

## Palaeozoic correlations and the Palaeogeography of the Sibumasu (Shan-Thai) Terrane - a brief review

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**Abstract** - Furongian sandstones yield shallow-water trilobite faunas along the length of the Sibumasu Terrane in the four regions of NW Malaysia (Langkawi), southern Thailand (Satun), the Shan States of Myanmar and the Baoshan Block of western Yunnan. These are associated with felsic plutonics, volcanics or volcanoclastics in all four regions. Correlations of Langkawi Island and Satun Province shallow-water carbonates reveal a succession of dominantly molluscan, stromatoporoid-brachiopod faunas which, from conodont evidence, range from the mid-Tremadocian to the Darriwilian, and which have dominantly North China-Australian affinities. A major increase in sea-level in the late Darriwilian led to trilobite-brachiopod faunas with very strong South China affinities. Deep-water conditions of more than 150 m prevailed in the Katian with the deposition of red, stromatolitic limestones with cool/deep-water trilobite and conodont faunas. This 'Pa Kae facies' re-occurs in limestones of Silurian and Devonian age in several areas of Sibumasu. Llandovery graptolitic shales occur along the length of the terrane. Silurian, probably outer shelf, limestones occur in NW Malaysia, the Shan States and Baoshan but have a limited distribution in Thailand. Most Katian to Devonian faunas in NW Malaysia, Thailand and Baoshan show evidence of deep-water deposition which continues into the Mississippian of NW Malaysia and into the Pennsylvanian of Thailand contrasting with the Baoshan Block's extensive, Devonian to Mississippian shallow-water, coral-rich carbonates.

A significant mid-Carboniferous to Pennsylvanian depositional gap in the Shan States and Baoshan may be due to regional uplift by the mantle plume that triggered Cisuralian rifting of Sibumasu from Gondwana. Palaeomagnetic results from Baoshan, along with biogeographic evidence and provenance data from Thailand show that Sibumasu was definitely part of the Australian sector of Gondwana until the Cisuralian and did not experience major deformation until Late Triassic collision with Indochina.

**Keywords:** Thailand, Malaysia, Yunnan, Ordovician, Devonian, biostratigraphy, palaeogeography

### 1. Introduction

The >3000 km long Sibumasu Terrane was established to include the continental areas of western Thailand, western peninsular Malaysia, Sumatra and the Baoshan and Tenchong blocks in western Yunnan, China (Metcalf, 1984; 1992) and therefore includes the Shan-Thai Terrane of Bunopas (1982) who did not explicitly include Baoshan and Sumatra (Fig.1). The Sibumasu Terrane is characterized by Cisuralian Gondwana marine faunas and glaci-marine sediments which contrast to the contemporaneous tropical, fusulinid and coral-bearing limestones of the Indochina and Inthanon Terranes (Shi and Archbold, 1995; Ueno and Charoentitirat,

2011; Wang *et al.*, 2001). Current models suggest that the Inthanon Terrane of northern Thailand was thrust over the Sibumasu Terrane in the Late Triassic (Metcalf and Henderson, 2017; Ueno and Charoentitirat, 2011). Lower Palaeozoic strata are well developed along the Sibumasu Terrane from northern peninsular Malaysia, through to the Baoshan Block in western Yunnan, China.

### 2. Paleozoic correlations

Good sections of Palaeozoic rocks, often with abundant fossils, are known in northwest Malaysia (particularly in the Langkawi Islands – Fig.1), in Satun Province in southern

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Thailand (including Tarutao Island), in the Shan States of Myanmar and in the Baoshan region of West Yunnan, China (Fig.1). We will briefly summarise the Palaeozoic in the four main, relatively well-studied areas, of Sibumasu listed above (Figs. 2-3), emphasise their similarities and differences, suggest correlations and summarise their palaeogeographic development. We plot, in detail and for the first time, the probable stratigraphic ranges of most described or illustrated taxa using the lithological units mapped in the Langkawi Islands and Satun Province and suggest correlations to the international chronostratigraphic column (Fig.2). In order to simplify lithostratigraphic comparisons between the four major fossiliferous areas of Sibumasu (Fig.3), lithologies are shown as either dominantly carbonate (brickwork pattern) or siliciclastic sequences (dotted pattern) plus the two major volcanic sequences (v pattern) of the Late Cambrian felsic Bawdwin Formation in Myanmar and the Early Permian mafic Woniusi Formation in Baoshan.

