Stratigraphy and palaeoenvironmental evolution of the mid- to upper Palaeozoic succession in Northwest Peninsular Malaysia

Meor H. Amir Hassan a,⇑, Aye-Ko Aung a, R.T. Becker b, Noor Atirah Abdul Rahman a, Tham Fatt Ng a, Azman A. Ghani a, Mustaffa Kamal Shuib a

a Geology Department, University of Malaya, 50603 Kuala Lumpur, Malaysia
b Institut für Geologie und Paläontologie, Corrensstraße 24, D-48149 Münster, Germany

Article info
Article history:
Received 3 October 2013
Received in revised form 7 January 2014
Accepted 15 January 2014
Available online 24 January 2014

Keywords:
Silurian
Devonian
Carboniferous
Ammonoids
Mid-Palaeozoic Unconformity

Abstract
The stratigraphy of the Devonian to Permian succession in Northwest Peninsular Malaysia is revised. The Timah Tasoh Formation consists of black mudstone containing graptolites and tentaculitids indicating a Pragian or earliest Emsian age. The Sanai Limestone overlies the Timah Tasoh Formation at Sanai Hill B and contains conodonts indicating a Late Devonian (Frasnian to possibly early Famennian) age. In other places, Late Tournaisian chert of the Telaga Jatoh Formation overlies the Timah Tasoh Formation. The overlying Kubang Pasu Formation is predominantly composed of mudstone and sandstone, and can be divided into 3 subunits, from oldest to youngest: (1) Chepor Member; (2) Undifferentiated Kubang Pasu Formation; (3) Uppermost Kubang Pasu Formation. The ammonoid Praedaraelites tuntungensis sp. nov. is reported and described from the Chepor Member of Bukit Tuntung, Pauh. The genus indicates a Late Viséan age for part of the subunit. Dropstones and diamictites from the Chepor Member indicate a glacial marine depositional environment. The Carbo-Permian, undifferentiated Kubang Pasu Formation consists of similar interbedded mudstone and sandstone. The uppermost Kubang Pasu Formation of Kungurian age consists of coarsening upward cycles of clastics, representing a shallow marine, wave- and storm-influenced shoreline. The Permian Chuping Limestone also represents shallow marine, wave- and storm-influenced deposits. A Mid-Palaeozoic Unconformity separating Early–Late Devonian rocks from overlying Late Devonian–Carboniferous deposits probably marks initiation of rifting on Sibumasu, which eventually led to the separation of Sibumasu from Australian Gondwana during the late Sakmarian (Early Permian).

1. Introduction
Northwest Peninsular Malaysia preserves a largely complete Palaeozoic succession, ranging from the Cambrian up to the Permian (Jones, 1981; Cocks et al., 2005; Meor and Lee, 2005; Lee, 2009) (Fig. 1). This paper focuses on the Devonian to Permian part of the succession. The best exposure is at a small hilly ridge (referred to as the Sanai Hills) in Kampung Guar Jentik, Perlis, which comprises Silurian, Devonian and Carboniferous rocks (Meor and Lee, 2002, 2005) (Fig. 2). Continuous quarrying of the hill, and also further south at Hutun Aji, has resulted in a progressive increase in data and understanding of the stratigraphy. A new exposure further east in Pauh, has also been recently reported, which preserves another Devonian–Carboniferous succession, in this case, represented by Mahang Formation slate being overlain by Mississippian, radiolarian-bearing chert and siliciclastics of the Chepor Member, Kubang Pasu Formation (Basir et al., 2010). This paper aims to: (1) highlight the numerous stratigraphic, sedimentological and palaeontological discoveries made in the last four years since the last review (Lee, 2009); (2) provide a revised stratigraphy of the Devonian–Carboniferous succession in Northwest Peninsular Malaysia, and; (3) synthesise a depositional history of the mid- to upper Palaeozoic, Northwest Peninsular Malaysia succession, which represents part of the Gondwana-derived terrane of Sibumasu (Metcalfe, 2011a, 2013a,b).

2. Development of the stratigraphic nomenclature
The early history of the stratigraphic nomenclature of the Palaeozoic succession of Northwest Peninsular Malaysia has been thoroughly documented in Meor and Lee (2005) and Lee (2009), and is therefore discussed only briefly here. Jones (1966, 1981) divided the Palaeozoic rocks of Langkawi, Perlis and Kedah into several lithostratigraphic units, from oldest to youngest: (1) the Cambrian Machinchang Formation; (2) the Ordovician to Early Devonian...
Setul Formation; (3) the Late Devonian–Permian Singa Formation, exposed on Langkawi and its lateral equivalent on the mainland, i.e. the Kubang Pasu Formation, and (3) the Permian Chuping Limestone.

