Journal of Asian Earth Sciences 214 (2021) 104775

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

The first systematic description of Cambrian fossils from Myanmar: Late Furongian trilobites from the southern part of the Shan State and the early Palaeozoic palaeogeographical affinities of Sibumasu

Shelly J. Wernette [a,*], Nigel C. Hughes [a,b], Paul M. Myrow [c], Aye Ko Aung [d]

[a] Department of Earth and Planetary Sciences, University of California, Riverside, Riverside, CA 92521, USA
[b] Geological Studies Unit, Indian Statistical Institute, 208 B.T. Road, Kolkata 700018, India
[c] Department of Geology, Colorado College, Colorado Springs, CO 80903, USA
[d] Department of Geology, Dagon University, Min-Ye-Kyaw-Swar Road, Dagon Myothit (East), Yangon 11422, Myanmar

ARTICLE INFO

Keywords:
Burma
Eosaukia
Asioptychaspis
Molohein
Palaeotethys
Mesotethys

ABSTRACT

The existence of late Cambrian (Furongian) trilobites in Myanmar (Burma) has been acknowledged since the 1970s, but no formal systematic descriptions of such fossils have been published to date. Herein, we provide such descriptions of some trilobites from the Molohein Group's Myet-Ye Formation from the Linwe area, Ye-Ngan Township of the southern Shan State. Three species from two genera are reported: *Asioptychaspis* (*A. asiatica*, previously known from the North China Block, and a new species, *A. lata*) and *Eosaukia buravasi*, also known from peninsular Thailand. The Molohein Group was initially assigned a late Cambrian age based on the reported, but unsubstantiated, occurrence of the Laurentian genera *Saukiella* and *Drumaspis*, and this age assessment is supported by the fauna we present, although *Saukiella or Drumaspis* remain unconfirmed from Myanmar. *Asioptychaspis asiatica* first appears in late Jiangshanian strata, and *Eosaukia buravasi* ranges up to the middle of Stage 10. Thus these ranges provide a more specific constraint on the age of the Molohein Group. Similarities are strong between upper Cambrian and Lower Ordovician successions in Sibumasu and northwestern Australia, particularly those from the Canning Basin succession. Regional geological data supports placement of Sibumasu adjacent to Western Australia during the Cambrian, without the Lhasa Block intervening between them, and Baoshan at the western end of Sibumasu during the early Paleozoic, towards the Himalayan margin. The new Burmese fauna is consistent with these suggestions, as they belong to the Sino-Australian faunal province.

1. Introduction

Myanmar is one of the few remaining countries on Earth that host fossil-bearing Cambrian deposits but from which no systematic descriptions of such fossils have yet been published. Here we describe several Cambrian trilobites from the Shan Plateau, the defining physiographic feature of the Shan State in Myanmar, which is marked by the uplift of a large mass of Precambrian, Palaeozoic, and Mesozoic rock. We also review constraints on the early Palaeozoic palaeogeography of this and adjacent regions. The Shan plateau is part of the ancient terrane termed Sibumasu by Metcalfe (1984), which is conventionally shown as being separated from the West Burma Block of western Myanmar by the Shan Scarp and associated Sagaing Fault (Ridd, 1971) (Fig. 1). In addition to part of eastern Myanmar, Sibumasu encompasses parts of southwest Yunnan, western Thailand, the northern part of peninsular Malaysia, and some of Sumatra (Metcalfe, 2013a, 2013b, 2017; Mitchell et al., 2012; Udchachon et al., 2018). Lower Palaeozoic faunal assemblages are a key source of evidence for determining palaeogeographic relationships and tectonic history among equatorial *peri*-Gondwanan terranes (e.g., Fortey and Cocks, 1998, 2003; Hughes et al., 2002; Laurie and Burrett, 1992; Metcalfe, 1992; Niko and Sone, 2015), and here we consider the implications of the newly discovered fossils for tectonic affinities. We use the term equatorial *peri*-Gondwana to include Sibumasu, the West Burma Block, North China (=Sino-Korea), South China, Tarim, Indochina, Simao, and other smaller putative terranes.

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* Corresponding author.
E-mail addresses: swern001@ucr.edu (S.J. Wernette), nigel.hughes@ucr.edu (N.C. Hughes).

https://doi.org/10.1016/j.jseaes.2021.104775
Received 6 November 2020; Received in revised form 13 March 2021; Accepted 4 April 2021

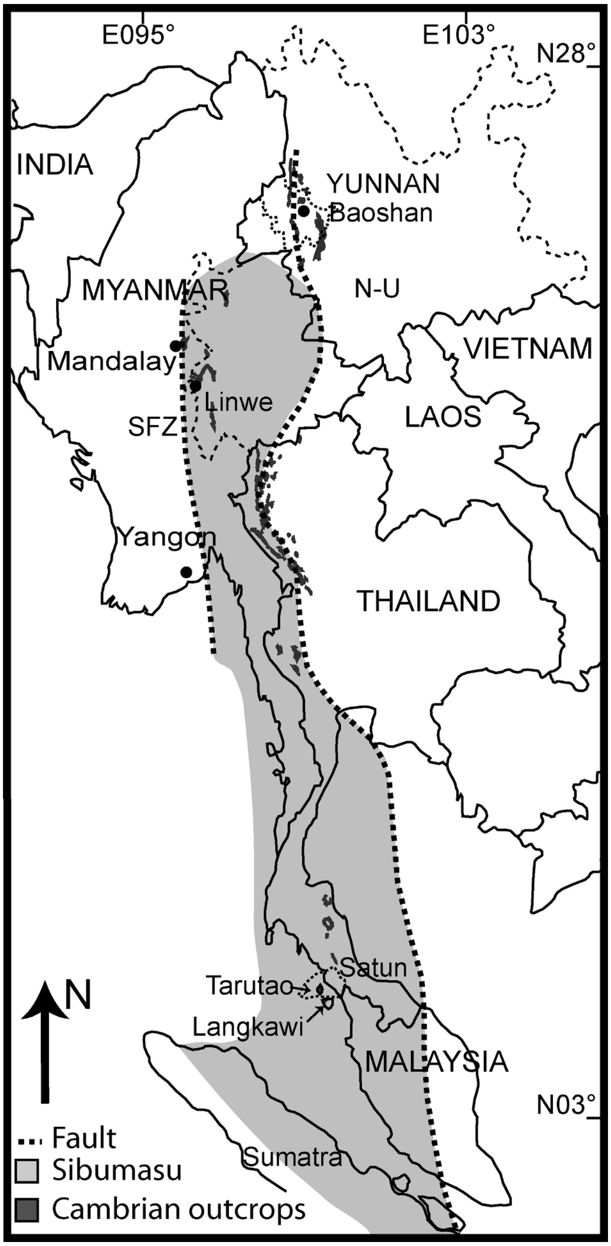

Fig. 1. The modern extent of the Sibumasu terrane. Modified from Wernette et al. (2020a). Suture and fault abbreviations are as follows: N-U = Nan Uttaradit Suture Zone; SFZ = Sagaing Fault Zone/Shan Scarp.

1.1. *Prior palaeontological work on the Cambrian of Myanmar*

Cowper Reed (1906, 1908, 1915, 1936) published descriptions of Ordovician through Devonian fauna as part of the Geological Survey of India's early work on the regional geology of the Myanmar region, including the "Lower Palaeozoic Faunas of the Southern Shan State" (Reed, 1936), but Myanmar's Cambrian strata were unrecognized at that time, as the Ordovician Naungkangyi beds were thought to directly, and unconformably, overlie the Precambrian Chaung Magyi (La Touche, 1913). Following an initial, informal conference report on Cambrian rocks from the Pangyun Formation in the northern Shan State (Thaw Tint, 1972), the Molohein Group was the first Cambrian unit to be described in a formal publication (Myint Lwin Thein, 1973). Although these Cambrian deposits have been mentioned in numerous subsequent publications on Burmese geology (e.g., Aye Ko Aung and Cocks, 2017; Bender, 1983; Bhargava, 1995; Wolfart et al., 1984), including the cursory application of several previously established trilobite species names (e.g., Myint Lwin Thein, 1973; Thaw Tint, 1972, 1974) and illustration of three unidentified saukiid pygidia (Aye Ko Aung, 2012, Fig. 1), no material has ever been formally described. Taxa historically reported from the Molohein Group include *Saukiella junia* (Walcott) var. A Winston and Nicholls, 1967*, Eosaukia buravasi* Kobayashi, 1957*,* and *Drumaspis texana* Resser, 1942 (Aye Ko Aung, 2012; Aye Ko Aung and Cocks, 2017; Myint Lwin Thein, 1973; Thaw Tint, 1972, 1974). The recognition of saukiids has been considered sufficient to assign an uppermost Cambrian age to the Molohein Group (e.g., Aye Ko Aung, 2012; Aye Ko Aung and Cocks, 2017; Bender, 1983; Wolfart et al., 1984), but given that *Saukiella* and *Drumaspis* are both characteristically Laurentian taxa, these generic assignments are surprising and, without published illustrations and descriptions, remain unconfirmed.

The only figured and described record of Myanmar's Cambrian trilobites is a comprehensive, but unpublished, Master's thesis on the lower Palaeozoic fauna and stratigraphy of the Ye-Ngan township (Soe, 1983). In his faunal analysis for this area, Soe (1983) did not suggest the occurrence of any new or endemic species, assigning all material to the following taxa: *Saukiella junia* (Walcott) var. B Winston and Nicholls, *Saukiella* cf. *S. junia* (Walcott) var. A Winston and Nicholls, *Saukiella* cf. *S. fallax* (Walcott), *Saukiella* sp., *Calvinella* cf. *C. prethoparis* (Longacre), *Calvinella* cf. *C. ozarkensis* (Walcott), *Calvinella* sp., *Eosaukia buravasi* Kobayashi, *Ptychaspis* cf. *P.* (*Asioptychaspis*) *delta* (Shergold), *Solenopleura* sp., *Prosaukia* cf. *P.*? *absoma* Shergold, and *Ptychaspis* sp. While this thesis provided valuable new information about the fauna of Myanmar, the specimens, which were predominantly from float material, were subsequently lost.

Based on specimens collected during an expedition to the Linwe area in November–December 2016 we describe the Cambrian trilobite fauna in the southern Shan State to include *Eosaukia buravasi*, *Asioptychaspis lata* n. sp., and *Asioptychaspis asiatica* Endo and Resser. This article is the first of several reports on the fauna, environments, and geochronology of upper Furongian and Lower Ordovician Burmese sections, and reviews in some detail what is currently known of the early Paleozoic history of the region. This will provide context for a series of forthcoming works on the geochronology of Sibumasu during that interval.

2. Geological setting

2.1. *Sibumasu*

Sibumasu was first recognized as a discreet entity based on its emergence as an isolated continental fragment following rifting from Gondwana, perhaps conjoined with the Qiantang block of Tibet (Audley-Charles, 1988; Cai et al., 2017, Fig. 9; Metcalfe, 1994, 2013a; Sengör, 1984; Sone and Metcalfe, 2008; but also see Xu et al., 2014a, Fig. 1). The opening of the ocean between Sibumasu and Gondwana, which in southeastern Asia is commonly referred to as Meso-Tethys (Metcalfe, 1994, 1998, 2011a, Fig. 5, 2013a,b, 2017), occurred by the late Carboniferous to earliest Permian (Metcalfe, 1996; Ridd, 2015), although some suggest that it was perhaps earlier (Zhao et al., 2017; Zhu et al., 2013). Prior to rifting from Gondwana, Sibumasu had formed part of the supercontinent's leading margin, a position obtained after other Asian material rifted away with the opening of the Palaeo-Tethys Ocean (e.g., Sengör, 1979; Metcalfe, 1994, 1996, 2006, 2013a, 2017; Li et al., 2004, p. 293; Torsvik and Cocks, 2017; Veveers, 2004). As Palaeo-Tethys closed in the Triassic, the eastern flank of Sibumasu collided with Indochina and South China (Aye Ko Aung and Cocks, 2017; Metcalfe, 2006, 2017; Ridd, 2015, 2016; Searle and Morley, 2011), forming the Lincang-Sukhothai–Lao fold belt (a continental arc) and the Chiang Mai–Chiang Rai–Bentong–Raub suture zone (Metcalfe, 1994, 2017, Fig. 12; Searle et al., 2007). Sibumasu's bounding faults (Fig. 1) encompass a unit with a unique Permian climatic history (Metcalfe, 1984, 1992, 2013a,b, 2017, but also see Ridd, 2016) related to its rapid migration as a continental fragment toward the tropics. The West Burma

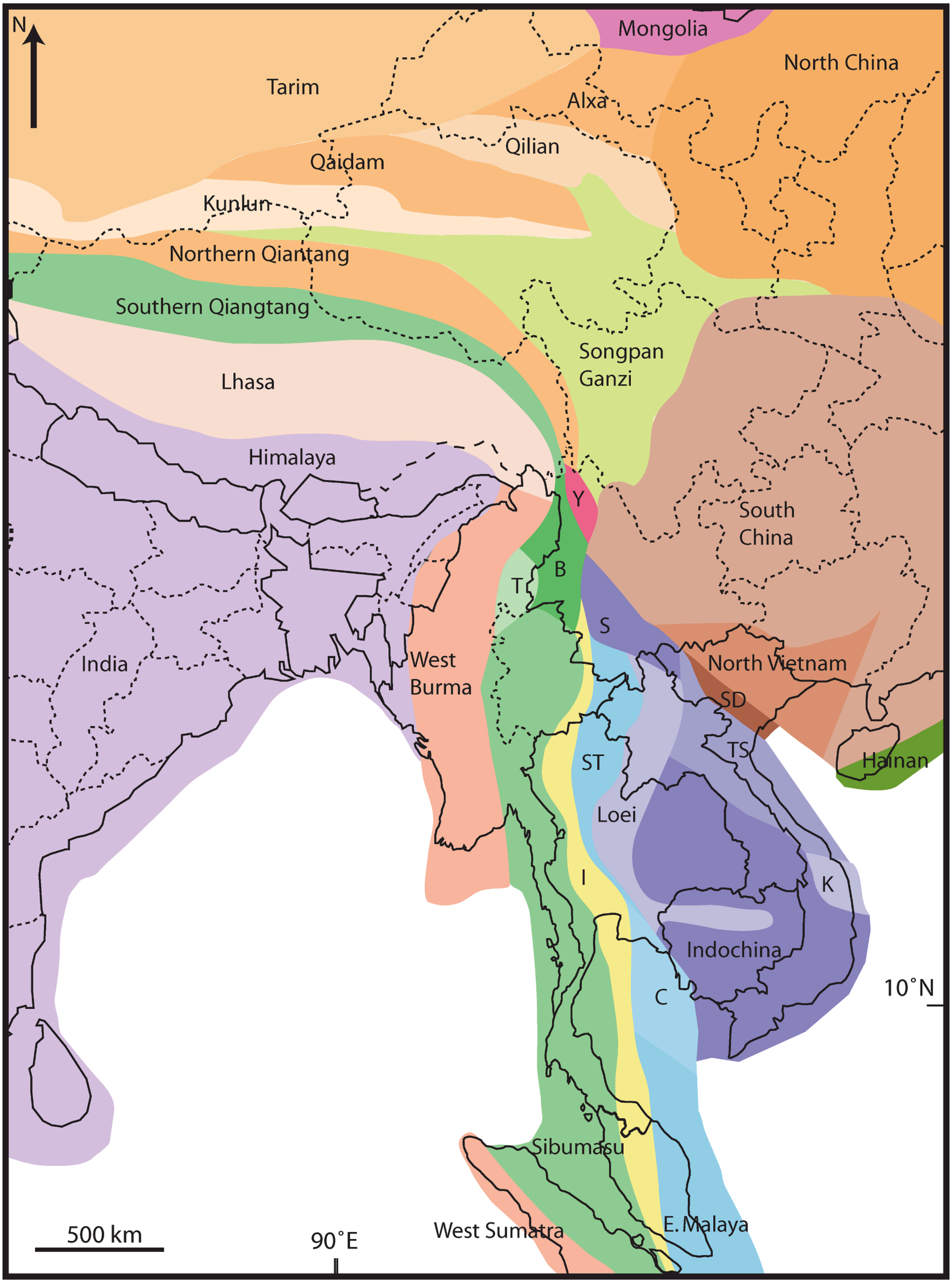

Fig. 2. Asian Equatorial Gondwanan terranes in their modern configuration. The full names of abbreviated terranes are: B = Baoshan; C = Chanthaburi Terrane; I = Inthanon; K = Kontum; L = Loei; S = Simao; SD = Song Da; ST = Sukhothai; T = Tenchong; TS = Truong Son; Y = Yunling Collage. Modified from Burrett et al. (2014), Cai and Zhang (2009), Hughes et al. (2002), Li et al. (2016), Metcalfe (2006, 2011, 2017), Xie et al. (2016) and Zhao et al. (2017).