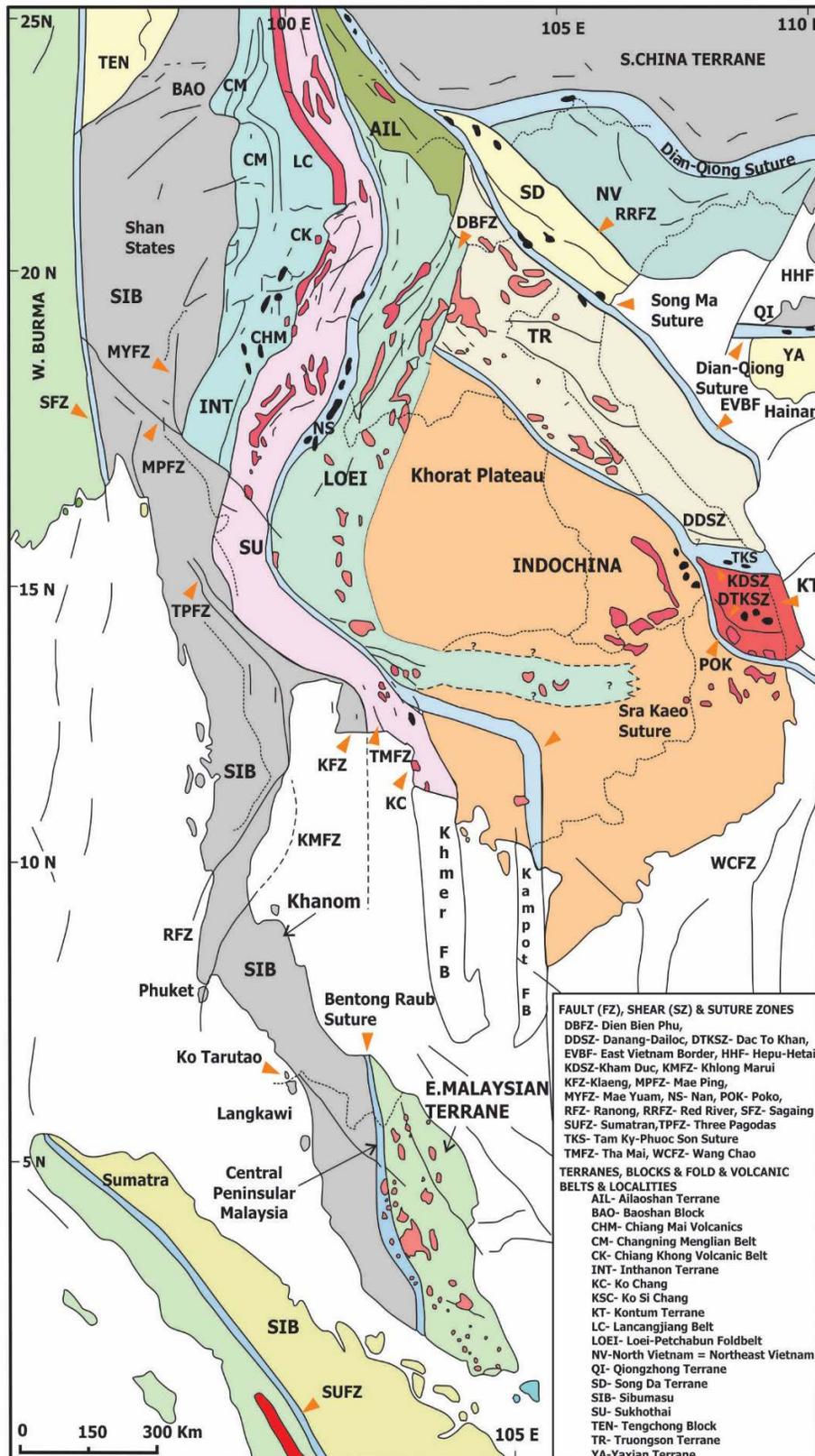
Despite a wealth of taxonomic studies, detailed correlations have not previously been attempted between the Ordovician sequences of Satun Province in southern Thailand and Langkawi. This is mainly because most authors have not attempted to subdivide the approximately 1900 m of the Kakit Bukit Formation (formerly the Lower Setul Limestone). However, our mapping in the Langkawi Islands showed that by using simple field-based criteria the formation could be divided into nine mappable members designated units E-M (Laurie and Burrett, 1992; Stait *et al.*, 1987; Wongwanich *et al.*, 1983; Wyatt, 1983) and that the formations mapped on Tarutao Island (Mason, 1986; Wongwanich *et al.*, 1983, 2002; Wongwanich 1990) could be recognized as metamorphosed units near the Kuah Granite in Langkawi. Figure 2 is the first attempt at a relatively detailed correlation between Satun and Langkawi pre-Hirnantian sequences by plotting all available palaeontological information against generalized lithostratigraphy. Figure 2 shows the diversity of pre-Hirnantian faunas described from numerous papers in both Langkawi and Satun. It emphasizes a paucity of Furongian to Tremadoc faunas in Langkawi, mainly due to metamorphism by the Late Triassic Kuah Granite. Because the lithological units are plotted by thickness, it also emphasises the great thickness of the Furongian - Sandbian carbonate sequences compared to younger, Katian to Carboniferous, possibly condensed sequences.

Cambrian, mainly siliciclastic sequences have been studied in Thailand, Malaysia, Myanmar and the Baoshan Block and good faunas have been described from these regions except from Malaysia. In the Langkawi Islands in Malaysia, the Machinchang Formation yields fragmentary trilobites that are generally not identifiable to species. The first Cambrian fossils in Thailand were discovered 60 years ago by Mr Saman Buravas on Tarutao Island and described by Kobayashi (1957). The Tarutao Group sandstones were recollected for trilobites and the fauna described by Shergold *et al.*, (1988) who identified 12 taxa (Fig. 2). This fauna is similar to that found in lithologically similar Furongian sandstones from Baoshan (Sun and Xiang, 1979)

and from the Shan States of Myanmar (Myint Lwin Thein, 1973). Correlations of the Chinchin and Jemurok Members of the Machinchang Formation to the Ao Tami and Ao Mo Lae Formations of the Tarutao Group are therefore based mainly on lithology (MTJGSC, 2013), (Fig. 2).

The upper Talo Wao Formation on Tarutao Island yields a Tremadoc trilobite faunule consisting of *Pseudokainella malakanesis*, *Rossaspis bunopasi*, *Asaphellus* sp and a harpid (Stait *et al.*, 1984). Ross *et al.*, (1993) consider that *R. bunopasi* is “indistinguishable” from *Rossaspis superciliosa* from the Middle Tremadoc of the USA. Limestone lenses from the upper part of the Talo Wao Formation also contain Tremadoc conodonts *Chosonodina herfuthi*, in a lower lens, and *Paltodus deltifer* in an upper lens (Teraoka *et al.*, 1982). The conformably overlying Thung Song Group carbonates on Tarutao Island contain Tremadoc-Floian conodonts, (Agematsu *et al.*, 2008), *Rossaspis* sp., the chiton *Chelodes whitehousei*, the gastropod *Peelerophon oehlerti* (Jell *et al.*, 1984) and the rostroconch *Euchasma* sp. (Fig. 2). *Rossaspis* is also found in the Ordovician of Kanchanaburi Province in western Thailand (Wolfart, 2001). Unidentifiable endocerid nautiloids are common in the lower formations, a new genus of discosorid is found in the Lae Tong Formation and the coiled nautiloid *Hardmanoceras chrysanthemum* is common in the upper formations (Stait and Burrett, 1984a). The uppermost formation on Tarutao Island, the Rung Nok Formation, yielded the conodont *Prioniodus evae* along with stromatoporoids and corals. Receptaculitids, probably assignable to *Fisherites* sp., are also present in the Rung Nok Formation and are common also in Thung Song correlates in Kanchanaburi, near Mae Sariang in northwest Thailand and in the Shan States of Myanmar (Kruse, 1989). The Lower Ordovician formations of Tarutao may be recognized lithologically on Langkawi Island to the west of the Triassic Kuah Granite (formerly Gunung Raya Granite) where they have been metamorphosed by the granite (Wongwanich *et al.*, 1983) (Fig. 2). The polyplacophoran (chiton) *Chelodes* sp. is the only fossil that has been identified in this sequence (Fig. 2). On Langkawi, nine members were mapped within the Kakit Bukit Formation (formerly the Lower Setul Limestone) and informally designated units E to M (Wongwanich *et al.*, 1983; Wyatt, 1983). The lower units E and F are strongly dolomitic and may overlap in age with all or part of the metamorphosed Lower Ordovician to the west of the Kuah Granite or to units on the Satun mainland but a lack of both macrofossils and conodonts prevents definite correlation.