An unconformity was proposed between the Setul and Singa/Kubang Pasu formations, based on angular strike relations and the interpretation of the basal red pebbly beds of the Singa/Kubang Pasu formations as evidence of uplift (Jones, 1981). However, this was not universally accepted, especially since there was no observable unconformity exposed anywhere (Ahmad bin Jantan, 1973; Yancey, 1975).

A second wave of studies prompted further revision to the stratigraphy (Meor and Lee, 2002, 2005; Cocks et al., 2005). This was mainly triggered by the then new exposure of the Sanai Hills in Kampung Guar Jentik, Perlis and also by more detailed work on the older outcrops on Pulau Langgun, Langkawi. Finer scale stratigraphic relationships were identified. The Setul Formation was further divided, with its previous members upgraded to formation rank. The Setul Formation was divided into: (1) Kaki Bukit Limestone (Ordovician); (2) Tanjong Dendang Formation (Ordovician–Silurian); (3) Mempelam Limestone (Silurian), and; (4) Timah Tasoh Formation (Early Devonian). Meor and Lee (2005) attempted a division of the lower Kubang Pasu Formation into smaller formations based on biostratigraphy: the Late Devonian Chepor and Mississippian Binjal and Wang Kelian formations in Perlis and the Langgun Red Beds in Langkawi. A Late Devonian limestone was also recognised in Perlis, based on conodonts (the Sanai Limestone of Meor and Lee, 2003, 2005), overlying the Chepor Formation at Sanai Hill B. Tournaisian chert beds (Basir, 1995; Basir and Zaiton, 2001), were given the name Telaga Jatoh Formation (Meor and Lee, 2005). Red mudstone beds of supposed Viséan age were named the Wang Kelian Formation, which was then overlain by diamictites and pebbly mudstone of the Kubang Pasu and Singa formations.

Continued excavation of the northern face of Sanai Hill B in Perlis led to further confusion regarding the stratigraphy. Ong and Basir (2007) refuted the presence of a Late Devonian Sanai Limestone and interpreted the Sanai Limestone as the top part of the Silurian Mempelam Limestone. This is based on the stratigraphic position of their observed limestone underlying dacryconarid and monograptid-bearing mudstone of the Timah Tasoh Formation.

It was further recognised that many of the stratigraphic units in the Sanai Hills were separated by thrust faults, and there were numerous repeated sections (Lee, 2009). The thrust faults are part of a fold-and-thrust belt that has been interpreted as the product of Late Triassic collision between Sibumasu and East Malaya/Indochina blocks (Barber and Crow, 2009; Ridd, 2013). Lee (2009) provided another revised stratigraphy. The suggested absence of a Late Devonian Sanai Limestone led Lee (2009) to combine the separated Chepor, Binjal and Wang Kelian formations into a single unit: the Chepor Formation (Fig. 3). Lee (2009) also introduced the term Setul Group, which encompasses the Ordovician Kaki Bukit Limestone, the Ordovician–Silurian Tanjong Dendang Formation and the Silurian Mempelam Limestone (Fig. 1).

In an attempt to resolve the confusion, Meor et al. (2013a) further modified the stratigraphic nomenclature. The Silurian and Early Devonian nomenclature remained unchanged. The Sanai Limestone was discarded. However, the Chepor Formation was reabsorbed into the Kubang Pasu Formation, based on the presence of pebbly sandstone in the Chepor Formation, which may be related to the glacial-marine dropstones of the Singa and Kubang Pasu formations (Stauffer and Lee, 1986).

The problem of the Devonian–Carboniferous succession of Northwest Peninsular Malaysia is still far from being resolved, with new data still coming out from rocks of Sanai Hill B, and also from new exposures further east (e.g. Basir et al., 2010). This paper provides an updated understanding of the stratigraphic succession (Fig. 3).