Block, possibly with the Lhasa Block attached to it, may have collided with Sibumasu's western flank in the Late Jurassic to Early Cretaceous (Gardiner et al., 2015; Mitchell et al., 2012; Searle et al., 2012, 2017), closing the Meso-Tethys ocean. Associations of the West Burma Block are currently in debate (Metcalfe, 2017, p. 37-39).

2.2. Sibumasu precursor relationships of the Shan–Thai area to the Gondwanan margin

The pre-Tethyan history of the Sibumasu Block is interpreted by linking its geology and biota to that of other regions. Recent early Palaeozoic reconstructions consistently show Sibumasu as one of several continental fragments located peripheral to the equatorial Gondwanan core, and placed adjacent to northwestern Australia (e.g., Ali et al., 2013, Fig. 19; Burrett et al., 2014, Figs. 11–13; Domeier, 2018, Fig. 19; Hu et al., 2015, Fig. 12a; Lin et al., 2013, Fig. 1; Metcalfe, 2013b, Fig. 11a; Niko and Sone, 2015, Fig. 3; Torsvik and Cocks, 2017, Fig. 5.5; Tran et al., 2014, Fig. 12; Xie et al. 2016, Fig. 7; Xing et al., 2017, Fig. 10a; Zhang et al., 2015, Fig. 12; Zhao et al., 2017, Fig. 9; Zhu et al., 2013, Fig. 7b). Most reconstructions (e.g., Boger and Miller, 2004; Cawood and Buchan, 2007; Cocks and Torsvik, 2013; Meert, 2003; Torsvik and Cocks, 2017, Fig. 5.1) suggest that core Gondwana, consisting of South America, Africa, India, Antarctica, and Australia, had amalgamated by the early Cambrian, although this view is not universally accepted (e.g., Schmitt et al., 2004).

Evidence for the specific placement of Sibumasu adjacent to northwestern Australia is based on the cumulative Palaeozoic history of the two regions prior to the opening of the Meso-Tethys ocean (e.g., Metcalfe, 2013b, Fig. 6). Four lines of evidence have been used: palaeomagnetic data, detrital zircon geochronology, tectonostratigraphy, and palaeobiology. Estimates of Sibumasu's paleolatitude are well established for Devonian and younger rocks (Ali et al., 2013; Domeier, 2018; Fang et al., 1989; Li et al., 2004, Figs. 3–5; Metcalfe, 2011a, Fig. 4; Torsvik and Cocks, 2004, Table 1), but no data for pre-Devonian strata are currently available for the Thai–Burmese part of Sibumasu. However, palaeomagnetic data for the Cambrian of Baoshan (Li et al., 2004, Fig. 4) suggests a low latitude Cambrian setting, similar to that for North China (Huang et al., 1999, 2000; Zhao et al., 2020), South China, and Australia (Li et al., 2004, Fig. 4) during that period, although the reliability of these data has been queried (Burrett et al., 2014).

Sibumasu's detrital zircon age profiles for Cambrian sandstone from peninsular Thailand's Tarutao Island (Burrett et al., 2014, Fig. 3A-C; McKenzie et al., 2014, Fig. 2) and Myanmar (Cai et al., 2017), span a wide range of grain ages, with distributions broadly characteristic of most late Cambrian equatorial Gondwana terranes (Myrow et al., 2010). These data suggest that the sedimentary material accumulating in Sibumasu and other equatorial Gondwanan terranes was similarly sourced, and thus part of the continuous margin. Based on comparing grain age distributions using the Kolmogorov–Smirnov statistical test, Burrett et al. (2014, p. 35) made the case that profiles of upper Cambrian sandstone samples from Tarutao, and a sample from the Ordovician Tumblagooda Sandstone of northwestern Australia, are notably similar ($p = 0.895$), but typically the similarity metrics between the pooled Tarutao sample and various Western Australian samples are notably lower, with the next highest sample yielding $p = 0.210$ (Burrett et al., 2014, Table 2). As for the associations between Sibumasu and other "outboard" terranes, the profiles of Cambrian samples from Sibumasu, North China, and the Himalaya appear comparable (McKenzie et al., 2014, Fig. 2), although such linkages receive very weak support from the Kolmogorov–Smirnov test statistic ($p < 0.01$; Burrett et al., 2014, Table 2). As is generally the case with statistical tests, the Kolmogorov–Smirnov test assumes that the distributions of grain age in the individual samples are drawn from the same underlying distribution of ages, unless a significant difference can be detected between them. As the ability to detect a significant difference depends on sample size, non-significant differences between individual, rather than pooled, samples are more prone to Type II error. Hence, although the apparent similarity between the Tumblagooda Sandstone and one of the Tarutao samples may suggest that they shared the same set of sediment sources, the result is not conclusive. The pooled Cambrian data from South China shows a broad peak of Neoproterozoic zircons that distinguishes it from some other Asian samples, including Sibumasu (McKenzie et al., 2014, Fig. 2), even though the test statistic hints at stronger association between Sibumasu and South China than between Sibumasu and North China. This similarity is particularly strong if northeast Vietnam is considered as part of South China (Burrett et al. 2014, Table 2). Other parts of south China, especially northwest Yangtze, suggest weaker association with Sibumasu according to the Kolmogorov–Smirnov test (Burrett et al. 2014, Table 2). Overall, the grain age distributions are consistent with widespread sediment transport and mixing along the *peri*-Gondwanan margin (Myrow et al., 2010), but do not presently provide strong evidence for distinctions within the region.

The temporal history of rifting and suturing on either flank of Sibumasu, discussed above, provides important constraints on Sibumasu's original position within the complex of "outboard" *peri*-Gondwanan terranes. Middle to late Palaeozoic rifting history places Sibumasu more "inboard" within *peri*-Gondwana than those areas that had earlier rifted from its now eastern margin. However, this does not constrain from whence Sibumasu rifted. Metcalfe (1996, Fig. 6; 2013b, Fig. 7) summarized Palaeozoic stratigraphic correlations between Sibumasu and Australia, which are mostly of a general lithologic nature, and highlight distinctive correlative horizons, such as the Permian diamictite deposits present in both regions (but also found widely elsewhere in Gondwana). For the upper Cambrian, Shergold et al. (1988, p. 305) suggested an "inner detrital belt" depositional environment extending across Australia, northern Vietnam, Yunnan, western Thailand, western Sichuan, Ganzu, and eastern Qinghai. He equated this to the "Sino-Burma geosyncline" of Sun (1945), and proposed that this outcrop belt was the onshore, siliciclastic-dominated equivalent of carbonate platforms that were developing in North China at the time. This is akin to the well documented inner detrital belt/carbonate platform association in the late Cambrian of Laurentia (e.g., Aitken, 1966; Palmer, 1960, 1971; Robison, 1960). Shergold (1988) considered both this "inner detrital belt", and the carbonate platform deposits of the North China block, to host the "tsinaniid-saukiid biofacies", which was interpreted to have occupied a shallow epiric sea. This suggestion of a continuous belt of nearshore siliciclastic facies contrasts with more recent sedimentological and tectonic investigations that show the northern part of this region to comprise a complex set of island arc and accretionary complexes, including the Qaidam Block (Chen et al., 2012; Xiao et al., 2009), the Qilian Block, and mobile belts (Zhang, 1988, chart 4; Fu et al., 2019; Huang et al., 2000; Song et al., 2013; Zhou et al., 1996), and the Alxa Terrane (Zhang et al., 2015), each with an individual history, including episodes of deep water siliciclastic deposition. Furthermore, the Cambrian of Vietnam, although it contains a fine-grained siliciclastic component in places, is almost exclusively carbonate (Pham, 2008), and is thus not "inner detrital". Accordingly, Shergold's (1988) and Shergold et al.'s (1988) concept of a continuous belt of clastic inner detrital belt facies spanning all these regions is no longer tenable.

That said, shallow shelf siliciclastic facies of both the Molohein and the Tarutao groups do sedimentologically resemble a set of "inner detrital" shallow marine sandstone units of similar age in Australia (Shergold, 1988), as also do slightly older rocks from Bhutan (Hughes et al., 2011). The comparable Australian rocks include the lower Nambeet Formation of the Canning Basin (Normore et al., 2018), the Clark and Pander sandstone units of the Bonaparte Basin, the Goyder and Pacoota sandstone formations of the Amadeus Basin, the Mootwingee Group of the Gnalta area (Shergold et al., 1985, Charts 1,5,6), and an unnamed sandstone/siltstone unit in Tasmania's Misery Hill (Jago and Corbett, 1990). The Pander Sandstone of the Bonaparte Basin, which is the part of Australia to which Sibumasu is placed most closely in the largest number of recent reconstructions, contains notable glauconite, which is absent from similarly aged rocks in Sibumasu. A core into the Canning Basin reveals at least 1000 m of sandstone unconformably overlying basement and underlying latest Tremadocian and Floian age limestone with conodonts and tuffs (Normore et al., 2018). This stratigraphic succession is comparable to the upper Cambrian–Tremadocian successions in the Shan–Thai region, and is specifically similar to the Ao Phante Malacca section on Ko Tarutao (Stait et al., 1984; Udchachon et al., 2018, Fig. 8). Compared to that succession, the limestone facies may be slightly younger in the Canning Basin, as indicated by conodont fauna (Agematsu et al., 2008; Normore et al., 2018), possibly reflecting a transgressive succession in which Ko Tarutao was located somewhat further offshore. Comparable sandstone facies are also found in Bhutan, although the part of the Bhutanese succession that has been precisely dated is slightly older stratigraphically (Hughes et al., 2011; Greenwood et al., 2016) than the dated Sibumasu Cambrian succession.

The Cambrian sedimentary rocks of Sibumasu, where dated, are all uppermost Cambrian (Kobayashi, 1957; Shergold et al., 1988; Wernette et al., 2020a,b). In Malaysia and the Satun Province of Thailand, the basement upon which these rocks rest is not exposed, but in Myanmar these upper Cambrian sedimentary rocks unconformably overly the poorly dated but possibly upper Neoproterozoic Chaung Magyi Group. In these areas the oldest dated Cambrian rocks are those bearing *Asioptychaspis asiatica* Endo and Resser, whose presence in Myanmar is first documented herein. In Baoshan, the succession extends lower into the Cambrian (Luo 1985a) (see below), but the age of the oldest Cambrian strata in Baoshan, and its basal relationship is also poorly constrained. In contrast, in some parts of peninsular Thailand the gneissic basement has a metamorphic age as young as 501.5 ± 7.5 Ma (Lin et al., 2013). Such an age is consistent with that of widespread granite bodies in the region and, at the younger end of its error margin, is equivalent to the depositional age of part of the Tarutao Group. Accordingly, the record of the oldest sedimentary rocks within Sibumasu is regionally variable, but upper Cambrian sedimentary successions are preserved in most parts of it.

A notable aspect of the upper Cambrian geology of Sibumasu is the presence of numerous volcanogenic deposits. Tuffs are common throughout many of the Tarutao and southern Shan State sections, and there is an extensive rhyolite body at Bawdwin in the northern part of the Shan State (Brinckmann and Hinze, 1981; Gardiner et al., 2017; Mitchell, 2018). At the regional scale, late Cambrian – early Ordovician intrusive magmatism was widespread along the equatorial margin of Gondwana (e.g., Hu et al., 2015, Fig. 12; LeFort et al., 1986; Li et al., 2016, Fig. 16; Lin et al., 2013; Liu et al., 2009; Miller et al., 2001; Shi et al., 2016; Zhu et al., 2012, Fig. 9a), but the occurrence of volcanogenic deposits is geographically confined, with Sibumasu bearing the most notable record. Middle Cambrian ophiolitic remnants in the Qilian mobile belt and adjacent areas and the flood basalts of the lower Cambrian Kalkarindji Igneous Province (e.g., Shergold et al., 1985, Charts 1–3,7,8; Cocks and Torsvik, 2013, Fig. 10) are unlikely to be directly related to marginal Gondwana's late Cambrian–Ordovician, mostly felsic magmatism, but the record of Lower Ordovician ash beds in the Nambeet Formation of the Canning Basin (Normore et al., 2018), along with a comparable stratigraphic succession to peninsular Thailand's Lower Ordovician sections (see above), provide a stratigraphic link between Australia and Sibumasu. An ash dated at 500 Ma ± 4 (Greenwood et al., 2016), and possible correlative upper Cambrian basalts from the Bhutanese Himalaya (Bhargava, 1995; Tangri and Pande, 1994, 1995), may also suggest association between Bhutan and Sibumasu during the late Cambrian.

Palaeontological evidence constraining the Gondwanan relationships of Sibumasu spans the full range of Palaeozoic sedimentary rocks (e.g., Metcalfe, 2013b, Fig. 6) and has recently been aptly summarized by Burrett et al. (2016). Particular associations between Western Australia and Sibumasu have been posited for the Carboniferous and Permian (e.g., Wang et al., 2001) but biotic evidence supports recognition of a broad "Sino-Australian faunal province" prior to the opening of Paleo-Tethys (Metcalfe, 2013b, Fig. 11; Zhan et al., 2014; Zhou and Dean, 1989). This province comprises the Australian sector of core Gondwana and the *peri*-Gondwanan terranes of South China, North China, Indochina, and Sibumasu, along with parts of Tibet and the Himalayan margin. Resolving specific paleogeographic relationships within this region using biotic data has proven to be challenging. With regard to the Cambrian through Tremadocian, palaeontological data suggests affinity between Shan–Thai and Australia faunas (Kobayashi, 1957; Shergold, 1991; Shergold et al., 1988; Wernette et al., 2020a,b), but also with North China faunas. All three terranes contain such genera as *Tsinania*, *Mansuyia*, *Parakoldinioidia*, *Pseudkoldinioidia*, *Pagodia*, *Asaphellus, Haniwa, Eosaukia, Lophosaukia, Quadraticephalus, Akoldinioidia,* and *Koldinoidia*, though some have not yet been formally described from Sibumasu. All of these, excluding *Quadraticephalus*, also occur in South China, although South Chinese specimens of *Eosaukia* and *Haniwa* are only tentatively assigned to those genera (Zhou and Zhen, 2008). Research on Early and Middle Ordovician cephalopod and brachiopod faunas allies Thai, northern Malaysian, and Burmese forms to Australian fauna (e.g., Laurie and Burrett, 1992; Niko and Sone, 2015), to North Chinese fauna (e.g., Niko and Sone, 2014; Stait and Burrett, 1982), or to both (e.g., Fang et al., 2018; Stait and Burrett, 1984). The relatively deep water Upper Ordovician Pa Kae Formation in Satun province, Thailand shares multiple trilobite genera (including 4 species) and facies in common with the Pagoda Limestone of the South China Block (Fortey, 1997; Zhou et al., 2016). Studies of conodont faunas from Satun and northern Malaysia show a coincident shift from shelf assemblages in the Early and Middle Ordovician to deeper water forms (Agematsu et al., 2007, 2008), consistent with the trilobite data (Fortey, 1997). Burrett et al. (2016) suggested that faunal links to South China increased in association with Late Ordovician sea level rise, and they noted that there may be some regional biofacies differences within Sibumasu itself (see below).