It is difficult to plot the range of the conodonts described by Agematsu *et al.*, (2008) using the mapped units of Wyatt, (1983) and Wongwanich *et al.*, (1983). However, by using thickness estimates, the obvious slumped limestone beds mentioned by Agematsu *et al.* (2008) which probably equate with those described by Wyatt (1983) from within unit H, (note 2 on Fig.2) and from the few conodont species identified by S. Carey *in* Laurie and Burrett (1992) and re-assigned by Burrett, a tentative range and correlation chart may be erected (Fig.2).



**Figure 1.** Location map of mainland South East Asia and part of Sumatra showing major terranes and sutures (modified from Burrett *et al.*, 2014, Thassanapak *et al.*, 2017 and Udchachon *et al.*, 2017). Note the major Sibumasu Terrane regions discussed in this review are (from the north) Baoshan, western Yunnan, Shan States, (Myanmar), Satun Province, (southern Thailand, including Tarutao Island) and northwest Malaysia (including the Langkawi Islands).



The ranges of the gastropods described by Hamada *et al.*, (1975), Kobayashi (1958, 1959), Kobayashi and Hamada (1964), Jell *et al.*, (1984) and Yochelson and Jones (1968), the brachiopods described by Laurie and Burrett (1992) and Cocks *et al.*, (2005), the stromatoporoids described by Webby *et al.*, (1984), the nautiloids described by Stait and Burrett (1982) and Stait *et al.*, (1987), and partially re-assigned by Niko and Sone (2014, 2015) from the Langkawi Islands are shown on the chart (Fig. 2). However, further work is clearly needed to substantiate and modify this preliminary diagram. Faulting is common on Langgun Island and on the main Langkawi Island and careful structural work needs to precede re-mapping and re-collection of these units. This faulting, which is often far from obvious, repeats and cuts-out lithic units, causing problems, mistakes and debates both on Langkawi and mainland Malaysia but also in mainland Satun Province (e.g. Lee 2009; Meor and Lee, 2002; Wongwanich *et al.*, 1990). Langkawi, units G to L range, therefore, from the upper Floian to the Sandbian and correlate with unnamed Thung Song Group limestones on the Satun mainland. These Satun limestones underlie the distinctive red limestone of the Pa Kae Formation and are generally, but not completely, (see note 5 on Fig. 2) younger than the Rung Nok Formation. Fossils have been collected from many scattered outcrops on the Satun mainland but no coherent stratigraphy has been erected. The Satun mainland outcrops include the conodonts from the Thung Wa sections described by Agematsu *et al.*, (2006b), brachiopods described by Hamada (1964) and Laurie and Burrett (1992), nautiloids by Stait and Burrett (1984), and *Serratognathus* sp. and other conodonts by Wilkinson (2008), and Cantrill (2002). The Floian *Serratognathus* from Satun (Langu district) drill-core found by Wilkinson (2008) shows that at least some Lower Ordovician limestone is present on mainland Satun. *Serratognathus* sp. has also been found in mainland northern Malaysia but not in Langkawi (Metcalf, 1980).

A calcareous shale, or decalcified limestone known as the "Satun Shale" has yielded the biogeographically interesting trilobites *Hungioides* sp., *Ovalocephalus* sp and *Encrinurella* sp. (Fortey and Cocks, 1998). This informal unit is thought to underlie the Pa Kae Formation but its exact composition, thickness, stratigraphic position and age have not yet been determined. The *Encrinurella* is similar to the type species from the Shan States (Reed, 1906), *Ovalocephalus* is a characteristic South China genus (Fortey and Cocks, 1998) and *Hungioides* has a peri-Gondwana distribution (Fatka *et al.*, 2008). Agematsu *et al.*, (2007) found the lower Sandbian zonal conodont *Pygodus anserinus* at the base of, or just below, the Pa Kae Formation, however the exact relationship between the trilobite, brachiopod and conodont ranges within the Pa Kae Formation have not yet been determined. Unit M in Langkawi and the Pa Kae Formation in Satun are distinctive red stromatolitic limestones that both contain a Katian to lower Ashgill trilobite and deeper/cooler 'North Atlantic' province conodont fauna (Agematsu *et al.*, 2007, 2008). Thirty nine species of trilobite have been described from

the Pa Kae Formation (Fortey, 1997) and 11 from unit M of the Kakit Bukit Formation (Kobayashi and Hamada, 1978). Nileids, cyclopygids and *Telephina* all suggest deep to very deep marine conditions and the conodont faunas also suggest cool or cool and deep seas. The *Foliomena* brachiopod fauna also indicates deep shelf conditions (Cocks and Rong, 1988; Zhan and Jin, 2005). The purple and green shales and micritic nodular limestones of the Pupiao Formation of the Baoshan block contains a generally similar trilobite deep-water fauna to that of Satun and the Shan States with *Ovalocephalus*, *Cyclopyge* and *Encrinurella* of Katian age with a *Foliomena* brachiopod fauna interbedded with graptolite shales and overlain by Hirnantian graptolitic shales (Zhang *et al.*, 2014).

The Pa Kae Formation in Satun and unit M in Langkawi are overlain by the Wang Tong and Tanjong Dendang Formations respectively. These contain the Ordovician-Silurian boundary, underlain by a typical Hirnantian fauna with *Mucronaspis mucronata*, *Hirnantia* and *Metabolograptus persculptus* overlain by shales with Llandovery graptolites (DMR, 2014; Wongwanich *et al.*, 1990; Cocks and Fortey, 1997; Cocks *et al.*, 2005; Agematsu *et al.*, 2006a). Although the Hirnantian fauna of the northern Shan States' Panghsa-Pye Formation contains typical Hirnantian elements such as *M. mucronata*, *Hirnantia*, *Kinnella* and *Hindella*, it is surprisingly different, in detail, to the Hirnantian faunas of both Satun and South China (Cocks and Fortey, 2002).