3. Study location and methods

This paper mainly focuses on the section exposed at Sanai Hill B, Kampung Guar Jentik, Perlis, which is part of an excavated hilly ridge trending north–south along the R121 road linking Kangar and Kaki Bukit, just south of the Timah-Tasoh Dam (Fig. 2A). Also, additional new information is provided from exposures in Hutan Aj, 5 km south of Kangar (Fig. 2C), and a new outcrop at Bukit Tuntung, Pauh, about 15 km east of Kangar (Basir et al., 2010). Detailed geological mapping was conducted on the northern face of Sanai Hill B. Fossils were collected from the localities to help in determining age and stratigraphic position. Selected well exposed sections were logged and studied in detail, using a facies analysis...
approach, describing lithology, grain size, sedimentary structure and bioturbation, in order to interpret the depositional environment.

4. The stratigraphy

Five main stratigraphic units are recognised in the mid- to upper Palaeozoic succession of Perlis: (1) Timah Tasoh Formation; (2) Sanai Limestone; (3) Telaga Jatoh Formation; (4) Kubang Pasu Formation, and; (5) Chuping Limestone (Meor et al., 2013a) (Fig. 3).

4.1. Timah Tasoh Formation

The Timah Tasoh Formation was defined by Cocks et al. (2005). This was previously known as the lower part of the Upper Detrital Member of Jones (1981). The Timah Tasoh Formation conformably overlies pelagic limestone of the Silurian Mempelam Limestone (Cocks et al., 2005; Meor and Lee, 2005; Lee, 2009) and ranges between 5 to 40 m in thickness (Figs. 2 and 4). It comprises dark to black mudstone, with occasional cherts. The Timah Tasoh Formation exposed at Sanai Hill A, B and C, Hutan Aji and Pulau Langgun, Langkawi, contains abundant dacryoconarid tentaculitids, including *Styliolina* sp., *Metastyliolina?* sp. cf. *M. lardeuxi*, *Nowakia (Turkestanella) acuaria acuaria*, *Nowakia (T.) acuaria posterior*, and *Nowakia (Alaina) matlockiensis* (Meor et al., 2013a). The graptolite *Monograptus langgunensis* is also found associated with the tentaculitids. Straight monograptids from the Timah Tasoh Formation were formerly identified as *Monograptus* sp. cf. *uniformis*, but may actually be *Monograptus telleri* (Meor et al., 2013a). Other taxa include the brachiopod *Plectodonta (P.) forteyi* and the trilobite *Plagiolaria* (Meor and Lee, 2005). The tentaculitids and graptolites indicate a late Pragian or earliest Emsian age for the

![Fig. 2. Maps of the study area. (A) Map of the Sanai Hill B area, Kampung Guar Jentik. (B) Map of the Sanai Hill C area, Kampung Guar Jentik. (C) Map of the Bumita Quarry, Hutan Aji area. Refer to Fig. 1 for map locations.](image-url)
The fine grained lithology, absence of current or wave generated facies, abundance of pelagic dacryocoanarids and the black colour indicate an anoxic–dysoxic, marine outer shelf environment. Abundant pelagic tentaculitids place the unit in Benthic Assemblage 4–5 of Boucot (1975), indicating water depths of between 150 and 200 m (Brett et al., 1993). The Timah Tasoh Formation is in fault contact with the overlying Sanai Limestone at Sanai Hill B, although in some localised parts of the Hill B exposure, the contact appears to be stratigraphic, with a sharp lithological change from black mudstone to limestone. The Timah Tasoh Formation is directly overlain by the Telaga Jatoh Formation in all other sections.

4.2. Sanai Limestone

The term Sanai Limestone (Meor and Lee, 2003) is resurrected, to refer to the limestone unit overlying the Timah Tasoh Formation and underlying the Telaga Jatoh Formation at Sanai Hill B (Figs. 2A and 3). Ong and Basir (2007) refuted the presence of a separate Devonian limestone, and considered it to be part of the Silurian Mempelam Limestone, based on their observation that the limestone is overlain by the Timah Tasoh Formation. The Timah Tasoh Formation is directly overlain by the Telaga Jatoh Formation in all other sections.