In summary, Sibumasu's Cambrian placement adjacent to, or close to, some part of the northern Australian margin is a consistent feature of recent palaeogeographical reconstructions, although its particular location is debated and not precisely constrained. Most characteristics shared between Sibumasu and Australia's Palaeozoic geology are general to the wider Sino–Australian region (as defined above), but some more specific lithostratigraphic and faunal similarities, including notable tuffs, may link Shan Thai Cambrian–Ordovician strata to those of this interval preserved in the Canning Basin of Western Australia.

2.3. *The peri-Gondwanan branch of Proto-Tethys*

Early Palaeozoic reconstructions of the *peri*-Gondwanan margin commonly use either the term Proto-Tethyan (e.g., Hu et al., 2015, Fig. 12) or Palaeo-Asian (Li et al., 2018; Han et al., 2016; Zhao et al., 2017) to refer to the ocean bordering the margin from Arabia to Australia. At a global scale, this ocean is considered to separate this sector of the Gondwanan rim from Baltica and Siberia (e.g., von Raumer and Stampfli, 2008). The ocean linked the Panthalassic ocean, which occupied much of the northern hemisphere at the time, to the Rheic/Ran ocean, located at higher southern latitude (Domeier, 2018). Gondwana's early Palaeozoic margin along the Proto-Tethyan ocean is commonly represented as an oceanic trench with subduction beneath the supercontinent (e.g., Domeier, 2018, Fig. 19). However, in the specific context of the early Palaeozoic history of the equatorial *peri*-Gondwanan margin, the term Proto-Tethyan has also been applied to a relatively short lived, early Palaeozoic branch of that wider ocean that separated continental crust from Gondwana across an oceanic trench.

The regional history of this branch of the Proto-Tethyan ocean is the subject of ongoing debate. The occurrence of extensive granitic intrusion around the equatorial Gondwana margin (e.g., LeFort et al., 1986) suggests widespread subduction about its rim (Cawood and Buchan, 2007; Cawood et al., 2007), but debate continues regarding the early Paleozoic positions of the various parts of the margin that were later defined by association with the Palaeo-, Meso-, Ceno-Tethyan oceans. Some reconstructions of Cambrian and early Ordovician paleogeography suggest that these ultimately Asian landmasses were contiguous during those times and formed the equatorial Gondwanan margin (e.g., Han et al., 2016, Fig. 4, Niko and Sone, 2014, Fig. 2, 2015, Fig. 3). In such a case, this would have been an Andean type margin, but this scenario is difficult to reconcile with the occurrences of granite bodies far inboard of what would later form eastern Asia (Cawood and Buchan, 2007; Cawood et al., 2007; Zhu et al., 2012; Lin et al., 2013; Zhang et al., 2014; Hu et al., 2015). Other authors view this inboard igneous activity to be associated with the closure of the equatorial *peri*-Gondwanan branch of the Proto-Tethys, and that it involved the accretion of continental material to the *peri*-Gondwanan rim. This would include either closure of an intracontinental basin on the Gondwanan side of the oceanic trench (Zhai et al., 2016, Fig. 13), accretion of exotic continental material derived from the other side of the subduction zone (Wang et al., 2012, Fig. 9), or some combination of events such as closure of a back arc basin and subsequent merger of the arc with a continental mass approaching from across the subduction zone (Li et al., 2016, Fig. 16; Li et al., 2018, Fig. 10).

Tectonic models involving the collision of continental crust derived exotically from across the trench differ widely in the identities proposed for such crust. Zhai et al. (2016, Fig. 13) showed all the terranes that later broke from equatorial *peri*-Gondwana to form eastern Asia as comprising a single "Asia Hun super terrane", which collided with core Gondwana during the Cambrian (also see Wang et al., 2015). In other reconstructions, those terranes that later rifted from Gondwana with the opening of Meso-Tethys and Ceno-Tethys (Metcalfe, 2017) formed part of core Gondwana in the early Palaeozoic, whereas most that left at the initiation of Palaeo-Tethys were not. The complement of exotic terranes within the proto-Tethys ocean varies widely among authors (Lin et al., 2013, Fig. 1; Hu et al., 2015, Fig. 12a; Xie et al., 2016, Fig. 7; Xing et al., 2017, Fig. 10; Xu et al., 2014b, Fig. 9; Zhao et al., 2017, Fig. 9; Zhu et al., 2011, Fig. 4; Zhu et al., 2012, Fig. 9; Zhu et al., 2013, Fig. 7; Li et al., 2018, Figs. 7, 10), partly reflecting ongoing debate about the later Phanerozoic histories of individual terranes.

In addition to basin closure/collision during the Cambrian – Ordovician boundary interval, other models for this time show narrow ocean basins opening at the distal edge of equatorial Gondwana, associated with the isolation of the North China block, and of the Alxa and Qilian terranes (Han et al., 2016, Fig. 4; Xing et al., 2017, Pan et al., 2012, Fig. 5, Fig. 10; Xiao et al., 2009, Fig. 12). Improved knowledge of the regional early Palaeozoic geology of the region is critical to deciding among the various models for both Proto-Tethys and the original disposition of the *peri*-Gondwana margin.

2.4. Palaeozoic position of the Lhasa Block

In early Palaeozoic reconstructions, the Lhasa Block (Fig. 2) has conventionally been placed to the north of the Indian subcontinent and adjacent to the western margin of Australia, to which Sibumasu was shown attached (Ali, 2013, Fig. 18; Domier, 2018, Fig. 19; Lin et al., 2013, Fig. 1; Torsvik and Cocks, 2009, Fig. 3, 2013, Fig. 10, 2017, Fig. 5.4; Tran et al., 2014, Fig. 14). More recently, many papers have placed the Lhasa Block directly adjacent to western or northern Australia, i.e., in the position that Sibumasu has conventionally occupied. In several such cases Sibumasu (along with other *peri*-Gondwanan terranes) is shown further to the east along Australia's northern margin (Ferrari et al., 2008, Fig. 9; Hu et al., 2015, Fig. 12; Xie et al., 2017, Fig. 11; Yao et al., 2014, Fig. 9; Zhai et al., 2016, Fig. 13; Zhang et al., 2015, Fig. 12; Zhu et al., 2012, Fig. 9). Other reconstructions retain Sibumasu in association with northwestern Australia but insert the Lhasa Block in between the two cratonic areas (Ridd, 2016, Fig. 8; Xie et al., 2016, Fig. 7; Zhao et al., 2017, Fig. 9; Zhu et al., 2011, Fig. 4, 2013, Fig. 7). In such reconstructions Sibumasu sits immediately outboard (i.e., distally) to the Lhasa Block, and thus is attached to Australia only indirectly via the Lhasa Block itself. Another reconstruction (Cai et al., 2017, Fig. 9A) offers a combination of the two models, with Sibumasu placed eastwards along the Australian margin, but with the Lhasa Block separating it from Australia at its western end. All these reconstructions require significant later right lateral displacement of the Lhasa Block to bring it to its current disposition.

The principal argument for an eastward position of the Lhasa Block in Gondwana relative to India is the presence of a 1.2 Ga detrital zircon peak in Lhasa Block samples, which is reportedly absent in profiles from the north Indian margin and Qiantang Block (Zhu et al., 2011). In their modern geographical configuration, these terranes are adjacent to the south and north of Lhasa, respectively, so the 1.2 Ga peak has been used by Zhu et al. (2011) to suggest a geographically separate origin for the Lhasa Block. However, a difficulty with this idea is that prominent peaks of 1.2 Ga detrital zircon grains occur in upper Vindhyan and Delhi Supergroup sandstone samples that accumulated on the Indian craton during the Neoproterozoic (Hughes et al., 2015, Fig. 6). Hence, abundant 1.2 Ga grains are not exclusive to the Australian sector of Gondwana, and thus do not link the Lhasa Block specifically to that region. Likewise, Cambrian–Ordovician samples from Sibumasu and Western Australia also show peaks of ~950 Ma zircons (Burrett et al., 2014, Fig. 10; McKenzie et al., 2014, Fig. 2), which Zhu et al. (2011) considered diagnostic of samples derived from the Indian sector of the *peri*-Gondwanan margin. Therefore, the argument that the Lhasa Block has a detrital signature that is characteristically different from that of the Indian sector of the Gondwana margin is questionable.

The idea of the direct Lhasa–Australia Palaeozoic connection has been previously questioned based on their differing geological records (Pan et al., 2012; Zhang et al., 2014), and recent studies of the Lhasa Block's Neoproterozoic record associate it with India and South China (Zhou et al., 2019, Fig. 9). Nor are there compelling biogeographic arguments for specific links between Australia and the Lhasa Block: Palaeozoic and early Mesozoic faunas from various parts of Tibet show general similarities with Australia, as they do with other parts of the "Sino–Australian province" (see Wright et al., 2000 and the papers therein), but evidence of a specific biotic association between the Lhasa Block and Western Australia (and/or Sibumasu) is scant.

In contrast, with respect to the early Palaeozoic record, there is strong stratigraphic evidence for the Lhasa block being associated with the Himalaya. As discussed above, sedimentation was relatively continuous from the late Cambrian into the Tremadocian in Sibumasu, and in the Canning Basin. However, in the Himalaya, there is a marked angular unconformity between the Cambrian marine sedimentary rocks and Ordovician molasse (Hayden, 1904; Myrow et al., 2016). A comparable angular unconformity between Ordovician and reportedly Cambrian clastic rocks containing metarhyolites exists in the Lhasa block (Hu et al., 2013, Fig. 2; Wang et al., 2015, Fig. 9). This angular unconformity is characteristic of the Himalayan sector of equatorial *peri*-Gondwana, including Qiantang (Yang et al., 2014), but is unknown in the Australian sector. Accordingly, in our view, association of the Lhasa block with the Australian sector of core *peri*-Gondwana is likely incorrect, and its association with the Himalayan margin is supported, although the metarhyolites will bear comparison both with those at Bawdwin in Myanmar, and with other Cambrian volcanic deposits reported in Bhutan (Bhargava, 1995; Greenwood et al., 2016) and elsewhere in the Himalaya (Garzanti et al., 1986).

2.5. The Baoshan Block and regional variation within the precursor of the Sibumasu terrane

Western Yunnan's Cambrian rocks around the city of Baoshan, and further southwest in the Mangshi area, are distinct from those in the Kunming region of the South China Block. The two areas are separated by the Ailaoshan and Lancangjiang faults, and the Changning–Menglian suture (Metcalfe, 1996). Between these structures lies the Simao–Qamdo Terrane, which apparently represents another, independent *peri*-Gondwanan fragment (Metcalfe, 2017; Stokes, 2008) but has commonly also been considered an extension of Indochina/Annamia (Metcalfe, 1996, 2006; Xie et al., 2016; Zhao et al., 2017). Western Yunnan's Cambrian rocks belong to the "Baoshan Block", which is generally viewed as part "of the same tectono-stratigraphic terrane" as the Shan–Thai sector of Sibumasu (Ridd, 2015, p. 172). Many authors include Baoshan as an integral part of Sibumasu without distinguishing it. The Permian record of Baoshan, like that of the Shan–Thai region, indicates rifting from the Gondwana margin as Meso-Tethys opened. The two regions are generally accepted to have been connected when Sibumasu was an isolated terrane (Ueno, 2003; Wang et al., 2001; Yan and Liang, 2005), although it has also been suggested that they amalgamated only after collision with South China and Indochina (Zhang et al., 2013). As detailed below, there are features of the geological record of the Baoshan Block that differ from those of the Shan–Thai region, and their original relationship merits further consideration.

In those palaeogeographic reconstructions of Gondwana prior to the opening of Meso-Tethys in which Baoshan is distinguished within Sibumasu, Baoshan is consistently shown to the west of the Shan–Thai sector, but its specific placement with respect to core Gondwana depends largely on where the authors position the Lhasa Block. Permian palaeomagnetic data (Ali et al., 2013, Fig. 13) place Baoshan at quite high latitude, consistent with the area between the Australian and India sectors of equatorial Gondwana. Metcalfe (1994, Fig. 3; 2013, Fig. 7) showed the generalized Palaeozoic stratigraphy from east to west across Sibumasu and across Australia, and illustrated some broad regional variations within Sibumasu, despite its narrow girth. Such differences occur even within the Baoshan block itself, where a lower Carboniferous shelf–slope transition is preserved (Wang et al., 2001).

The Baoshan Cambrian succession differs from the sandstone “inner detrital” facies in the Malaysia–Thai border area and in both the southern and northern parts of the Shan State of Myanmar. There are six principal differences. Firstly, the Cambrian succession in Baoshan is substantially thicker than in the Shan–Thai region, with individual sections spanning up to 3000 m of Cambrian rock, and the entire succession possibly substantially thicker (Luo, 1985a, Fig. 1). Secondly, the Baoshan section encompasses a markedly greater span of Cambrian time, with reports of the trilobite *Cyclolorenzella*, a Guzhangian genus dated to ~500 Ma (Zhou and Zhen, 2008), undated Cambrian rocks beneath with sponge spicules beneath this (Luo, 1985a), and a section that extends upwards to the Cambrian-Ordovician boundary. Thirdly, sections of the Baoshan Cambrian succession that are of equivalent age to those of the Shan State and Malay Peninsula include sandstone units similar to those in the Shan–Thai region but also have thick and repeated intervals of carbonate and shale, with carbonate possibly suggesting a more distal depositional setting. Fourthly, the abundant tuff beds known from the Shan–Thai region have not been reported from Baoshan, although metabasites interbedded among sedimentary rocks have recently been recorded within the Cambrian Gongyanghe Group (Li et al., 2016; Yi and Yang, 2012; Wang et al., 2015), possibly comparable to, but apparently predating, those at Bawdwin in the northern part of Shan State (Brinckmann and Hinze, 1981; Mitchell, 2018). Fifthly, a notable erosional unconformity is reported at the contact between uppermost Cambrian and overlying Ordovician sedimentary rocks in some, but not all, parts of the Baoshan Block (Huang et al., 2009, 2012, Figs. 3, 7; Li et al., 2016, Fig. 1c; Wang et al., 2015, Fig. 9), unlike the Cambrian successions in the Shan–Thai region. Sixthly, crustal model age data (Gardiner et al., 2015) question whether the Baoshan and “Shan–Thai” parts of Sibumasu were contiguous before development of the Palaeo- and Meso-Tethyan oceans.