Successive Llandovery graptolite zones are recorded in Langkawi (Jones, 1973), have been studied in the Shan States recently (Loydell and Kyi Pyar Aung, 2017) and are probably present in Satun but have not been studied in detail (Meesook, 2014). Similarly, the Jenhochiao Formation in Baoshan contains a succession of well-studied graptolite zones from the latest Ordovician Hirnantian to the *Monoclimacis griestoniensis* Zone of the uppermost Llandovery (Ni *et al.*, 1982). These widespread Llandovery graptolitic shales are overlain by limestones in Langkawi, Myanmar and Baoshan belonging to the Mempelam, Linwe and Lichaiba formations respectively. Llandovery, Wenlock and Pridoli-Lockhov age conodonts have been described from the Mempelam and Lichaiba formations (Igo and Koike 1973, Zhang *et al.*, 2014) and *Monograptus* is recorded in the Linwe Formation of Myanmar. Other than a few undescribed graptolites, Silurian faunas are not yet definitely known from Satun (Meesook, 2014). However, Silurian conodonts are known from coastal outcrops of nautiloid bearing 'Thung Song Group' limestones near Khanom, in Nakhon Si Thammarat province (Burrett unpublished) and possibly from limestones referred to the 'Rung Nok Formation' in mainland Satun (Sashida *in* Meesook 2014). Late Silurian to Early Devonian limestones of the Mae Ping Formation in northern Thailand (Burrett *et al.*, 1986), yield conodonts and probable elements of a distinctive nautiloid fauna that has recently been described by Niko *et al.*, (2017) from the Mempelam Formation of Langkawi and which is also illustrated by Zhang *et al.*, (2014, p. 112) in the Lichaiba Formation in Baoshan (see Number 3 on Fig. 3).

The Lichaiba Formation is overlain by purple 'reticulate' limestones of the Pridoli-Lochkov Niushiping Formation and may be a similar facies to the Pa Kae Formation (Zhang *et al.* 2014). A photograph of the red, 'phacoidal' Linwe Formation in Myanmar shows that it is also very similar in appearance to the Pa Kae Formation (Bender, 1983, fig.37b), to the red limestone of the Early Devonian Kuan Tung Formation in Thailand and to the thrombolitic limestone of the Silurian Mempalam Formation illustrated by Lee (2009). Thus the deep-water Pa Kae lithofacies, the distinctive texture of which has been shown by Wongwanich (1990) to be stromatolitic and thrombolitic in origin, may be widespread in Sibumasu and probably occurs in Late Ordovician, Silurian and Devonian limestones (see Number 2 on Fig.3). Wongwanich (1990) estimated the depositional depth of the Pa Kae Formation as about 200 m, which is consistent with both the presence of psychrospheric and benthonic trilobites, the deep-shelf *Foliomena* brachiopod fauna and cool-water conodonts. The 'Pa Kae Facies' is very similar to the red and partially stromatolitic and thrombolitic, filament and coccooid rich, 'Ammonitico Rosso' of the European Jurassic, widely used as a facing stone and which has also been interpreted as a low-oxygen, quiet water, 'pelagic' limestone (Martire *et al.*, 2006; Massari, 1979). The red colouration of deep-water limestones is probably due to iron-bacteria mediated deposition of hematite (Mamet and Preat, 2006).

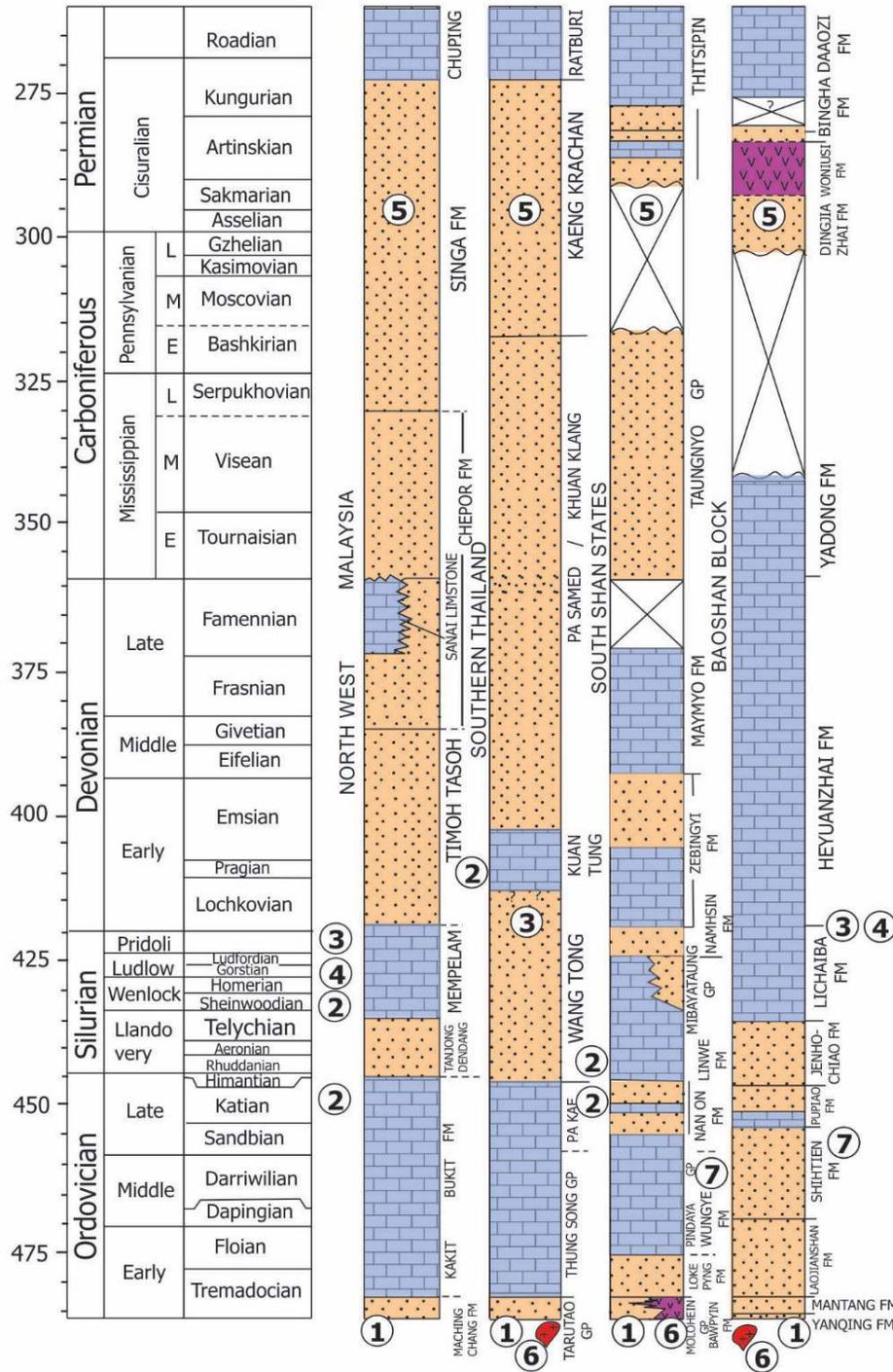
Remarkably, the Ludlow-Pridoli Niushiping Formation of Baoshan contains the unusual, but distinctive, loboliths (bulbous floating holdfasts) of the crinoid *Camarocrinus* or *Mahrhoumacrinus* which are also described from the coeval Mempalam Formation of Langkawi (Lee, 2005; Zhang *et al.*, 2014, p.118) (see Number 2 on Fig.3). The Mempalam Formation also contains a Llandovery trilobite fauna consisting of 15 species and named the *Prododontochile* fauna by Kobayashi and Hamada (1971) but this fauna has not been found elsewhere. Thus the Silurian graptolitic shales of all four regions are similar and the Silurian limestones are faunally and lithologically similar except for Satun Province. However, the Emsian trilobite (Fortey, 1989) and conodont (Long and Burrett, 1989a) faunas described from the Kuan Tung Formation of Satun Province have not been found elsewhere in Sibumasu.

