (Squire *et al.* 2006; Yoshida & Upreti, 2006; Cawood, Johnson & Nemchin, 2007; Myrow *et al.* 2010). Events associated with this orogen

took place between approximately 530 to 700 Ma. Gondwana assembly resulted in extensive organic systems (Cawood, Johnson & Nemchin, 2007) with large-scale alluvial and fluvial depositional systems stretching across an unvegetated landscape, leading to extraordinary distances of sediment transport (Squire *et al.* 2006; Myrow *et al.* 2010). The 500 Ma grains may have been locally derived in association with widespread granitic intrusion around the margin of Gondwanaland, including India (Debon *et al.* 1986; LeFort *et al.* 1986; Cawood, Johnson & Nemchin, 2007).

McQuarrie *et al.* (2008) provided a detrital zircon spectrum from their sample BU07–1 from the 'Chekha Formation' collected from the Ura klippe to the east of the Wachi La. The spectrum is similar to those in our Wachi La samples, except that it lacks grains younger than approximately 800 Ma. Given that Himalayan sedimentary rocks of Cambrian age in nearly all cases include grains of approximately 500 to 650 Ma age (Myrow *et al.* 2010), we suggest that the sample, collected near the base of the Chekha Formation, may be of Neoproterozoic depositional age. In contrast, recent work has suggested that Greater Himalayan rocks immediately beneath the Chekha Formation have ages as young as 460 Ma (Long & McQuarrie, 2010). These authors argue that the Chekha Formation unconformably overlies the Greater Himalaya, and that its age must be younger than 460 Ma. In the Wachi La area, rocks assigned to the Chekha Formation are thought to underlie the Pele La Group, here shown to be of Furongian age. A possible explanation of this significant anomaly is that rocks currently assigned to the Chekha Formation are of different depositional age in different regions. Additional stratigraphic constraints on the depositional age of the Chekha Formation are required.

Several samples collected in southern Bhutan, south of the Main Central Thrust from the Baxa Group and its lateral equivalents, also resemble our Wachi La spectra (McQuarrie *et al.* 2008, fig. 5). In particular, NBH-5 and NBH-18 bear similar profiles, except for a grain of about 300 Ma age in sample NBH-18, which we consider likely to be unreliable. We concur with McQuarrie *et al.* (2008, p. 112) in interpreting these spectra to indicate depositional continuity between the Lesser Himalaya and Tethyan Himalayan parts of the Cambrian margin in Bhutan, supporting the continuous margin model of Myrow *et al.* (2003) and others. We also note that the proportion of Mesoproterozoic and Palaeoproterozoic grains is significantly higher in samples in which 500 Ma grains are absent or uncommon (McQuarrie *et al.* 2008, fig. 5; Myrow *et al.* 2010). As Proterozoic grains are present in all samples of Cambrian rocks from the Himalaya, even those with many younger grains, we consider their reduced prominence in the younger samples to be the result of dilution.

We note that a sample from a trilobite-bearing interval from the Tal Group of India with a depositional

age of *c.* 515 Ma lacks any grains younger than 625 Ma, but that a younger sample with a depositional age of *c.* 511 Ma contains grains as young as 553 Ma (Myrow *et al.* 2010). The interval between the deposition of these two samples could span the time of the earliest exhumation of the Cambrian Himalayan granites in the west-central Himalaya. Sedimentary rocks that lack grains of about 500 Ma were thus likely deposited more than 515 Ma ago. McQuarrie *et al.*'s (2008) sample NBH-7 lacks grains younger than about 850 Ma, and given the abundance of young Neoproterozoic grains in every published Cambrian sample in the Himalaya, was likely deposited significantly earlier in the Neoproterozoic. Hence we disagree with McQuarrie *et al.* (2008, p. 112) in viewing the age of the Baxa Group as *entirely* Cambrian or younger. Rather, we consider it likely that it represents a Neoproterozoic to Cambrian succession, as in the outer Lesser Himalaya of western central India. That aside, the lack of biostratigraphic data from the Baxa Group makes it difficult to correlate precisely this LH unit in Bhutan with any unit in the Chekha Formation, Pele La Group, or other units along strike in the Himalaya.