These differences notwithstanding, there are also important similarities between the Cambrian rocks of the Baoshan Block and the Shan–Thai region. Upper Cambrian/Lower Ordovician granite bodies are present in both areas (Lin et al., 2013; Kanjanapayont et al., 2019; Kawakami et al., 2014), but these formed widely along the *peri*-Gondwana margin at the time (Li et al., 2016; Liu et al., 2009; Wang et al., 2015; Zhao et al., 2017). Despite Baoshan’s more complete upper Cambrian record, in all three regions sedimentary rocks of the same depositional age are present. In these directly comparable units, the reported trilobite fauna (Huang et al., 2009, 2012; Kobayashi and Hamada, 1981, 1984; Luo, 1982, 1983, 1984, 1985a,b; Sun and Xiang, 1979) are comparable and are generally consistent with other shelfal trilobite assemblages from the Sino–Australian province (Shergold, 1988). Although such trilobites have been reported from several sites on the Baoshan Block, many are strongly tectonically deformed, hindering their confident identification. A curious occurrence is the unfigured and undescribed report of *Hedinaspis* from the Mangshi area by Kobayashi and Hamada (1984). This report is interesting because this genus is consistently associated with slope facies (see Taylor, 1976; Zhou and Zhen, 2008), and apparently would suggest deepening of the Baoshan shelf to the east, which is inconsistent with other data. It may also be that tuffs are present within comparably aged successions from Baoshan but have yet to be recognized. Furthermore, limestone and shale, in addition to sandstone, are also reported from what may be an upper Cambrian succession, the Kyaukpulu Formation in Kayin state in southeastern Myanmar, although no unconformity between Cambrian and Ordovician strata has been reported (Udchachon et al., 2018).

Additional stratigraphic and palaeontological work is needed to further resolve the relationships between the Cambrian of the Baoshan block and that of the Shan–Thai sector, but two points deserve further comment. First, the presence of a locally substantial Cambrian–Ordovician erosional unconformity on the Baoshan block not only contrasts markedly with the Shan–Thai region, but may also correspond to the widely known and important angular unconformity marking the Kurgiakh Orogeny in the western Himalayan and southern Tibet sectors of the *peri*-Gondwana margin (Myrow et al., 2016; Wang et al., 2015; Zhou et al., 2004), also recorded on the Lhasa block (Hu et al., 2013). The presence of a correlative unconformity in Baoshan might support a closer connection between Baoshan and the Himalayan/Lhasa region than between the Himalaya and the rest of the Shan–Thai, supporting reconstructions that place Baoshan at the western end of Sibumasu. If this is correct, it may be consistent with the idea that the unconformity cut deeper toward the Indian sector of the *peri*-Gondwanan margin, because upper Cambrian rocks are present in the Shan-Thai region, in Baoshan, and also in Bhutan (Hughes et al., 2011), but absent in the western Himalaya (Peng et al., 2009; Myrow et al., 2016). Secondly, the presence of lower Palaeozoic granite in Baoshan is also similar to that along the Himalayan margin, and also in other sectors of the *peri*-Gondwana rim (Cawood et al., 2007; Zhu et al., 2012; Zhang et al., 2014; Hu et al., 2015; Wang et al., 2015). Ganitoids of this age are also present in Thailand (Lin et al., 2013). Several authors have suggested that these granites are associated with accretion of continental material to the Gondwanan margin with the early Palaeozoic closure of the Proto-Tethys ocean. The Shan-Thai part of Sibumasu contains the best record regionally of volcanic rocks of this age, but there may be correlatives in Bhutan, and possibly on the Lhasa bock and Himalayan margin.

2.6. *Stratigraphy of the southern Shan State*

The lowest sedimentary unit (Fig. 3) of the Shan Plateau is the mildly metamorphosed Chaung Magyi Group (La Touche, 1907), which is interpreted as Precambrian in age (La Touche, 1913; Mitchell et al., 1977; Myint Lwin Thein, 1973). The Chaung Magyi is characterized by greywacke, whitish-gray siltstone, red or gray quartzite, and slate, with a minor carbonate component (Aye Ko Aung and Cocks, 2017; Wolfart et al., 1984). Sedimentary structures include flute casts and soft-sediment deformation (Wolfart et al., 1984). Its uppermost member, the Tawngma Siltstone (Mitchell et al., 1977), purportedly contains horizontal burrows, although the burrows are not figured or described in any publications to date; this member of the Chaung Magyi is limited to the northern Shan State. The presence of metamorphism and horizontal burrows led Garson et al. (1976) and Mitchell et al. (1977) to interpret the Chaung Magyi as latest Precambrian to Cambrian in age. The Furongian Molohein Group and Pangyun Formation, which overlie the Chaung Magyi with an angular unconformity (Myint Lwin Thein, 1973), are not metamorphosed. Near Bawdwin, the Tawng Peng granite intrudes the Chaung Magyi but not the Pangyun Formation. The intrusion, angular unconformity, and metamorphism suggest a substantial time interval between the deposition of the Chaung Magyi and the overlying, definitively Cambrian strata (Krishnan, 1968).

In the southern part of Shan State, the oldest definitively Palaeozoic unit is the Molohein Group, which we show here to be Furongian in age, at least in part. Although good exposure of the Chaung Magyi–Molohein

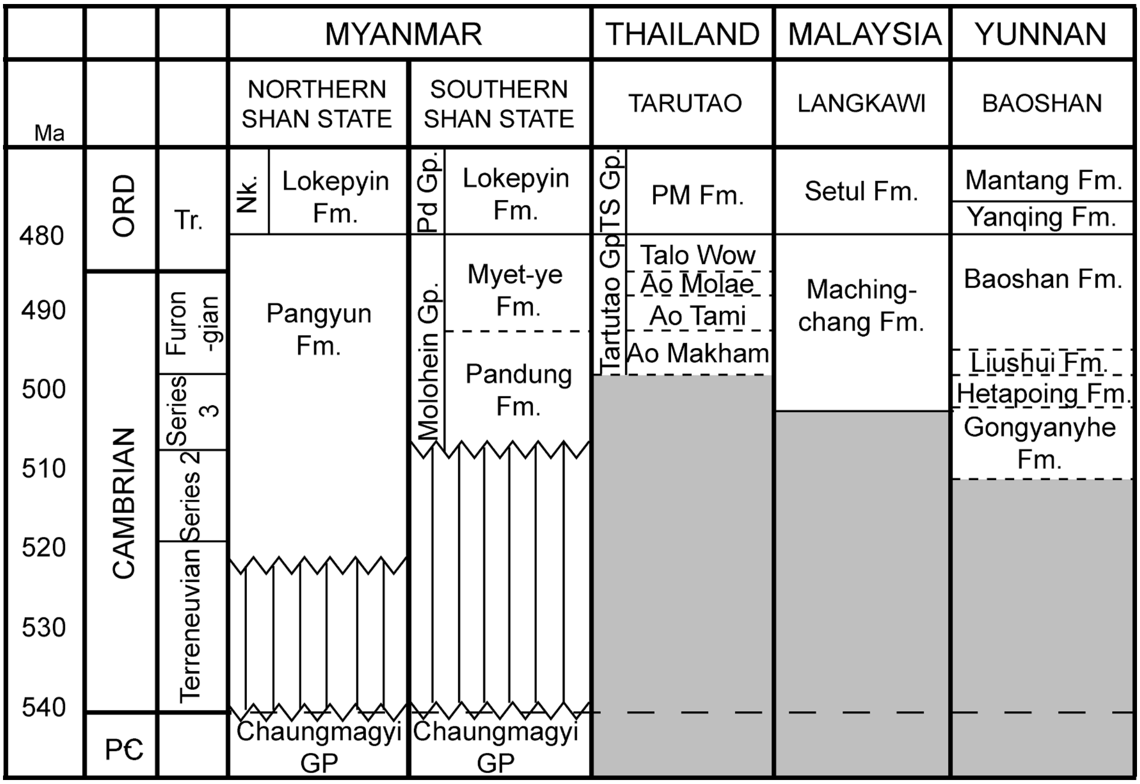

Fig. 3. Precambrian-lower Ordovician stratigraphic successions for each area of Sibumasu including Myanmar's northern and southern Shan State, western Thailand, southwestern Yunnan, and northern Malaysia. Abbreviations are as follows: Tr. = Tremadocian; Nk. = Naungkangyi Group; Pd. = Pindaya Group. Vertical stripes indicate unconformity; gray indicates unknown strata with no outcrops. Modified from Aye Ko Aung and Cocks (2017) using Imsamut and Yathakam (2011) and Luo (1985b).

boundary is sparse, a thin basal conglomerate of quartzite pebbles and an angular unconformity reportedly marks the boundary of the Chaung Magyi and Molohein Group (Wolfart et al., 1984). The Molohein Group is a siliciclastic succession of red, gray, white, or purple sandstone with thin interbedded siltstone and mudstone. The sandstone contains ripples, is trough cross-bedded, and shows hummocky cross stratification. Carbonate lenses are also reported in some places (Aye Ko Aung and Cocks, 2017; Wolfart et al., 1984). The Pandung and Myet-Ye formations together comprise the Molohein Group (Myint Lwin Thein, 1973), though most authors refer to the group as a whole. The Pandung Formation is more quartz-rich with a pinkish-white colour, whereas the overlying Myet-Ye Formation is generally darker pink or purple; both are micaceous, although the Myet-Ye Formation is reportedly more so (Wolfart et al., 1984). To date, upper Cambrian fossils have been reported only from the Myet-Ye Formation (Aye Ko Aung and Cocks, 2017). The collective thickness of the Molohein Group is poorly understood, with various estimates being 300 m (Myint Lwin Thein, 1973), 1200 m (Wolfart, et al. 1984), or even 2400 m (Garson et al., 1976). Soe (1983) estimated a thickness of 540 m for the Pandung Formation and 230 m for the Myet-Ye Formation in the Ye-Ngan area. All of these estimates are rough, compiled from many isolated outcrops (Maung Kyi Soe pers. comm. 2020). The Shan State's heavy forestation, sharp topographic relief, and numerous faults hinder establishing a continuous section. Furthermore, given that the base of the Pandung Formation is an angular unconformity, it is likely the thickness of this unit varies laterally.

The Molohein Group includes both siliciclastic deposits and volcanic tuffs. This unit's counterpart in the northern portion of the Shan State, the Pangyun Formation, refers only to the sedimentary rocks that interfinger with the Bawdwin Volcanic Series (Aye Ko Aung and Cocks, 2017). The Molohein Group's volcanic deposits are not as thick as those to the north, where a remnant volcanic center is preserved, and thus the lithostratigraphic nomenclature is undifferentiated for sedimentary and volcanogenic components. The Molohein Group's rhyolitic tuffs are commonly welded into a flinty texture, with a dull to bright green tinge. These tuffs may be up to a meter or more thick.

The upper boundary of the Molohein Group is marked by a gradual reduction of grainsize into the siltstone of the Ordovician Lokepyin Formation, the lowest unit of the Pindaya Group, which is the equivalent of the northern Shan State's Naungkangyi Group (Aye Ko Aung and Cocks, 2017; Reed, 1936; Myint Lwin Thein, 1973). In addition to the reduction of grain size, the Lokepyin Formation is marked by a distinct buff or tan colour to its siltstone, rather than the purple, pink, red, or white of the Molohein sandstone.

3. Material and methods

Sampling localities for the 2016 excursion (Fig. 4) were chosen based on Soe's (1983) thesis, though most, if not all, of that material was found in float. At each locality, where possible, detrital zircon samples, fossils, and tuff beds were collected. Fossils were collected on a bed-by-bed basis, each bed marked as a separate collection. Four localities with Cambrian fossils (PG1–PG4) were found on the unpaved, poorly developed truck road to Padongaing village, and one locality was found near Kyauknget Monastery (KY). PG1 (21°8′56.82″N, 96°32′57.42″E) is adjacent to where the road crosses a stream; this is the only location at which identifiable fossils were found in multiple beds (Fig. 5). PG2 (21°8′54.06″N, 96°33′3.00″E) is a roadcut about 200 m east along the road from PG1. PG3 (21°8′53.58″N, 96°33′4.26″E) comprises sparse, intensely weathered blocks of sandstone jutting out from an outcrop otherwise surrounded by mud on the inside of the bend in the road. PG4 (21° 8′53.97″N, 96°33′5.06″E) also consists of material from the next rocky but poorly exposed outcrop further up the track from PG3.

The KY (21°11′6.60″N, 96°33′3.12″E) sample is from the stream bed

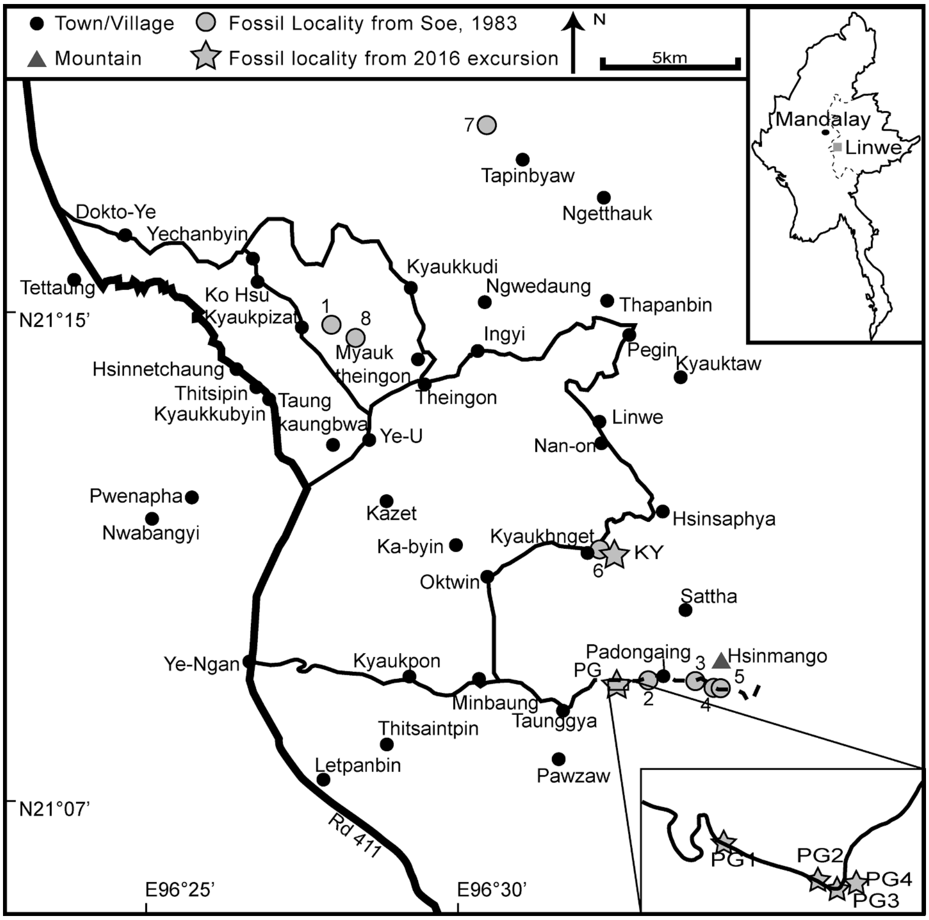

Fig. 4. Map of the Linwe area with localities of fossil collections.

down the foot trail running south of Kyauknget Monastery, collected where a bamboo bridge crosses the stream. Fossils at KY were collected from loose, well-rounded cobbles.