The limestones of the Mempalam and the Kuan Tung Formations are overlain conformably by the mainly siliciclastic Timoh Tasoh (formerly the Upper Detrital Member) and the Pa Samed formations respectively. These contain a tentaculitoid fauna near their bases containing *Nowakia* (*Turkestanella*) *acuaria* which extends to Baoshan (Agematsu *et al.*, 2006a; Burton, 1967, 1970). This tentaculitoid fauna is found with the southern Thai brachiopods *Plectodonta forteyi* and *Lissatrypa?* and the southern Thai trilobite *Plagiolaria poothai* Kobayashi and Hamada 1968, in mainland Perlis, northern Malaysia (Meor and Lee, 2005; Ong and Jasin, 2007). These are the only

Devonian brachiopods and trilobite described from southern Thailand that are also found in northern Malaysia. Lower Devonian *Monograptus* species occur in both formations. *Nowakia* (*Turkestanella*) *acuaria* is found with *Monograptus atopus*, and the Satun brachiopods *Plectodonta cf. forteyi* and *Clorinda cf. wongwanichi* in the Zebingyi Formation of Myanmar (Aye Ko Aung, 2012). The Devonian of Baoshan is represented mainly by limestone and contains an abundant coral fauna which is reefal in part (Wang, 1994) whereas the coral-brachiopod rich Devonian limestone in the Shan States is limited stratigraphically (Aye Ko Aung, 2012). These coral-rich Devonian limestones contrast with the non-coralline, deep-water Devonian limestones in southern Thailand (Emsian, Kuan Tung Fm) and the Upper Devonian Sanai Limestone of Malaysia (Lee, 2009, Aye Ko Aung *et al.*, 2013). Deep-water, occasionally turbiditic, Middle to Upper Devonian limestones are known in NW Thailand near the Myanmar border (Long and Burrett, 1989b; Savage, 2013) and Devonian limestones are also present in Kanchanaburi province, western Thailand (Savage *et al.*, 2006).

The oldest, well-dated Carboniferous fauna in Satun consists of deep-water Tournaisian radiolarians found in a chert within the Khuan Klang Formation (Imsumat, 2012; Saesaengseerung and Saiid, 2016) and these Tournaisian cherts are also well studied in NW Malaysia (Jasin and Harun, 2011). The siliciclastics of the Khuan Klang Formation contain goniatites, *Langgonbole vulgaris* and *Posidonomya* sp which are also found in the lithologically similar 'redbeds' (the Langgon Red Beds) of the lower Singa Formation in the Langkawi islands (Jasin, 2015). Younger Carboniferous faunas have not definitely been found in Langkawi but the Namurian (Late Mississippian to Early Pennsylvanian) brachiopod/goniatite fauna of the Pa Samed Formation (Wongwanich *et al.*, 2004) suggests that the Khuan Klang and Pa Samed formations in Satun and the revised Singa Formation of Langkawi are, at least in part, lithological and biostratigraphic correlates (Figs.2-3). The Carboniferous in the Shan States is poorly known and most belongs to the mainly siliciclastic Taungnyo Formation (Metcalf and Kyi Pyar Aung, 2014). In contrast, the Lower Carboniferous of Baoshan is mainly carbonate and rich in brachiopods and corals (Shi *et al.*, 2005).

Because of their close lithological similarities, there is no problem correlating the upper, glacial part of the Singa Formation in Langkawi and the outcrops of the Kaeng Krachan Group in the Adang-Rawi Islands and mainland Satun and further north to better exposures in Phuket (Fig. 1) and nearby provinces (MTJGSC, 2013; Ridd, 2007, 2009 a,b). Cisuralian faunas from siliciclastics in NW Malaysia, Thailand, and Baoshan are similar and strongly support contiguity with Gondwana (Shi and Archbold 1995; Wang *et al.*, 2002; Xiaoichi, 2002; Chaodumrong, 2010; Chaodumrong *et al.*, 2007).



**Figure 3.** Correlation between major sections of Palaeozoic in Sibumasu showing simplified lithologies. Mainly carbonate sections are shown by brickwork, dominantly siliciclastics by dots and major volcanic units by v's. Columns are Northwest Malaysia (mainly Langkawi Islands), Southern Thailand (mainly based on sections in Satun province, including Tarutao Island), Myanmar (based mainly on southern Shan States) and Baoshan, western Yunnan, China. Numbers in circles 1= Furongian trilobite fauna in sandstones, 2 = Pa Kae facies, in Katian, Silurian and Devonian limestones. 3= Silurian nautiloid fauna, Number 3 in Southern Thailand is Silurian limestones at Khanom, Nakhon Si Thammarat Province. 4= Occurrences of loboliths of *Camarocrinus* in Late Silurian limestone. 5= Glacimarine sediments in N.W. Malaysia, S. Thailand, Myanmar, and Baoshan. Myanmar glacimarine sediments are restricted to the area south of the Shan States suggesting that most of eastern Myanmar was (glaciated?) land during the Cisuralian, hence the gap in strata shown in the Myanmar column. 6= Occurrences of major felsic magmatism in the Late Cambrian to Early Ordovician. Thailand occurrence is in the upper peninsula near Hua Hin (Lin *et al.*, 2013). 7= Occurrence of Darriwilian *Saucrorthis* brachiopod fauna.