The ages of the youngest components of sample WL-1 indicate that the Deshichiling Formation is also Furongian (upper Cambrian). The striking abundance of 500 Ma grains in both the Deshichiling and Quartzite formations indicates that granitic intrusions associated with the Himalayan Kurgiakh (Srikantia, 1981) or Bhimphedian Orogeny (Cawood, Johnson & Nemchin, 2007), part of the late assembly of Gondwanaland, were cooled, exhumed, and eroded shortly after their emplacement.

7. Relationships with sedimentary successions in the Central and Western Himalaya

The presence of post-early Cambrian and pre-Permian Palaeozoic rocks in Bhutan has been used to suggest similarity of the Wachi La regional stratigraphy with the Tethyan Himalaya in other parts of the Himalaya. In particular, correlations have been proposed with the Martoli and Garbyang formations of Kumaon (Nautiyal *et al.* 1964; Chaturvedi, Mishra & Mulay, 1983*b*) and the Parahio Formation of Spiti (Bhargava, 1995). In fact, the trilobites and brachiopods described in this paper are not direct correlatives with deposits known anywhere else in the Himalaya, because the Bhutan strata are younger than any other Himalayan Cambrian strata. Our Wachi La collections are from Stage 9 of the Furongian Series (about 493 Ma old), whereas the youngest Cambrian faunas known elsewhere in the Himalaya are from the *Proagnostus bulbus* Zone of the Guzhangian Stage, and are thus about 501 Ma old (Peng *et al.* 2009). Given that the Deshichiling Formation also contains zircon grains as young as 489 ± 8 Ma, it is possible that the entire Bhutanese succession that we have studied is younger than the youngest Cambrian deposits recorded in Spiti. Our collections are also younger than the putative late

Cambrian trilobite fauna described from Kashmir (Jell, 1986) which, in our opinion, is also likely to be Guzhangian in age.

Lesser Himalayan sedimentary successions are distinguished from Tethyan Himalaya ones by the distinctive Permian unconformity (Brookfield, 1993), which cuts out all other post-Cambrian Palaeozoic rocks (see above). However, recent work on Himalayan Cambrian deposits has shown that at that time a continuous passive margin occupied the areas now represented by the Lesser Himalaya, Greater Himalaya and Tethyan Himalaya (Myrow *et al.* 2003, 2009, 2010; Hughes *et al.* 2005). Although some of the Bhutanese Cambrian rocks are younger than those known elsewhere in the Himalaya, the siliciclastic shelfal lithofacies of the Cambrian succession in Zanskar, Spiti, Kumaon and Qomolangma are broadly comparable to those in Bhutan, and the detrital zircon populations appear to be fundamentally similar. Hence Bhutan may have been part of the same passive margin sequence.

Relationships between the Pele La Group and the overlying Wachi La Formation on the Wachi La are uncertain due to incomplete exposure. However, tabulate corals recovered in the Wachi La limestone, above the fault at the top of our section (Fig. 5), suggest a late Ordovician/early Silurian age (Dr Bernard Hubmann, pers. comm. 2009). If this identification is confirmed, it significantly revises the inferred age of the Wachi La Formation, currently considered to be of late Palaeozoic age (Bhargava, 1995; Tangri & Pande, 1995).

In the western-central Himalaya region, including the Kumaon, Spiti and Zanskar, Cambrian deposits are unconformably overlain by a thick coarse red conglomerate and sandstone succession that is probably Middle Ordovician or earlier in age (Torsvik *et al.* 2009). However, in Tibet, Cambrian deposits are in fault contact with Early Ordovician blue-weathering limestone (Myrow *et al.* 2009). Correlation of any of those rocks with the Bhutan sequence is presently unclear. It has been suggested that a polymictic conglomerate that reportedly underlies the Quartzite Formation near Kha-Khola of the Tongsa district in the southern Black Mountains (Gupta, 2004; Gupta & Bandyopadhyay, 2009) correlates with the Thango conglomerate of India (Chaturvedi, Mishra & Mulay, 1983*b*, p. 228). This horizon is also associated with copper sulphide mineralization in the adjacent Gongkhola–Nobji Chu region (Gupta, 2004; Gupta & Bandyopadhyay, 2009). We have examined a prominent conglomerate above the town of Ura at N 27°29.565′, E 090°55.154′ at 3548 m altitude in the Ura klippe that has been specifically correlated with the Kha-Khola conglomerate (Chaturvedi, Mishra & Mulay, 1983*b*, p. 227). It has characteristics significantly different from the Indian conglomerate. First, the clasts consist entirely of well-sorted and well-rounded cobbles of white, mature quartzite, which are surrounded by matrix of similar grain size and texture. The Ordovician conglomeratic deposits in northern