Within the Molohein Group, trilobites are preserved as undeformed or only mildly deformed internal and external molds in very fine to fine-grained quartzarenite with varying quantities of mica; the mica is, in cases, concentrated on the surface of the fossil, imparting a smooth, almost glittery appearance. Other specimens show a slight infilling of limonite that leaves an orange film on the mold. Diagenetic pyrite cubes occur within the sandstone; the pyrite is in the matrix, and is not associated with fossil preservation.

The specimens were prepared manually using a Dremel tool, then blackened with India ink, whitened with ammonium chloride, and photographed with a Leica stereoscopic camera model MZ16 or M205C. All figures and plates were created using Adobe Photoshop CC2017 and Adobe Illustrator CS2.

Morphometric analysis used the following software created by H. David Sheets as part of the Integrated Morphometrics Package: CoordGen8, BigFix8, Regress8, and PCAGen8 (Webster and Sheets, 2010; available free of charge at http://www.filogenetica.org/cursos/Morfometria/IMP_installers/index.php). Statistical tests for allometry of *Asioptychaspis lata* n. sp. were performed using PAST4.01 (Hammer et al., 2001).

In agreement with senior scientists in Myanmar, specimens are reposited at the Cincinnati Museum Center as CMC IP87051–IP87137.

4. Palaeogeographic distribution and biostratigraphic correlation

There is currently a limited set of known fossils by which to spatiotemporally constrain the Cambrian units of Shan State. Two species from the southern Shan State's Cambrian fauna are known to occur elsewhere, *Asioptychaspis asiatica* Endo and Resser (1937) and *Eosaukia buravasi* Kobayashi, 1957. Of these only *Eosaukia buravasi* is known to occur elsewhere in Sibumasu, common in the Thailand's Tarutao Group (Kobayashi, 1957; Shergold et al., 1988). This species is also likely present in the Bonaparte Basin of Western Australia (Shergold et al., 2007). *Asioptychaspis asiatica* Endo and Resser (1937) was recovered in the Liaoning Province of the North China Block (Endo and Resser, 1937). The recovery of these two species are consistent with Furongian palaeogeographic reconstructions that place Sibumasu adjacent to northwest Australia with the North China Block nearby (see section 1.2.2 above).

Asioptychaspis asiatica is found in the *Tsinania–Ptychaspis* zone of North China (Zhou and Zhen, 2008); alternatively known as the *Asioptychaspis–Tsinania* Zone or *Asioptychaspis* Zone (Choi et al., 2016; Park and Kihm, 2015), which is the latest part of the Jiangshanian (Peng et al., 2012) (Fig. 6). All Chinese species of *Ptychaspis* or *Asioptychaspis* date to this interval (Park and Kihm, 2015; Zhou and Zhen, 2008), but *Asioptychaspis delta* Shergold (1975) occurs in Cambrian Stage 10 of Australia. *Asioptychaspis lata* n. sp. co-exists with *E. buravasi. Eosaukia* is distinctive of Cambrian Stage 10 (Choi et al., 2016; (Zhou and Zhen, 2008)), and *E. buravasi* co-exists with numerous other Cambrian Stage 10 taxa such as *Quadraticephalus* and *Pagodia* (Kobayashi, 1957; Shergold et al., 1988). Therefore, like *A. delta*, *A. lata* is apparently a later species of *Asioptychaspis*. Between the latest Jiangshanian *A. asiatica* and the Stage 10 *E. buravasi*, the stratigraphic range of the Molohein Group covers at least upper Jiangshanian through the middle of Cambrian Stage 10. Additional field observations in 2020 of a taxon assemblage similar to the Ordovician fauna of Ko Tarutao (Stait et al., 1984) suggest the Molohein Group extends into strata at least as young as middle

Tremadocian.

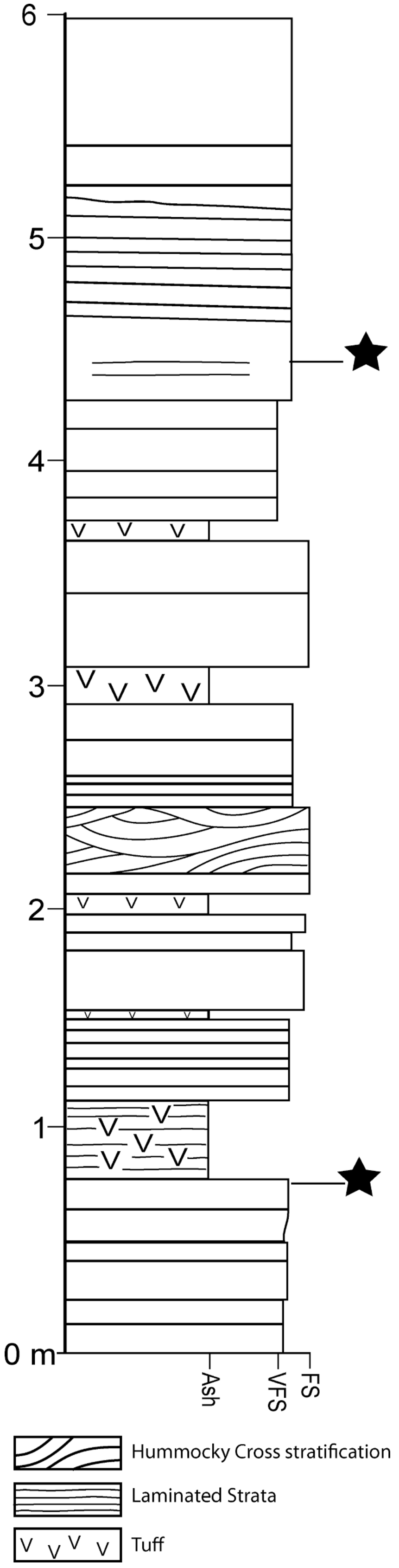

Fig. 5. Measured section from Locality PG1. Black stars indicate trilobite fossils; height is in meters; VFS = Very Fine Sand; FS = Fine sand.

5. Systematic palaeontology

This section is by Shelly Wernette and Nigel Hughes.

Institutional abbreviations. CMC, Cincinnati Museum Center; UMUT, University Museum of the University of Tokyo.

Family PTYCHASPIDIDAE Raymond, 1924

Genus *Asioptychaspis* Kobayashi, 1933

Type species: *Ptychaspis ceto* Walcott, 1905 from the Chaumitien Formation of Shandong Province, China.

Remarks: The possible synonymy of *Asioptychaspis* and *Ptychaspis* Hall, 1863 has been repeatedly debated. Kobayashi (1933) erected *Asioptychaspis* to contain some Asian species formerly assigned to *Ptychaspis*. Shergold (1975) recognized differences between the genera but did not consider these to be sufficient to warrant generic distinction, relegating *Asioptychaspis* to a subgenus within *Ptychaspis*. Westrop (1986) disagreed, returning *Asioptychaspis* to generic level based on the flat, poorly defined pygidial border found in *Asioptychaspis* but not in *Ptychaspis*. Zhang and Jell (1987) thought these differences insufficient for even subgeneric distinction. Sohn and Choi (2007) expanded the list of characters differentiating *Asioptychaspis* from *Ptychaspis* including a strongly convex, long, parallel-sided or forward expanding glabella and large palpebral lobes situated anteriorly to glabellar midlength. We follow Sohn and Choi's (2007) differential diagnosis herein.

Asioptychaspis lata n. sp.

Fig. 7A–M, 8

Holotype: CMC IP87078, Fig. 7D–F; Molohein Group, Myet-Ye Formation; Furongian, lower to middle of Cambrian Stage 10; Padongaing 1, 4.50 m. Paratypes: CMC IP87051–87057, IP87060–87066, IP87068–87072, IP87074, IP87076–87078, IP87080–87084, IP87087, IP87090–87094, IP87096–87098, and IP87100–87111.

Diagnosis: Species of *Asioptychaspis* with particularly wide fixigena, width (tr.) at anterior corners of palpebral lobes ~ 1.5 times preoccipital glabellar length (sag.); midpoint of palpebral lobes anterior to S2. Glabella inflated and anteriorly extended above and beyond strongly ventrally curved frontal area. Pygidia effaced, pleural and interpleural furrows weakly incised; axis strongly tapering with four rings and terminal piece; entire pleural field with fine granular texture including broad, flat border overlying equally long (sag., exsag.) doublure.

Ocurrence: Linwe Area of the southern Shan State, Myanmar at Padongaing (PG) 1, beds 0.75 m and 4.50 m, and as float at Soe (1983) locality 6; Myet-Ye Formation, Molohein Group; Furongian, lower to middle Cambrian Stage 10.

Description: Cranidium subtrapezoidal; glabella occupies entire cranidial length (sag.) with inflated anterior lobe protruding over anterior cranidial margin; cranidial width (tr.) at posterior end of palpebral lobe 1.5–2.1 times preoccipital glabellar length (sag.) and 2.0–2.3 times glabellar width across anterior lobe; frontal area slopes ventrally with gently inflated frontal area separated from glabella by firmly-incised furrow; anterior margin forms straight line from preglabellar margin to anterior tip of palpebral lobe, oriented ~15° from transverse, and medially gently curved. Glabella parallel-sided or gently narrowing at L2; S1 firmly incised and medially continuous, bowed posteriorly; S2 posteriorly oblique to transverse and variably medially continuous or effaced, deeply impressed laterally and shallowing medially; anterior lobe equal width or broader (tr.) than rest of glabella with strong anterior expansion but dorsally not inflated above height of L2. SO firmly incised evenly or with slight medial shallowing across glabella and transverse to slightly posteriorly bowed; LO broader (tr.) than L1 and subequal in length (sag.) and dorsal inflation, occipital spine absent. Cranidial posterior border short (exsag.) and defined by broad, deep furrow; posterolateral projections broad (exsag.) and short (tr.) with the maximum cranidial width (tr.) at the posterolateral projection 1.1–1.15 times cranidial width (tr.) at posterior corner of palpebral lobe; posterior facial suture branch curves gently posterolaterally. Palpebral lobe

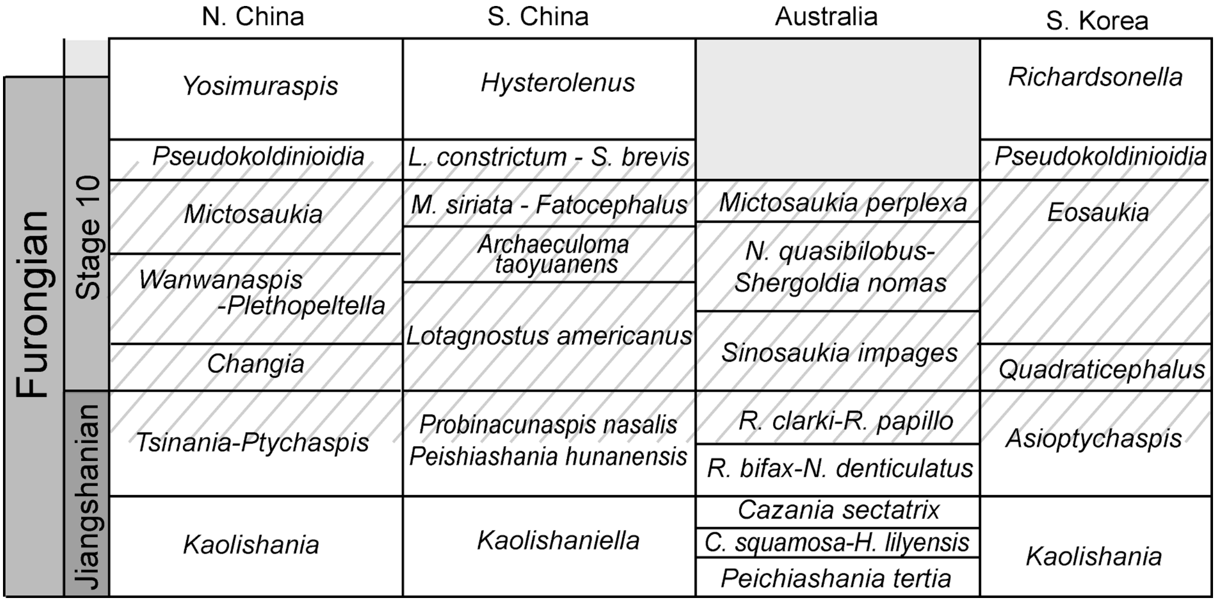

Fig. 6. Upper Jiangshanian and Cambrian Stage 10 trilobite zones for northern Gondwanan terranes. Hatching indicates the likely range of the fauna described herein. Some genera have been abbreviated in the chart for readability; the full names are: *Caznaia squamosa, Hapsidocare lilyiensis, Leiostegium constrictum, Mictosaukia striata, Neoagnostus denticulatus, Neoagnostus quasibilobus, Rhaptagnostus clarki, Rhaptagnostus papillo, Rhaptagnostus bifax,* and *Shenjiania brevis*. The South Korean biozones are for the Taebaek Group. Zone correlations are compiled from Choi et al. (2016) and Ogg et al. (2016).

weakly curved and anteriorly positioned with palpebral midpoint opposite or anterior S2; palpebral lobe, 40–50% preoccipital glabellar length; fixigena expanded (tr.) little or not at all across palpebral area.

Pygidium wide (tr.), width at anterior corners ~1.6 times pygidial length (sag.); anterior margin gently curved; posterior margin strongly curved, median portion of posterior margin transverse or slightly embayed. Axis ~75% pygidial length, conical with 4 axial rings and terminal piece; first three transverse axial furrows strongly incised and last axial furrow faint. Pleural field nearly effaced with only faint pleural furrows; furrows nearly straight and parallel to anterior pleural furrow; furrows become completely effaced near margin; pleural field covered in fine granules. Doublure occupies entire postaxial length and narrows only slightly from postaxial position to anterior corners.

Etymology: lata, Latin for wide, referring to the wideset eyes that differentiate this species from other *Asioptychaspis*.

Material: 41 cranidia from Padongaing (PG) 1 0.75 m (CMC IP87128) and 4.50 m (CMC IP87052–87054, IP87056, IP87057, IP87060 – external mold, IP87061–87064, IP87065 – external mold, IP87069–87072, IP87076, IP87078, IP87080 – external mold, IP87081, IP87082, IP87083 – external mold, IP87084, IP87087, IP87090–87094, IP87096 – external mold, IP87097 – external mold, IP87098, IP87100–87109, and IP87111). 11 pygidia from PG1 0.75 m (CMC IP87127) and 4.50 m (CMC IP87051, IP87055, IP87057 – internal and external mold, IP87066 – external mold, IP87075, IP87077 – internal and external mold, IP87085 – external mold, IP87088, IP87089 – external mold, and IP87110). All internal molds unless otherwise indicated.