### 3. Palaeogeographic development

It is clear that, in the Furongian, a shallow shelf siliciclastic sea extended from Malaysia to Baoshan. Conglomerates and heavy mineral bands suggest that the source region was nearby and palaeocurrent indicators suggest this source was to the present day west (Akerman, 1986). In Baoshan, sandstones become coarser and conglomeratic toward the west (Zhang *et al.*, 2014). In Malaysia, the Furongian sandstones were probably deposited in a delta complex grading into the barrier bar complex of Thailand (Lee, 2006). Furongian rhyolites are well known around the Bawdwin Mine in Myanmar and are probably associated with the belt of felsic plutons and volcanics that extends from Sibumasu through the Tibetan terranes and along the Himalayan margin of Gondwana (Wang *et al.*, 2015) (Number 6 on Fig.3). Evidence of volcanism occurs as ash deposits in the Upper Cambrian and Lower Ordovician of Malaysia, Thailand, Myanmar and Baoshan. The cause of this belt of Furongian to Darriwilian S-type calc-alkaline magmatism (Lin *et al.*, 2013; Shi *et al.*, 2016; Wang *et al.*, 2015) is debatable but a syn- to post-orogenic origin is most likely and is possibly due to a ‘Pan African’ age collision of South China or all of the main Chinese terranes with Gondwana (Xu *et al.*, 2016; Zhai *et al.*, 2016). Siliciclastic sand-sea deposition continued into the Tremadoc in all areas of Sibumasu and, as the siliciclastic source region was depleted, it converted to a shallow, tropical carbonate platform or ramp by the mid-Tremadoc and through the Floian and Dapingian in Malaysia and Thailand and also possibly in Myanmar. Myanmar and part of western Kachanaburi in western Thailand, seem to have experienced subtidal conditions with a diverse trilobite-brachiopod-ostracode fauna and may have belonged to a separate basin in the mid-Ordovician (Agematsu *et al.*, 2008; Agematsu and Sashida, 2009; Wolfart, 2001). However, in Baoshan, the Floian and Dapingian are represented by deeper water fine quartz sandstones, shales and minor gravel beds of the Liaojianshan Formation. Rare macrofossils include the trilobites *Neseuretus*, *Basiliella* and *Ampyx*, the brachiopods *Leptellina pulchra* and a cystoid along with graptolites *Callograptus* and *Didymograptus*. The fauna suggests mid- to outer shelf conditions whilst some of the sediments suggest shallow water. The conformably overlying Shitien Formation contains abundant mid- to late Darriwilian graptolites such as *Didymograptus murchisoni* and *D. spinulosa* and *Hustedograptus teretiusculus*. Trilobites include *Birmanites birmanicus*, *Cyclopyge*, *Encrinurella*, *Lonchodomas*, *Neseuretus*, *Ovalocephalus*, *Pseudosphaerexochus*, *Hexacopyge* and *Sinocybele* which suggest both deep water and affinities with the (?slightly) younger Ordovician trilobites of Myanmar and Thailand. This formation also contains 50 genera of the relatively deep-water ‘*Saucrorthis*’ brachiopod fauna which is also found, but with lower diversity, in the Shan States of Myanmar, South China and Iran (Zhan *et al.*, 2014b). In contrast, the dominantly peritidal Darriwilian carbonates of Malaysia and Thailand, contain the widespread, shallow-water ‘*Aporthophyla*’ brachiopod fauna (Laurie and Burrett, 1992; Zhan *et al.*,

2014a) (Fig.2). In Baoshan, the Katian Pupiao Formation consists of mudstone with some micritic limestone in its lower part. Graptolites indicate the *P.linearis* Zone and the formation also contains deep-water trilobites *Encrinurella*, *Ovalocephalus* and *Cyclopyge* which are generically similar to those from the Katian of Thailand (Fig.2) as is its *Foliomena* brachiopod fauna. The Upper Katian is probably absent across Baoshan (Zhang *et al.*, 2014). As in Thailand, the Ordovician–Silurian boundary in Baoshan is defined with graptolites of the *Metabolograptus persculptus* and *P. acuminatus* biozones, within the shales of the Jenhochiap Formation. In all four Sibumasu areas, the Llandovery is represented by deep-water graptolitic shales. In Malaysia, graptolitic shales and the trilobite *Cyclopyge* (Kobayashi and Hamada 1970) appear to be eastern deep-water correlates of the Ordovician shallow water carbonates of the west (Lee, 2010). In Malaysia and Thailand most of the Devonian and Carboniferous is represented by siliciclastics.

The Silurian Mempalum Formation and the Famennian Sanai Limestone in Malaysia, the Devonian Kuan Tung Formation in Thailand and the Wenlock to Ludlow Lichaiba and Niushiping formations in Baoshan all contain suggestions of relatively deep-water conditions (e.g the Pa Kae facies and basinal conodonts). However, transported calcareous algae and plants in the Niushiping Formation could suggest shallow-water conditions (Zhang, 2014). In Myanmar and Baoshan shallow marine carbonates are definitely present in the Devonian (Bender, 1983; Aye Ko Aung 2012). The Devonian in Baoshan is represented by shallow water carbonates of the Heyuanzhai Formation which contain an abundant and diverse coral fauna (Wang, 1994) overlain by the limestones of the Yudong Formation (Shi *et al.*, 2005). The Pennsylvanian is missing from Baoshan (Shi *et al.*, 2005) perhaps due to initial doming and uplift by the Pennsylvanian to Cisuralian, mantle plume centred around northern Greater India (see below). The Carboniferous of NW Malaysia and southern Thailand is represented by siliciclastics that grade eastwards into definite deep-water deposits often containing radiolarians (Jasin and Harun, 2011; Sashida *et al.*, 2000; Saesung-seerung and Saiid, 2016). In the west of Sibumasu, the often turbiditic Pa Samed and Khuan Klang Formations in Thailand contain Carboniferous faunas including radiolarians and goniatites along with brachiopods and the thin-shelled bivalve *Posidonomya* (Imsumat, 2012; Jasin, 2015; Wongwanich *et al.*, 2004) suggesting relatively deep-water. The relatively deep-water Carboniferous of Malaysia and Thailand contrasts with the fossiliferous, shallow-water Mississippian carbonates of Baoshan. In Myanmar the Carboniferous Taungnyo Group consists of interbedded marine sandstones, mudstones and minor limestone that yields a Pennsylvanian macrofauna near its top and a Tournaisian conodont fauna and possibly a Viséan macrofauna elsewhere in the section (Metcalf and Kyi Pyar Aung, 2014) but little is known about the group’s age range, lithology or environment of deposition.