More recent sampling and description of the Sanai Limestone conodonts resulted in additional records, which prove a longer time interval (Aye Ko et al., 2013). A number of spot samples taken from the southern part of Hill B yielded approximately 2000 conodonts. Identified genera include: Ancryodella gigas Younquist, 1947; Ancryodella nodosa Ulrich and Bassler, 1926; Ancryodella asymmetrical Ulrich and Bassler, 1926; Palmatolepis hassi Palmatolepis jamiae Ziegler and Sandberg, 1990; Palmatolepis rhenana Bischoff,

Fig. 3. Summary of the stratigraphy of Perlis in Northwest Peninsular Malaysia. The stratigraphic nomenclature and ages of the units have been revised based on improved stratigraphic correlation and dating. The two columns on the left are previous schemes used for the region. Thicknesses of the stratigraphic units are not to scale.
Palmatolepis linguiformis Müller, 1956; Polygnathus decorosus Stauffer, 1938; Polygnathus webbi Stauffer, 1938; Icriodus alternatus Branson and Mehl, 1938; Ozarkodina sp. and Belodella sp. The new conodont assemblage recovered from the Sanai Limestone exposed on the northern side of Hill B represents the latest linguiformis Zone, of Frasnian age (Aye Ko et al., 2013). This, combined with the

Fig. 4. Sedimentary logs of the study areas. (A) Composite section from northern part of Sanai Hill B, Kampung Guar Jentik. (B) Section from Kampung Hutan Aji. Location of sections shown in Fig. 2.
previous conodonts collected at the topmost Sanai Limestone bed on the southern side of Hill B (Meor and Lee, 2003) indicate a Late Devonian (latest Frasnian to early Famennian) age range for the unit.

The fine grained and bedded Sanai Limestone, containing abundant pelagic tentaculitids and cephalopods, is interpreted as pelagic deposits associated with a carbonate platform to ramp depositional environment, below the normal storm wave base.

4.3. Telaga Jatoh Formation

The term Telaga Jatoh Formation was used by Meor and Lee (2005) to refer to the thin, yet widely distributed, Mississippian chert beds of Northwest Peninsular Malaysia. Basir et al. (2010) consider the Telaga Jatoh Formation as the base of the Kubang Pasu Formation, due to it being too thin and limited in extent to be called a formation. However, given that the unit is lithologically distinct and mappable, its designation as a formation is retained here.

The Telaga Jatoh Formation is an important marker bed separating underlying Devonian beds from the overlying Kubang Pasu Formation, and is present in many of the mainland exposures.

The Telaga Jatoh Formation is exposed at Sanai Hill B and C, Kampung Guar Jentik, Bukit Tuntung in Pauh (Basir et al., 2010) and in several localities further south in Kedah (Basir, 1995; Basir et al., 2003; Basir and Zaiton, 2001).

In Perlis, The Telaga Jatoh Formation overlies Devonian rocks of the Timah Tasoh Formation. Locally, at Sanai Hill B, it stratigraphically overlies the Late Devonian Sanai Limestone (Fig. 4A). The Telaga Jatoh Formation is then overlain by the Chepor Member of the Kubang Pasu Formation. The unit tends to form discontinuous lenses below the Kubang Pasu Formation at Sanai Hill C and Bukit Tuntung, suggesting a fault contact at these localities (Basir et al., 2010; Meor et al., 2013b).

The Telaga Jatoh Formation is thin, ranging between 3–11 m in thickness. It comprises rhythmically alternating, cm-thick beds of grey to black coloured chert and black mudstone. The carbon content ranges between 1–2.5% (Basir et al., 2003). The beds are commonly moderately to strongly folded, with the folding only restricted to the unit (intraformational folding). The intraformational folds have been interpreted as slump folds, although it is also possible that they were formed due to tectonic compression, resulting in more intense deformation in the less competent rocks of the unit. Radiolarians extracted from the chert indicate a Mississippian age (Basir, 1995; Basir and Zaiton, 2001, 2011a; Basir et al., 2003, 2010). The regionally recognised Albailella deflandrei and A. indensis Zones correlate in Europe with the Late Tournaisian (Tn3) to lower Viséan (e.g., Braun and Gursky, 1991; Won and Seo, 2010). The Telaga Jatoh Formation is interpreted as continental margin cherts (Basir and Zaiton, 2011b). The depositional environment of the Telaga Jatoh Formation ranges from outer shelf to deep marine continental rise (Basir and Zaiton, 2011b). Generally, it appears that the outer shelf cherts are restricted to west Perlis, while the deeper cherts are restricted to east Perlis and further south in Kedah.