Remarks: In the horizons in which it occurs near Padongaing village, *Asioptychaspis lata* is the dominant taxon. The collection from the horizon at 4.50 m in the Padongaing 1 section contains 41 cranidia of *A. lata* and only 5 other cranidia, including *Eosaukia buravasi* Kobayashi, 1957, indeterminate saukiids, and another indeterminate cranidium; the horizon at 0.75 m contains only *A. lata*, but the sample size is only two. *Asioptychaspis lata* is readily distinguishable from all other species of the genus by its exceptionally wide (tr.) fixigena. In a set of 25 individuals, with preoccipital glabellar lengths ranging from 1.7 mm to 8.25 mm, there is a subtle trend of the cranidial width increasing relative to the preoccipital glabellar length. The smallest specimens have an average cranidial width versus preoccipital glabellar length ratio of ~1.5 and the largest a ratio of ~1.65. However, when the logarithms of glabellar length and cranidial width are plotted against each other using ordinary least squares regression (OLS; Fig. 9), the slope is 1.0293, with a 95% confidence bracket of 0.91548–1.1322. A slope of 1, indicating isometry, is well within this confidence interval suggesting no significantly detectable allometry.

The cranidial width (tr.) of *A. lata* at all sizes considerably exceeds that of other species of *Asioptychaspis*. For comparison, the largest known specimen of the *Asioptychaspis* type species, *A. ceto* (Wacott, 1905), has a glabellar length of 14 mm, including LO, but a width to length ratio less than 1.42, less than the average of the smallest specimens of *A. lata*, 1.5. There are nine heretofore recognized species of *Asioptychaspis* (Sohn and Choi, 2007): *A. ceto* (Walcott, 1905), *A. calyce* (Walcott, 1905), *A. cacus* (Walcott, 1905), *A. calchas* (Walcott, 1905), *A. asiatica* (Endo and Resser, 1937), *A. subglobosa* (Sun, 1924), *A. brevicus* (Sun, 1935), *A. fengshanensis* (Sun, 1935), and *A. shansiensis* (Sun, 1935), all of which have narrower fixigenae than *A. lata*. The wideset, anteriorly positioned eyes of *A. lata* contribute to a more box-like, rectangular shape with longer (exsag.) posterolateral projections and a more gently curved margin than in other *Asioptychaspis*. The exceptionally broad (tr.) and deep axial furrows occupy much of the palpebral areas as opposed to the more inflated palpebral areas common in other *Asioptychaspsis*. However, because all these characters are attributable to the outward and anterior movement of the eyes, they do not prevent the assignment of this new species to *Asioptychaspis*, such that a new, monspecific genus is uncalled for. *Asioptychaspis lata* was identified and figured by Soe (1983, p. 151–154, pl. 3, Fig. 27) as *Ptychaspis* sp. from cobbles found at his locality 6 (Fig. 4).

Ptychaspis sp. cf. *P. asiaticus* Resser and Endo (*sensu* Shergold et al., 2007) has nearly similarly broad fixigenae, but its occipital ring is strongly dorsally expanded. Its anterior border is also strongly sloped, and almost completely dorso-ventral in orientation. The most dorsal point of the occipital ring of *A. lata* is on the same plane as the most dorsal points of the other glabellar lobes, and the frontal area is more gently sloped.

Asioptychaspis lata co-occurs with *Eosaukia buravasi*, which occurs in Cambrian Stage 10 in the Tarutao Group on the southern end of Sibumasu. However, most known species of *Asioptychaspis* date to the *Ptychaspis–Tsinania* Zone of the latest Jiangshanian (Peng, 2009; Peng et al.,

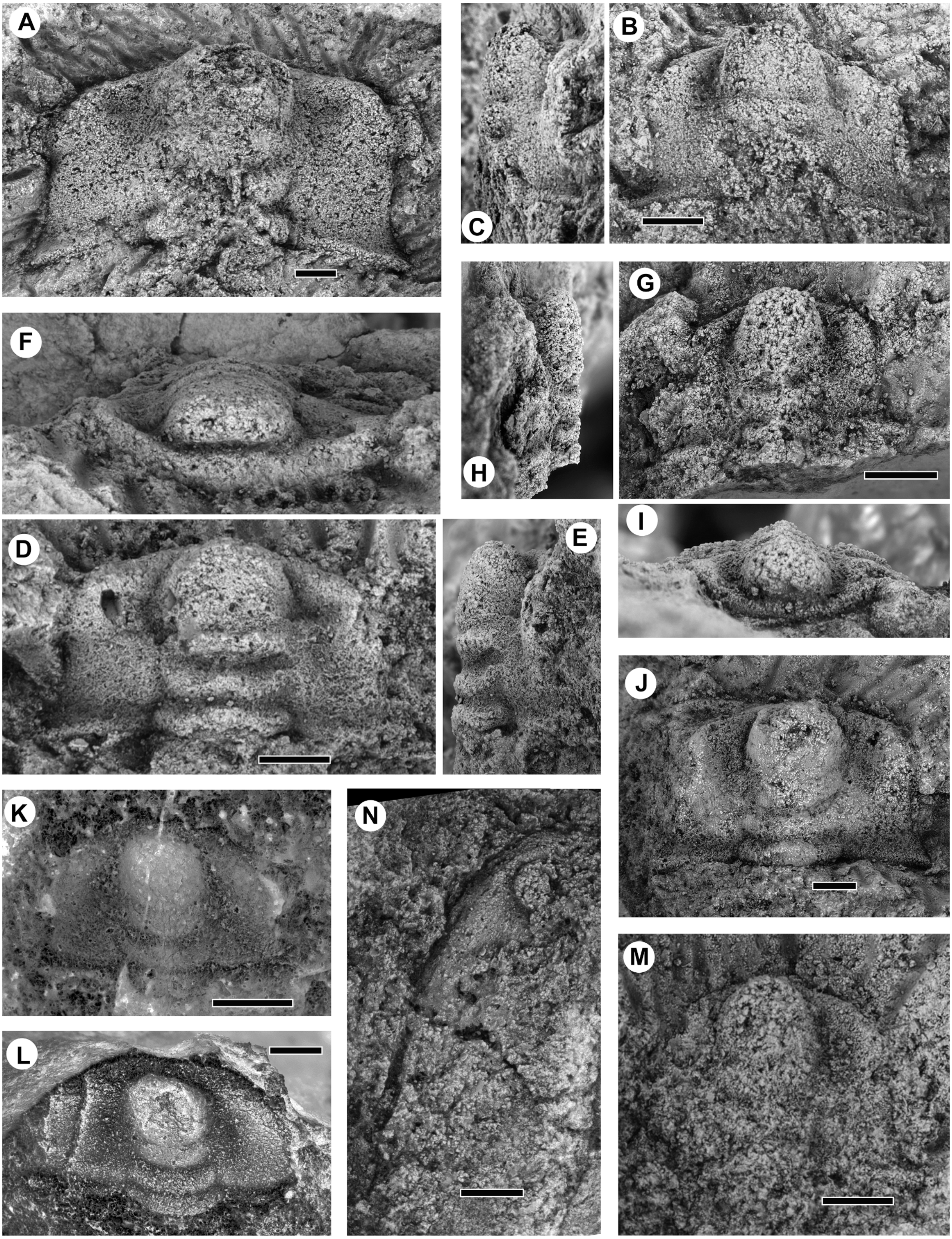

Fig. 7. A–M *Asioptychaspis lata* n. sp. (A) CMC IP87061, cranidium, internal mold, dorsal view; (B,C) CMC IP87084, cranidium, internal mold, B dorsal view, C right lateral view; (D–F) CMC IP87078, cranidium, internal mold, D dorsal view, E right lateral view, F anterior view; (G–I) CMC IP87056, cranidium, internal mold, G dorsal view, H left lateral view, I anterior view; (J) CMC IP87052, cranidium, internal mold, dorsal view; (K) CMC IP87065, cranidium, external mold with inverted colours, dorsal view; (L) CMC IP87060, cranidium, latex peel of external mold, dorsal view; (M) CMC IP87128, cranidium, internal mold, dorsal view; (N) CMC IP87079, indeterminate librigena, internal mold, dorsal view. All scale bars 2 mm.

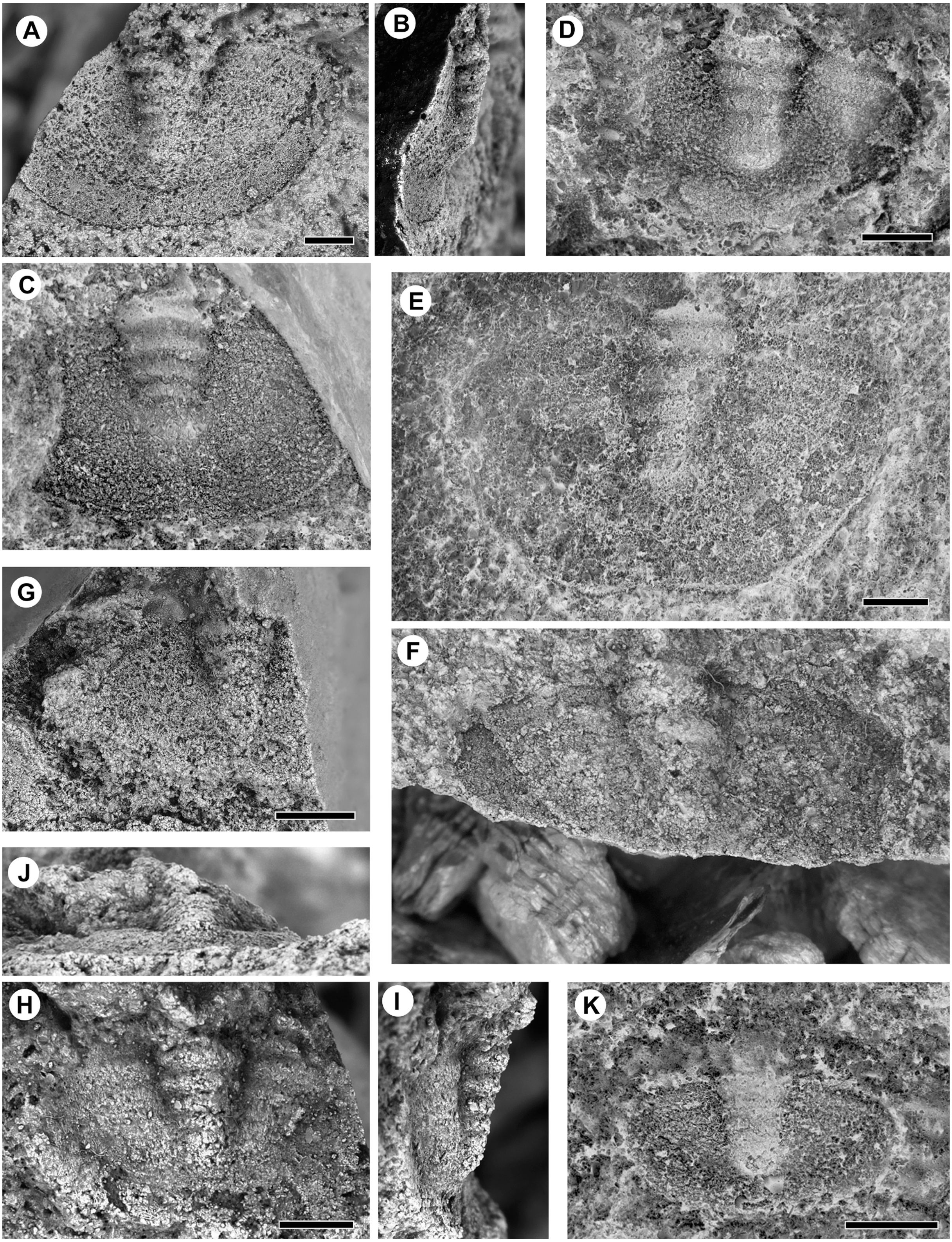

Fig. 8. *Asioptychaspis lata* n. sp., all pygidia. (A–C) CMC IP87051, A internal mold dorsal view, B internal mold left lateral view, C external mold dorsal view; (D) CMC IP87083, internal mold dorsal view; (E, F) CMC IP87057, E internal mold dorsal view, F external mold dorsal view; (G) CMC IP87055, internal mold, dorsal view; (H–J) CMC IP87075, internal mold, H dorsal view, I left lateral view, J posterior view; (K) CMC IP87088, external mold, dorsal view. All scale bars 2 mm.

2012; Zhou and Zhen, 2008). The wideset eyes of *A. lata* may be a derived feature of this later-occurring ptychaspid.

The only associated librigena (Fig. 7N) is a potential but uncertain match. It has a narrow genal field and a broad and deep posterior border furrow comparable with *A. lata*. The eye is large and strongly rounded, and where palpebral lobes are preserved on the cranidium, they widen (tr.) at their midpoint, possibly being able to fill this space. The overall morphology of the librigena is similar to that of *A. subglobosa* (Sun,

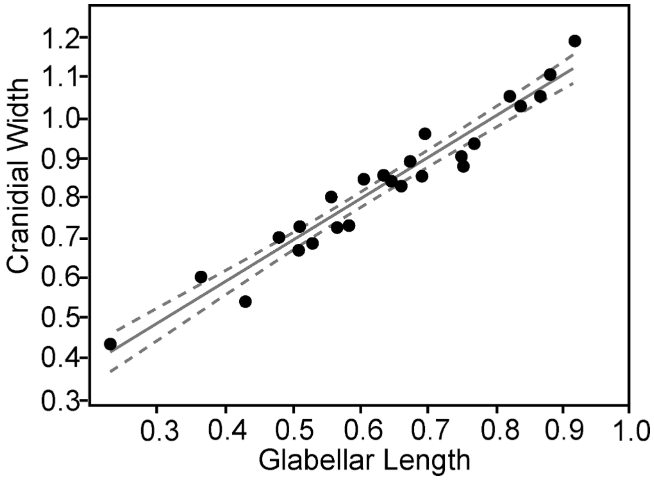

Fig. 9. Log of preoccipital glabellar length (sag.) versus log of cranidial width (tr.) using ordinary least squares regression. Preoccipital glabellar length is used as a standardization of size; cranidial width was measured across the anterior corners of the palpebral lobes. The slope is 1.0293 with 95% confidence intrvals (N = 1999) of 0.91548–1.1322). All units are in mm.

1924). However, in the one specimen available the preservation is incomplete and it appears that there is not sufficient postpalpebral length (exsag.) to allow this librigena to be paired with the cranidium of *A. lata*. Without additional and better preserved librigenae, the assignment of this sclerite is tentative.

Asioptychaspis asiatica (Endo and Resser 1937)
Fig. 10

1937 *Ptychaspis asiatica* Endo and Resser, p. 272–273, pl. 56, Figs. 4–9

1987 *Ptychaspis asiatica* Zhang and Jell, p. 228, pl. 112, Figs. 12,13, pl. 113 Figs. 1–4

Lectotype: "*Ptychaspis*" *asiatica* Endo and Resser, 1937 pl. 56, Fig. 4 USNM 86895a designated in Zhang and Jell, 1987.

Occurrence: Linwe area of the southern Shan State, Myanmar at Kyauknget (KY) and as float at Soe (1983) locality 1, Myet-Ye Formation, Molohein Group; Furongian, upper Jiangshanian.

Material: Cranidia: Five internal molds (CMC IP87130, IP87133, IP87431, IP87136, and IP87137). Thoracic segments: one internal mold (CMC IP87131). All from float at Kyauknget (KY).

Remarks: The cranidium of *A. asiatica,* first known from Liaoning (formerly southern Manchouko) in north China, is recognizable by its anteriorly expanding glabella, pustulation, medially shallowing lateral glabellar furrows, and subtriangular pygidium, all of which are visible in the material from Kyauknget. The anteriorly expanding glabella differentiates it from *A. calchas* (Walcott, 1905) which can also have granulation. *Asioptychaspis brevicus* (Sun, 1935) lacks both granulation and the medial shallowing of the lateral glabellar furrows.