The 1 km thick sequences of Lower Permian siliciclastics of Thailand and Malaysia display abundant

evidence of glacial conditions (Stauffer and Lee, 1986; Hills, 1989; Ampaiwan, 2009; Chaodumrong, 2010; Chaodumrong *et al.*, 2007). In Myanmar, these glacial siliciclastics are only found south of the Shan States and are represented by a very thin non-glacial sequence in the Shan States. The Lower Permian in Baoshan is also thin, but contains evidence of glacial conditions (Xiaochi, 2002). By the Middle Permian (Roadian) and possibly in the Kungurian, limestones are established in all four regions. The basal, chert-rich, limestone of the Ratburi Group in Thailand contains Lower Permian conodonts (Burrett *et al.*, in prep), and no evidence of a tropical fauna (Hills, 1989; Chaodumrong *et al.*, 2010). Similarly the low fusulinid diversity of the Wordian to Capitanian limestone of Baoshan suggests a warm water sub-tropical environment rather than the tropical conditions that characterise South China at that time (Huang *et al.*, 2015).

#### 4. Palaeobiogeography

The Furongian trilobite faunas of Sibumasu have affinities with several parts of Asia but most notably with North China (Shergold *et al.*, 1988; Sun and Xiang, 1979). Lower to Middle Ordovician nautiloid faunas have affinities to North China and Australia and include *Tasmanoceras* (Tasmania and Shan-States), *Georgina* (Thailand, Lhasa Terrane and Georgina Basin, Australia), *Madiganella* (southern Thailand and Central Australia) and *Mesaktoceras* (Lhasa and Georgina Basin), *Ordosoceras* (Shan States and N. China Terrane), *Paratunkoceras* (Shan States and North China) and *Kogenoceras nanpiaoense* (Langkawi, Lhasa and North China) (Stait and Burrett, 1982, 1984a, 1987; Stait *et al.*, 1987; Stait and Laurie, 1985; Niko and Sone 2014, 2015; Tongtherm *et al.*, 2014). Because of their lack of planktonic larval stages and the frequent presence of heavy cameral deposits (in contrast to the modern Pearly Nautilus, *Nautilus pompilius*) many of these nautiloids are unlikely to have floated very far *post-mortem* and are therefore excellent indicators of terrane palaeoproximity (Burrett and Stait, 1985, 1987). The brachiopod genus *Spanodonta* is common in the Kaki Bukit Limestone of Malaysia and rarely in mainland Satun Province and is also found elsewhere only in Western Australia (Laurie and Burrett, 1992). The Sibumasu-North China- Australia link is also shown by the conodonts (Agematsu and Sashida, 2009), the chiton (polyplacophoran) *Chelodes whitehousei* (Stait and Burrett, 1984b) and the stromatoporoids *Labechia variabilis* and *Rosenella woyuensis* (Webby *et al.*, 1985). The slightly deeper-water subtidal *Saucrorthis* brachiopod fauna replaces the coeval, Darriwillian peritidal *Aporthophyla* brachiopod fauna in the Shan States and in Baoshan (Zhan *et al.*, 2014). A major tectonic and/or environmental change in the Darriwillian, led to a major switch to South China affinities for the majority of the macrofossils and conodonts throughout the Sibumasu Terrane and, by the Katian, the trilobite and conodont faunas have very strong South China affinities and depositional depths change from a few metres to hundreds of metres.

Silurian and Devonian faunas from Sibumasu have

mainly peri-Gondwana distributions as illustrated by Silurian nautiloids from Langkawi and Baoshan (Niko *et al.*, 2017), by Llandovery graptolites from the Shan States (Bohemia and Saudi Arabia, S China and Northern Europe) (Loydell and Kyi Pyar Aung, 2017) and by the Early Devonian reduced-eyed trilobite *Plagiolaria* (Sibumasu, N Vietnam, Uzbekistan and Czech Republic (Cronier and Fortey, 2006; Cronier and Tsmeyrek, 2010). Aye Ko Aung and Min (2011) note that some Lower Devonian corals from the Zebingyi Formation of the Shan States show close relationships with those from peri-Gondwana southern France and that their Emsian *Dohmophyllum graveyardense* is a common species in north Queensland, Australia. The Devonian and Carboniferous corals of Baoshan have widespread affinities to parts of Laurasia but the Mississippian brachiopod species *Stegacanthia strigis*, *Podtshermia* aff. *thomasi* and *Rugosochonetes obtectus* are also found in the Bonaparte Basin of NW Australia and *Unispirifer striatoconvolutus* is found in eastern Australia (Shi *et al.*, 2004; Wang *et al.*, 2001). The Mississippian thin-shelled bivalve *Posidonomya*, found in NW Malaysia and southern Thailand has a peri-Tethyan distribution from South China to SE Laurasia (Jasin, 2015). The trilobite *Langgonbole* from the Mississippian of Satun and NW Malaysia and the brachiopod *Aseptella* from the Pennsylvanian of Satun are found elsewhere in peri-Gondwanan Spain and, the latter, also in Argentina (Gandl, 1983; Imsamat, 2012; Martinez-Chacon and Winkler-Prins, 1999; Wongwanich *et al.*, 2004).

Cisuralian faunas of Sibumasu show strong relationships to cool-water faunas in Australia and other Gondwana terranes but these Australian affinities weaken through the Permian as Sibumasu drifted away from Australia into progressively warmer seas (Shi and Archbold, 1995; Wang *et al.*, 2001, 2002; Zhang *et al.*, 2013).