India are poorly sorted, variably rounded and highly polymictic (Myrow *et al.* 2006*b*). Second, the cobbles of the Bhutan conglomerate are strongly deformed parallel to bedding. These cobbles are stretched so that originally spherical clasts presently have aspect ratios of 10:1. Confirmed Cambrian rocks in Bhutan are relatively unmetamorphosed in comparison with the marked deformation represented by these clasts. For these reasons, we consider this conglomerate may represent a different deformation (also see Tangri & Pande, 1995).

In summary, important questions remain to be resolved concerning the correlation of Bhutanese Cambrian and Ordovician rocks with those along the Himalayan margin. With regard to the Wachi La section, no conglomerate is evident in Pele La Group, and no marked unconformity is indicated within the group or at the boundary with the Wachi La Formation. At Wachi La the boundary between the Quartzite Formation and the Wachi La Formation is a fault (see above).

8. Relationships with sedimentary successions in other parts of Asia

Himalayan Cambrian rocks described to date record parts of the first three series of the Cambrian System. This paper is the first record of Himalayan rocks of the fourth Cambrian series, the Furongian. Although older Cambrian faunas have been described from North and South China, Australia and Iran, such information is lacking for several significant tectonic units such as the Lhasa-Myanmar block, Sibumasu, Tarim and Indochina. These latter areas have deposits of Furongian age, as do both North and South China, and this permits a broader evaluation of the regional context of the Himalayan fauna.

Lithologically the Bhutanese fauna is part of a sandstone succession broadly comparable to that of the 'inner detrital belt' of Laurentia (Palmer, 1960). The lithology resembles that of trilobite collections made from the Northern Shan States of Myanmar (Myint, 1973), Tarutao Island in Thailand (Shergold *et al.* 1988) and the Baoshan region of western Yunnan (Sun & Xiang, 1979; Luo, 1982, 1983, 1984, 1985). However, although the Bhutanese fauna is Asiatic and resembles that from the areas just listed in a general way, it shows specific affinity with that collected from a carbonate lithofacies in North China. Hence, while our faunal and detrital zircon analysis suggests that the Himalayan margin was contiguous with that of other areas of southeastern Asia during the late Cambrian, faunal evidence suggests particularly close linkage between Bhutan and North China.

9. Conclusions

The low-diversity trilobite fauna from the Quartzite Formation of the Pele La Goup at the Wachi La is representative of a late Cambrian Furongian (stage 9)

age, approximately 493 Ma. This age is consistent with the ages of the youngest detrital zircon grains in a sample analysed from the trilobite-bearing beds. Similarity of the Bhutanese faunal assemblage to that of the North China block argues for geographic proximity between North China and north India during the Cambrian.

Detrital zircon spectra from the Pele La Group are similar to spectra from rocks of comparable age throughout the Himalaya, suggesting these strata where deposited in the same continuous margin as the rest of the Himalaya. The presence of *c.* 500 Ma zircons in the upper part of the Deshichiling Formation provides a maximum age constraint of late Cambrian for the deposition of this unit. This is conformably overlain by the Maneting Formation, which is then conformably overlain by the Furongian Quartzite Formation. This result suggests that the stratigraphic interval from the upper part of the Deshichiling to the Quartzite Formation in the Wachi La section is all Furongian in age. Claims that the transition from the Deshichiling Formation to the Maneting Formation marks the Precambrian–Cambrian boundary are here rejected. The high concentration of 500 Ma zircons in relatively young strata (*c.* 493 Ma) is a signature of the Cambro-Ordovician tectonic event seen throughout the Himalayan margin.

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