Ptychaspis sp. cf. *P. asiaticus* Resser and Endo (*sensu* Shergold et al., 2007 from Bonaparte Basin, Western Australia) has broader fixigenae compared with *A. asiatica* as well as a more strongly ventrally curved frontal area. An unusual trait shared by both species is the expanded LO that is strongly elevated along the posterior margin.

Family SAUKIIDAE Ulrich and Resser, 1930
Genus *Eosaukia* Lu, 1954

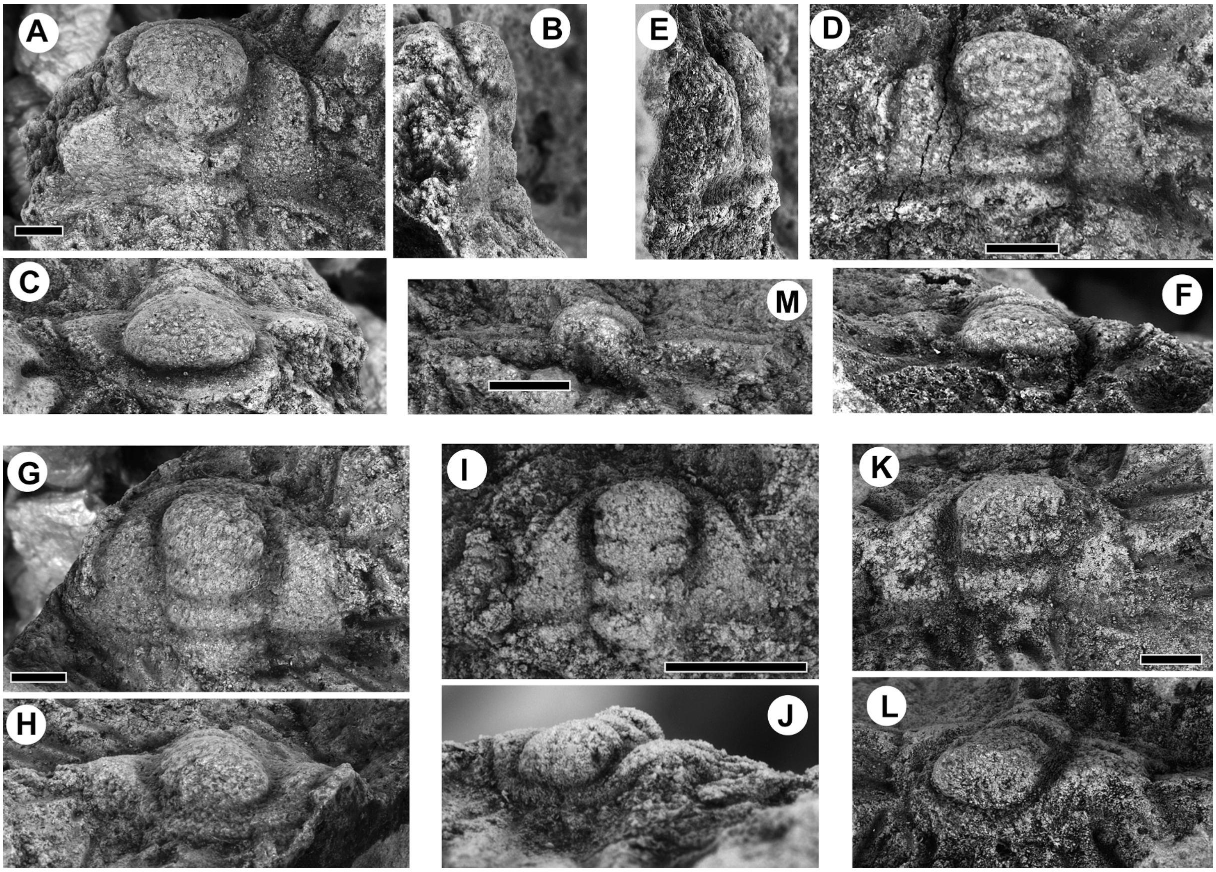

Fig. 10. A–L *Asioptychaspis asiatica* (Endo and Resser, 1937), M indeterminate thoracic segment. (A–C) CMC IP87130, cranidium, A dorsal view, B left lateral view, C anterior view; (D–F) CMC IP87133, cranidium, D dorsal view, E left lateral view, F anterior view; (G, H) CMC IP87134, cranidium, G dorsal view, H anterior view; (I, J) CMC IP87137, cranidium, I dorsal view, J oblique view; (K, L) CMC IP87136, cranidium, K dorsal view, L oblique view; (M) CMC IP87131, indet. thoracic segment;. All internal molds; all scale bars 2 mm.

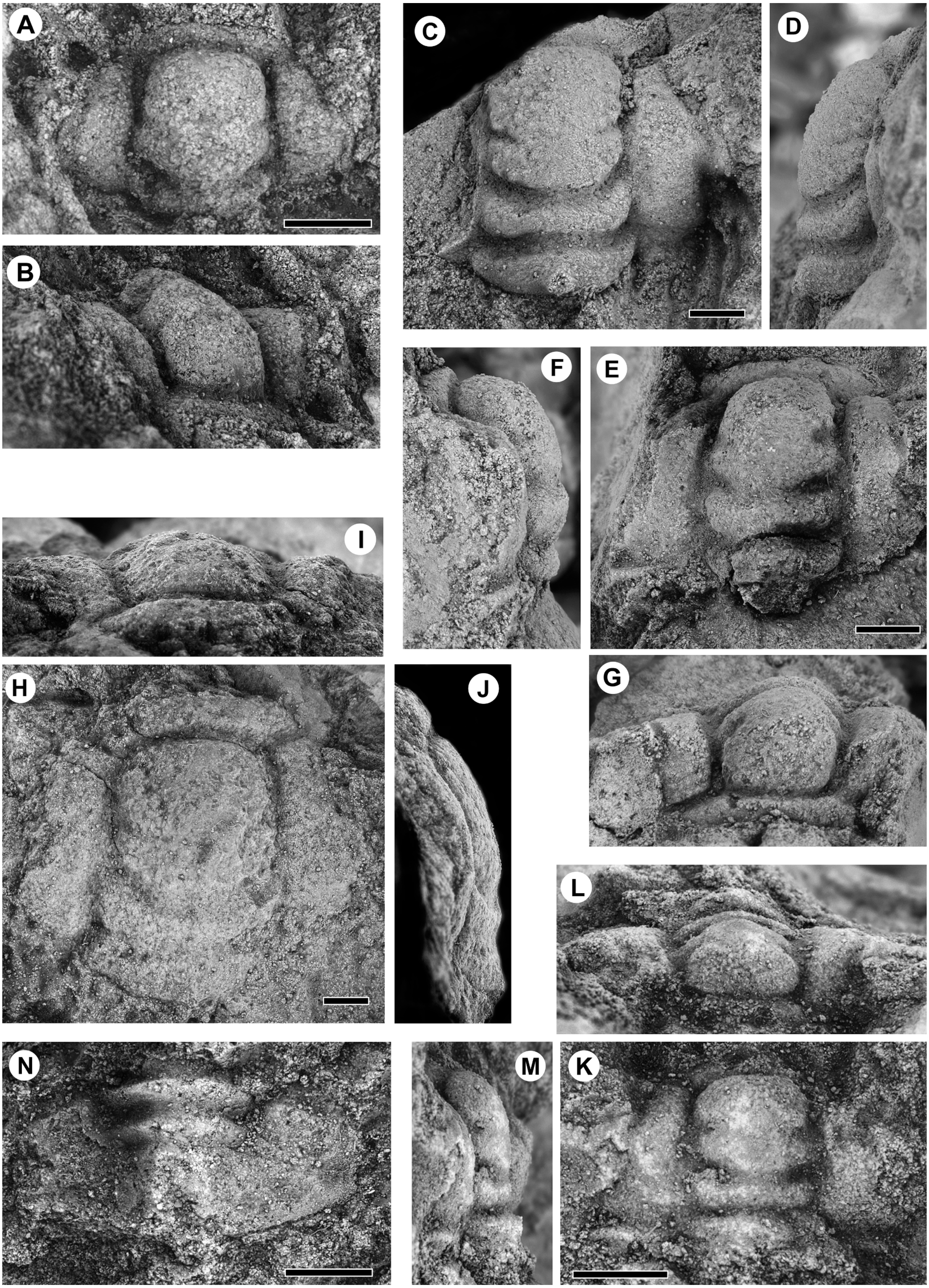

Fig. 11. *Eosaukia buravasi* Kobayashi (1957). (A, B) CMC IP87121, cranidium, A dorsal view, B oblique view; (C, D) CMC IP87120, cranidium, C dorsal view, D right lateral view; (E–G) CMC IP87112, cranidium, E dorsal view, F left lateral view, G anterior view; (H–J) CMC IP87113, cranidium, H dorsal view, I anterior view, J left lateral view; (K–M) CMC IP87117, cranidium, K dorsal view, L anterior view, M left lateral view; (N) CMC IP87115, pygidium, dorsal view. All internal molds; all scale bars 2 mm.

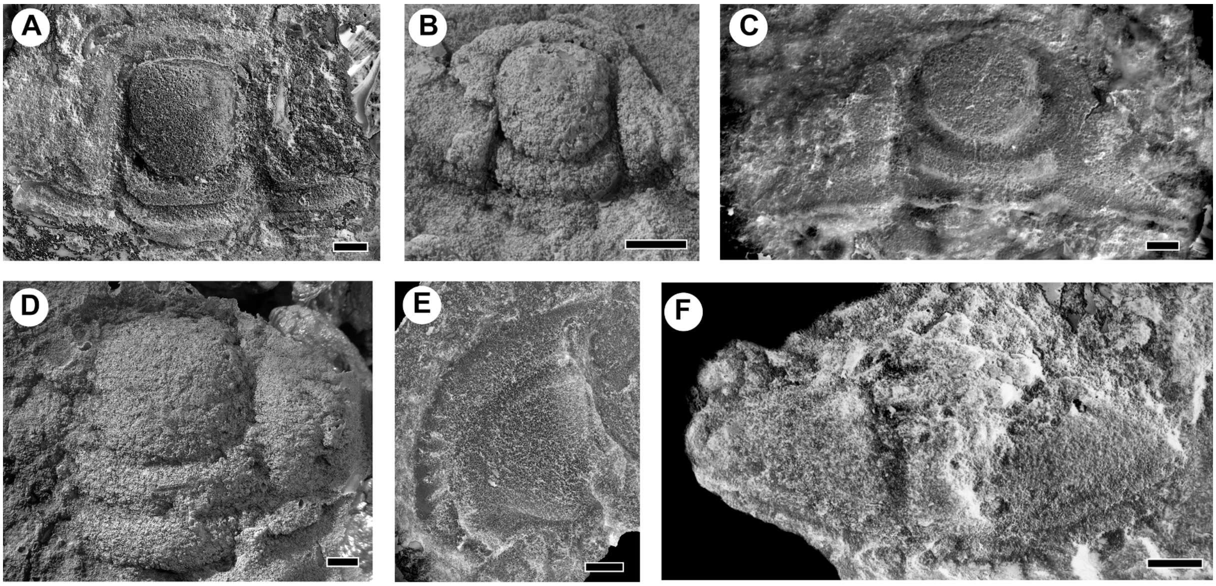

Fig. 12. *Eosaukia buravasi* Kobayshi 1957. Originals of type material produced from vinyl polysiloxane casts. (A) CMC IP87025, holotype, cranidium, from UMUT PA02298b-1, Kobayashi, 1957, pl. 5, Fig. 5; (B) CMC IP87043, cranidium, from UMUT PA02299, previously unfigured; (C) CMC IP87035, cranidium, from UMUT PB02299, previously unfigured; (D) CMC IP87042, cranidium, from UMUT PA02299c-3, Kobayashi, 1957, pl. 5, Fig. 6; (E) CMC IP87027, librigena, from UMUT 02298b-3, Kobayashi, 1957, pl. 5, Fig. 8; (F) CMC IP87022, pygidium, from UMUT PB02297b-2, Kobayashi, 1957, pl. 5, Fig. 5. All scale bars 2 mm.

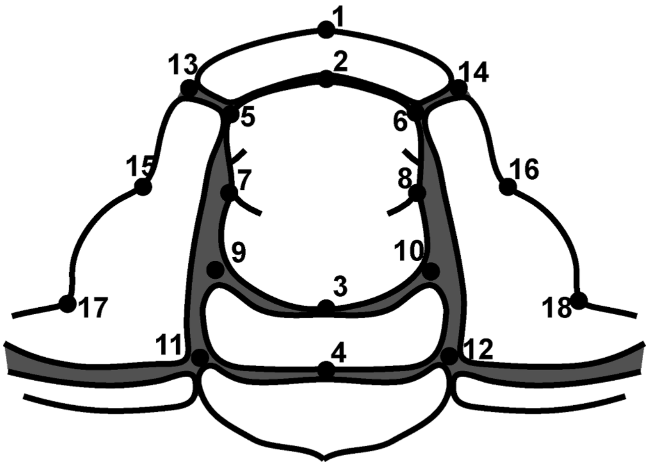

Fig. 13. Landmark scheme showing the 18 landmarks used in the morphometric analysis of *Eosaukia buravasi.*

Type species.—Eosaukia latilimbata Lu, 1954

Remarks.— Species of *Eosaukia* have often been erroneously assigned to other genera, particularly to *Mictosaukia* Shergold, 1975. However, following the work of Lee and Choi (2011) it is clear that *Eosaukia* is distinguished from other saukiids by the lack of a preglabellar field, the strongly incised, anterolaterally oblique furrows separating the fixigena from the anterior border, and the short (sag.), lenticular pygidial axis with four or fewer axial rings (Kobayashi, 1957; Lee and Choi, 2011). The cranidium of *Eosaukia* is distinguished from that of *Mictosaukia* particularly by the lateral segments of the anterior border furrow being anterolaterally oblique in the former and posterolaterally oblique in the latter (Lee and Choi, 2011). *Saukia* also has anterolaterally oblique furrows in many species, but, compared with *Eosaukia*, *Saukia* has narrower fixigena, longer palpebral lobes, and no occipital spine or node. Both *Mictosaukia* and *Saukia* possess a more typically rounded saukiid pygidium rather than the lenticular pygidium of *Eosaukia.*

Eosaukia buravasi Kobayashi, 1957

Figs. 11, 12

1957 "*Eosaukia*" *buravasi* Kobayashi, p. 376–368, pl. 5, Figs. 1–10, 13–20

1988 *"Eosaukia" buravasi* Kobayashi, Shergold *et al.*, p. 310, Fig. 4. O–X

2007 *Ptychaspis*? sp. aff. *P. cacus* (Walcott 1905) Shergold *et al.*, p. 65, Fig. 38

Material: Cranidia: One from Padongaing (PG) 1 (CMC IP84059), eight from PG3 (CMC IP87112–87114, IP87116, IP87120, IP87121, and IP87124), and one from PG4 (CMC IP87128). One pygidium from PG3 (CMC IP87115). All internal molds

Occurrence: Linwe area of the southern Shan State, Myanmar at Padongaing (PG) 1 and PG3 and Soe (1983) localities L-1, L-2, and L-7, Myet-Ye Formation, Molohein Group; Furongian, lower to middle Cambrian Stage 10.