#### 5. Tectonic summary

The deposition of considerable thicknesses of siliciclastic material, including coarse conglomerates, in the Furongian and Tremadoc suggests that Sibumasu was part of an eroding continent. Spectra of detrital zircon ages from the Furongian Tarutao Group sandstones and its heavy mineral bands show close similarities with the Ordovician Tumblagooda Sandstone of western Australia (Burrett *et al.*, 2014; Cawood and Nemchin 2000). Shallow-water Floian-Dapingian conodonts (Agematsu and Sashida 2009) and nautiloids, which were unlikely to have floated far *post-mortem* (Burrett and Stait, 1985; Burrett *et al.*, 1990; Niko and Sone, 2014, 2015) suggest that this continent was Australia. Extensive Cisuralian glacial deposits with Gondwanan fauna show that Sibumasu was still attached to Gondwana at this time. Detrital zircons from a clast within the Kaeng Krachan Group of Phuket Island form a peak at 1860 Ma which suggests northern Australia as a source; though, of course, clasts in pack-ice may be transported considerable distance from their source (Burrett *et al.*, 2014 p. 36).

Palaeomagnetic data from Sibumasu are sparse and only data from Baoshan are reasonably reliable. Both

Devonian (Fang *et al.*, 1989) and Permian data (Ali *et al.*, 2013; Xu *et al.*, 2015) suggest that Sibumasu was part of Australia until the Sakmarian or Artinskian and oriented with Baoshan near the Himalayan margin and Sumatra closer to Irian Jaya. This orientation of Sibumasu is supported by the palaeocurrent data from the Furongian of Thailand, by the coarsening of siliciclastics westwards in Baoshan and by the deepening of Ordovician to Triassic sequences eastwards in southern Thailand and NW Malaysia (DMR 2014; Lee, 2009; Ridd, 2009, a, b; Sashida *et al.*, 1995, 2000). However, all palaeomagnetic data have a few degrees of error (at least 6° for the Devonian limestone pole of Fang *et al.*, 1989 and 8° for the Permian basalt pole of Xu *et al.*, 2015) which could place Baoshan closer to or further from the Himalayas. 1° of latitude is about 111 km which means that the Baoshan error may amount to 900 km. Many, if not most, palaeomagnetic results derived from sedimentary rocks may suffer from inclination shallowing mainly due to sedimentary compaction (Li and Kodama, 2016) and this limitation should be borne in mind for the Devonian data from Baoshan, i.e. Baoshan may have been at a higher palaeolatitude than indicated by its palaeomagnetic inclination. The Cisuralian data are from the 400 m Woniusi Basalts and therefore their inclination (and hence palaeolatitude) is probably more reliable. However, volcanics are not immune from inclination shallowing as Pavon-Carrasco *et al.*, (2016) have shown 3° of shallowing within 400 years in historical volcanics.

The Woniusi Basalts of Baoshan are almost certainly part of a large plume dated at 301 to 285 Ma, centred in northern Greater India and including the Abor and Panjal Traps of India (Liao *et al.*, 2015). These rift basalts and mantle plume probably triggered the rifting of Sibumasu and Qiantang terranes from the Australian sector of Gondwana along with the deposition of thick rift-related sediments (Liao *et al.*, 2015; Ridd, 2007, 2009 a,b, 2016).

In southern Thailand, the Triassic limestones of the Chaiburi Formation continue to the Late Triassic (see Fig. 2 in Burrett *et al.*, 2014; DMR 2014). There is no notable stratigraphic gap in the Palaeozoic to Triassic of Sibumasu or in the Sukhothai Terrane which suggests that the timing of collision between Sibumasu and the Sukhothai Arc Terrane was a Late Triassic probably late Norian event (Chaodumrong and Burrett 1997 a, b). This is confirmed by the deformation of Carboniferous to middle Triassic radiolarian cherts in southern Thailand (Kamata *et al.*, 2013) and by detailed studies in northern Thailand (Hirsch *et al.*, 2006).

## 6. Conclusions

Although there are some notable differences in faunas and facies along the 3000 km length of the Sibumasu Terrane there are many obvious correlations that suggest that it constituted one terrane. Late Cambrian faunas and sandstones and Late Cambrian felsic magmatism is found from Malaysia to Baoshan (Fig.3). Ordovician faunas are similar along the terrane with differences being probably

due to bathymetry with, for example, the shallow water, mainly peritidal, Darriwilian molluscan-*Aporthophyla* community in Malaysia and Thailand differing from the coeval subtidal *Saucrorthis*-trilobite community in Myanmar and Baoshan. Llandovery graptolitic shales, Silurian crinoid loboliths, Lower Devonian *Nowakia acuaria* shales with *Plectodonta forteyi* and sometimes *Plagiolaria* show continuity across the terrane. However, coralline limestones in Myanmar and thick coralline reefal limestone sections in Baoshan are notably different to the thin, deeper water Devonian limestones of southern Thailand and NW Malaysia. Devonian to Mississippian coral-rich carbonates in Baoshan contrast with the deeper water siliciclastics of NW Malaysia and S Thailand. Cisuralian glaci-marine sediments with a Gondwana marine fauna, although absent from the Shan States, are present in the Malaysian, Thai, southern Myanmar and Baoshan parts of Sibumasu.

The Woniusi Basalts in Baoshan were part of a large mantle plume that triggered the rifting of Sibumasu in the Cisuralian and initiated its drifting into the progressively warmer Palaeotethyan seas prior to collision with the Sukhothai Volcanic Arc and the Indochina Terrane in the Late Triassic.

Although some authors have regarded Sibumasu as a vagrant terrane, and unattached to a parent continent in the Early Palaeozoic (e.g. Cocks and Torsvik, 2002) or have the terrane moving along the margin of Gondwana (e.g. Agematsu *et al.*, 2008, fig. 7) it is clear from provenance, palaeomagnetic and palaeobiogeographic studies that it formed a fixed part of the northern Australian crust prior to Cisuralian rifting and was oriented with Baoshan close to the eastern Himalayan margin of Gondwana and with Sumatra close to Irian Jaya.

From almost continuous platform sequences in western Sibumasu and from deep-water shales and cherts in eastern Sibumasu, without any significant unconformities, it is clear that Sibumasu was not involved in any terrane collision between the Late Cambrian and its collision in the Norian with the Sukhothai Terrane.

Although the Shan-Thai and Indochina terranes have been subdivided and renamed, work in the last 35 years has confirmed the model of Sangad Bunopas (1982) who first proposed Early Permian rifting from Australia and Late Triassic collision of the Shan-Thai Terrane with Indochina.

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