Remarks: Kobayashi (1957) expressed uncertainty regarding the nomenclatorial validity and family-level association of *Eosaukia* by using quotation marks to dub this species *"Eosaukia" buravasi.* Though its cranidium resembled that of *E. latilimbata*, the only *Eosaukia* species then known, Kobayashi (1957) thought the *E. buravasi* pygidium, the first *Eosaukia* pygidium discovered, is too short and pauci-segmented to be saukiid. Rather he thought it resembled *Asioptychaspis* or *Quadraticephalus.*

Shergold (1975) moved *E. buravasi* to *Mictosaukia* when first describing the latter genus. However, Shergold et al. (1988) later returned it to *"Eosaukia"* on account of its relatively short palpebral lobes, wide fixigena, and small, lenticular pygidium compared to species of *Mictosaukia.* Shergold et al. (1988) retained the quotation marks around "*Eosaukia*" though without comment regarding Kobayashi's (1957) original use of the quotations marks or the choice to retain them. The later study excluded some of Kobayashi's specimens attributed to the species, referring these to *Lophosaukia* cf. *jiangnanensis* Lu and Lin, in Lu et al. (1984), an assignment herein rejected in recognition of substantial intraspecific variation within *E. buravasi* and the lack of the distinctly angular cranidial anterior margin that characterizes *Lophosaukia.* Considering that other *Eosaukia* species subsequently discovered have a similarly short pygidium, such as *E. bella* (Walcott, 1906; genus designation by Lee and Choi, 2011) and *E. micropora* (Qian, 1985; genus designation by Lee and Choi, 2011), there is little doubt that *E. buravasi* is a typical member of this genus.

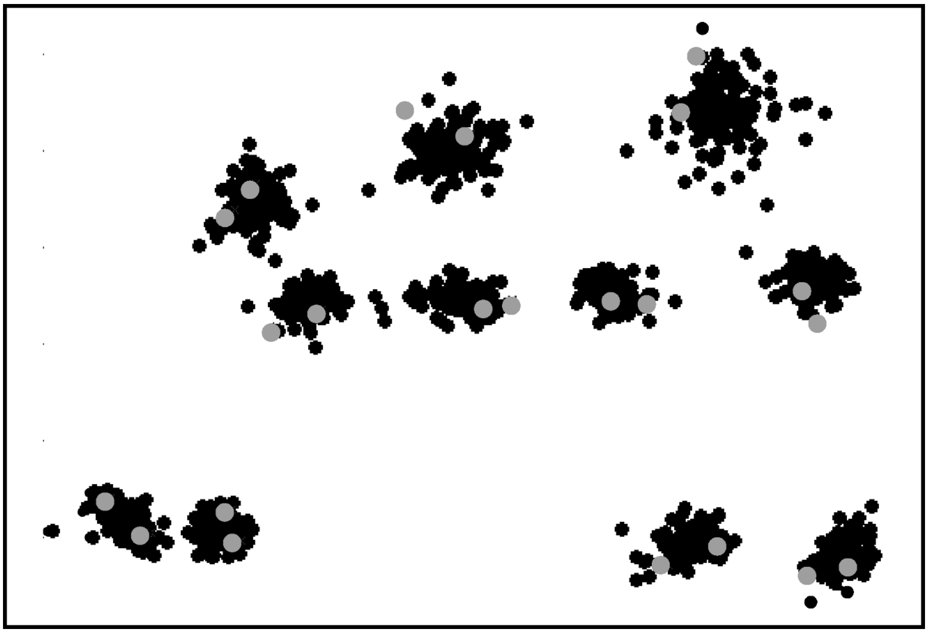

Fig. 14. Landmark distribution plot using Procrustes superimposition for 120 specimens of *Eosaukia buravasi* from the Tarutao Group, Thailand (black) and 2 from the Myet-Ye Formation, Myanmar (grey). See Fig. 13 for the landmark scheme.

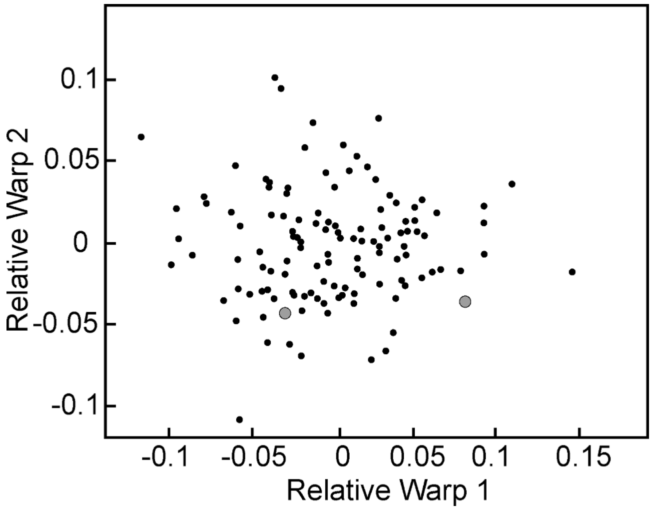

Fig. 15. Relative Warps 1 and 2 for 122 specimens of *Eosaukia buravasi* from the Tarutao Group, Thailand (black) and the Myet-Ye Formation, Myanmar (grey. See Figs. 13 and 14 for the landmark scheme and landmark distribution plot. Relative Warp (RW) 1 accounts for 27.48% of variance and RW 2 accounts for 17.38%.

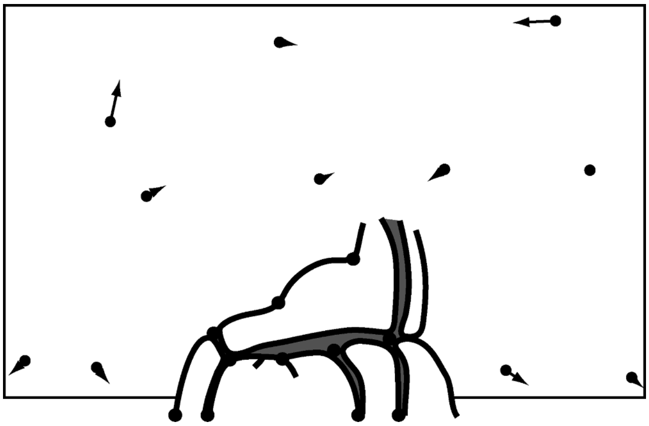

Fig. 16. Size-related shape change in *Eosaukia buravasi* Kobayashi (1957), accounting for 3.6% of overall variance, $p < 0.000625$ for generalized Goodall's F value over 1600 bootstraps. Based on partial Procrustes distance regressed against log centroid size with three smallest specimens as reference.

There is a high level of intraspecific variation within *E. buravasi.* This variation is apparently independent of geographic or stratigraphic distribution. A morphometric analysis was conducted on 120 specimens recently collected from the Ao Mo Lae Formation, Tarutao Group, Thailand and two sufficiently complete specimens from the Myet-Ye Formation (CMC IP87113 and IP87116). The analysis used 18 landmarks (Fig. 13); non-axial landmarks were reflected across the axis in order to optimize sample size. A Procrustes superimposition (Fig. 14) shows that both Myanmar specimens lie within the range of variation exhibited by the Thai material. The first two relative warps (RW) of a thin plate spline analysis of these cranidia shows that the Myanmar specimens do not form an independent grouping. They do have similar second relative warp (RW2) scores, but this is within the range of RW2 scores of specimens from Thailand (Fig. 15). RW1 and RW2 account for 27.48% and 17.38% of the variance respectively.

Shergold et al. (1988) suggested that much of the variation within *E. buravasi* was likely due to ontogenetic change. Using the same set of landmarks and specimens as for the thin plate spline detailed above, we compared the regression of partial Procrustes distances with the natural log of the centroid size, a technique for determining the extent to which shape change is related to size (Webster and Sheets, 2010). The mean of the three smallest specimens was used as the reference form. Statistically significant size-related shape change accounts for $<5\%$ of variation (test for generalized Goodall's F value, boot-strapped 1600 times, $p < 0.000625$). Allometric growth is most prominent in the lateral movement of the cranidium's anterolateral corner and anterior movement of the palpebral lobe's posterior point (Fig. 16). Shape variance, measured by distance-based (Foote) disparity, across all 122 specimens of *E. buravasi* was 0.0079 (bootstrapped by 1600 repetitions with a 95% confidence interval of 0.0068–0.0088). Although comparative studies of intraspecific variation in cranidial shape remain in infancy, what comparisons can be made (e.g., Hong et al., 2014) apparently suggest that

E. buravasi displayed a high degree of variance, particularly when not associated with clear ontogenetic changes. For comparison, a single specimen was remounted, photographed, and marked for landmarks ten times; the variance for these ten images of a single specimen was 0.0005 over 1600 bootstraps.

Shergold et al. (1988) reassigned many of the librigena and cranidia included as "*E.*" *buravasi* by Kobayashi (1957; pl. 5 Figs. 6, 7, 13–15, 19, 20) to *Lophosaukia* cf. *jiangnanensis* Lu and Lin in Lu et al. (1984). After reexamining Kobayashi's material (Fig. 12) we revert all specimens that Shergold et al. (1988) transferred to *L.* cf. *jiangnanensis* back to *E. buravasi.* Variation among this material is attributable to the intraspecific variation recognized in the geometric morphometric analysis described herein.

Eosaukia sp. (Shergold et al., 2007, p. 61) from the Bonaparte Basin of Western Australia differs from *E. buravasi* in the pygidium possessing a third, though poorly developed axial ring, and a more robust occipital spine. While these differences are sufficient to recommend a separate species for the Australian material, cranidia with poorly preserved occipital lobes are indistinguishable from *E. buravasi*.

A different set of specimens from the Bonaparte Basin was assigned to *Ptychaspis*? Sp. aff. *P. cacus* (Walcott, 1905) (Shergold et al., 2007p. 65, Fig. 38). These specimens may belong to *Eosaukia buravasi*. Certainly, the anterolaterally oriented lateral segments of the anterior border furrow are characteristic of *Eosaukia* rather than *Ptychaspis*, and both the Myanmar and Thai collections contain notably bulbous, anteroventrally curved cranidia (e.g., CMC IP87112; Fig. 11E–G). However, apart from fig. 38.I,J of Shergold et al. (2007) the fixigenae of *P.*? sp. aff. *P. cacus* are generally narrower than those the *E. buravasi* from Sibumasu. *Ptychaspis*? Sp. aff. *P. cacus* may be a variant of *E. buravasi* with a tendency towards narrower fixigena or it may be a separate species.

6. Conclusions

Myanmar's Shan State belongs to the Sibumasu terrane, one of many continental blocks that made up the Gondwanan margin during the lower Paleozoic and now compose South, Southeast, and East Asia. The limited Cambrian–Ordovician fossil material available from the Shan State links Sibumasu with North China and northwestern Australia, a position supported by the more extensive material of similar age known from Thailand, and questions placement of the Lhasa block between Sibumasu and western Australia. The new fossil material described herein demonstrates that the Molohein Group's Myet-Ye Formation extends from the late Jiangshanian through the middle of Cambrian Stage 10. The fossiliferous support for these paleogeographic and biostratigraphic conclusions comes from the first Cambrian fossils to be formally described from Myanmar: *Eosaukia buravasi*, which was previously reported but not figured; *Asioptychaspis asiatica*, previously known from North China; and *Asioptychaspis lata*, a new species endemic to Myanmar. Considerable additional diversity may exist within the Myet-Ye Formation, which will permit further test of the above biostratigraphic and paleogeographic conclusions.

Author contribution

Shelly J. Wernette: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Nigel C. Hughes:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing - original draft, Writing - review & editing. **Paul M. Myrow:** Conceptualization, Funding acquisition, Investigation, Writing - review & editing. **Aye Ko Aung:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge with sincere thanks residents of the Padongaing village for the warm welcome to their land and community, and for their kind help in the field. We are greatly indebted to Oo Kyaing Sein and the Myanmar Geosciences Society (MGS) for tremendous logistic support in Myanmar. Thanks also to Han Nyein of the MGS, and Nyan Soe of DHL for assistance with shipping. We are most grateful to Kye Soe for his enthusiasm for our work, that builds on his pioneering efforts. Andrew Mitchell gave sage advice as we planned our work. Cody Colleps kindly assisted in the field. Sincere thanks to our three manuscript reviewers, including Ian Metcalfe and Clive Burrett for their valuable suggestions that improved our manuscript and to Khin Zaw for editorial input and overseeing the manuscript through the review process. Funding for this work includes student grants to Wernette from the Geological Society of America, the American Museum of Natural History (Lerner-Gray Memorial Fund), the Evolving Earth Foundation, the American Association of Petroleum Geologists (David Worthington Named Grant), and the Paleontological Society (Allison R. "Pete" Palmer Grant) as well as National Science Foundation grant EAR-1849963 to Hughes and EAR-1849968 to Myrow. Our activity in Myanmar was initiated through NSF EAR-1124303 (Hughes) and EAR-1124518 (Myrow). Hughes acknowledges receipt of Fulbright Academic and Professional Excellence Award 2019 APE-R/107 and thanks the Geological Studies Unit, Indian Statistical Institute, Kolkata for kindly hosting him. This research contributes towards UNESCO IGCP 668: Equatorial Gondwanan History and Early Palaeozoic Evolutionary Dynamics.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jseaes.2021.104775.

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Shelly J. Wernette is a paleontologist and stratigrapher working as a postdoctoral researcher at the University of California, Riverside under the mentorship of Nigel Hughes. She has focused on the lower Paleozoic trilobite fauna of Sibumasu and integrating the biostratigraphic data with geochronologic and various stratigraphic data types. As secretary of IGCP668 she facilitates the program's meetings and excursions throughout the Sibumasu field areas. She has also contributed to the program's place-based outreach efforts to Myanmar children as well as co-led educational outreach for California high schoolers through an NSF-funded geoscience development program.

Nigel Hughes is a paleontologist and stratigrapher working on various geological issues in South and Southeast Asia, and on the paleo-evolutionary developmental biology of trilobites. He uses knowledge of the Cambrian of the region to constrain its more recent geological history. He is a co-leader of IGCP668 and is interested in geoscience educational outreach in the region. Author of *monishar pathorer bon (Monica and the Stone Forest),* a place-based illustrated story in Bengali about fossilized wood, he and others are currently developing an animated series about the region's geological history called *The Ocean on Top of Our Mountain.*

Paul Myrow is Professor of Geology at Colorado College (Colorado Springs, CO, USA), and has been a visiting professor and lecturer at Caltech, MIT, and Yale University. He has published on a variety of topics, including the details of sedimentary processes, sedimentary structures, and facies models; Earth history, including strata and events from the Mesoproterozoic through the Mesozoic; and Himalayan geology, including tectonics, detrital and igneous geochronology, palaeomagnetism, stratigraphy, and palaeontology. He is currently a leader of IGCP Project 668: Equatorial Gondwanan History and Early Palaeozoic Evolutionary Dynamics. He is a long-time Associate Editor of the Journal of Sedimentary Research.

Aye Ko Aung is a Paleozoic stratigrapher and paleontologist with a Ph.D. from the University of Queensland. He has taught at various universities in Myanmar and in Malaysia. An expert of Paleozoic corals, he has done extensive work on the Paleozoic strata of Myanmar authored important syntheses of current knowledge of regional Paleozoic history. He is a member of IGCP668 *Equatorial Gondwanan History and Early Palaeozoic Evolutionary Dynamics* and is also committed to geoscience outreach to the children of Myanmar in his role as the translator into Burmese of *The Ocean on Top of Our Mountain*.