4.4. Kubang Pasu Formation

The Kubang Pasu Formation comprises mainly quartz and feldspathic sandstone interbedded with metres to tens of metres thick
mudstone of various colours, including red, white, grey, brown and black. The thickness of the unit has been estimated to be about 1372 m (Jones, 1981). However, given the faulted and folded nature of the succession, this is most probably an overestimation. The basal unit of the Kubang Pasu Formation is represented by a thick unit of grey–red mudstone interbedded with sandstone. This unit, referred to previously as the Chepor Formation (sensu Lee, 2009), was reinstated as a member of the Kubang Pasu Formation (Meor et al., 2013a,b), as it cannot be differentiated from overlying rocks of the Kubang Pasu Formation without help from fossils. The Kubang Pasu Formation in Perlis is divided into three general stratigraphic divisions, from oldest to youngest: (1) Chepor Member; (2) Undifferentiated upper Kubang Pasu Formation; (3) Uppermost Kubang Pasu Formation.

4.5. Chepor Member

The Chepor Member, as defined in Meor et al. (2013a), comprises thick, grey to red fossiliferous mudstone with interbedded quartzitic and occasional feldspathic sandstone. The Chepor Member is very fossiliferous, with abundant but small brachiopods (Hamada, 1968, 1969; Meor and Lee, 2002, 2004) in close association with cyrtosymbolid trilobites (Kobayashi and Hamada, 1973), gastropods, tabulate corals (Michelinia, Meor and Lee, 2005), and the bivalve Posidonia (Sarkar, 1972; Jones, 1981).

4.5.1. Palaeontology and age

Previous studies suggest a Late Devonian–Carboniferous (Mississippian) age for the Chepor Member, based on long ranging
cyrtosbold trilobite and brachiopod taxa (Kobayashi and Hamada, 1973; Meor and Lee, 2004). The stratigraphic position of the Chepor Member directly overlying late Tournaisian cherts (as observed at Sanai Hill B, Sanai Hill C and Bukit Tuntung, Pauh) indicates a latest Tournaisian or younger age for the unit. The trilobite assemblage is composed of Waribole perlisensis, Langgonbole vulgaris, Macrobole kedahensis and Diacoryphe? sp. and associated with Posidonia sp. aff. P. becheri. Macrobole kedahensis is now placed in Chlupacula (Chlupacula), which has a proven range from the Lower Tournaisian to the Lower/Middle Viséan (Hahn et al., 2012). A second species of Langgonbole was discovered by Gandl (1983) in the Namurian B (now Serpukhovian) of northern Spain. Examination of a new specimen of Diacoryphe? sp. collected from Sanai Hill C, Kampung Guar Jentik, indicates that the taxa is better placed in the genus Weyeraspis (Rudy Lerosey-Aubril, in Meor et al., 2013a), based on the fan-shaped, yet narrow preglabellar field and conical yet blunt glabella (Hahn et al., 1995). Weyeraspis is currently known as a Lower Tournaisian taxon. The trilobite fauna is consistent with a Mississippian age (Hahn et al., 1995). Its endemic composition prevents a reliable specific assignment but the Langgonbole and similarities of the Chlupacula with an Upper Tournaisian species of southern Morocco (Hahn et al., 2012) point towards a Late Tournaisian to Late Viséan age.

Goniatiid ammonoids have been reported previously from the mudstone of the Chepor Member, but never described in detail. Several well preserved specimens from the new exposure at Bukit Tuntung, Pauh, display sutures. They occur above cherts with radiolarians indicative of the Late Tournaisian/Early Viséan Albailella indensis Zone (Basir et al., 2010; Basir and Zaiton, 2011a,b). The ammonoids are described in detail here by one of the authors (R.T. Becker) (Figs. 5 and 6). Two taxa are identified: (1) ?Goniatiites sp.; (2) Praedaraelites tuntungensis n. sp. The first displays low median saddles, strongly sharpened and high ventral saddles and somewhat trifid adventitious lobe, characteristic of advanced species of the genus, above the base, but within the lower half of the Late Viséan (Fig. 5). The genus Praedaraelites ranges from the Late Viséan to the Serpukhovian. The combination of only two outer umbilical lobes with the serration of three flank lobes places it at a median morphological level within the group, in which the number of U-lobes and the serration level increased with time (Fig. 6). The morphologically simpler type-species of the genus, Praed. culmiensis, characterises a level well above the base of the Late Viséan and above advanced species of Goniatiid (Korn, 1988; Korn and Horn, 1997). But Praed. loeblichi of North America and praedaraelitids with similarly complex sutures of Xinjiang co-occur with Goniatiid (Liang and Wang, 1991; Korn and Titus, 2011). In summary, the age of the Chepor Member is concluded as Carboniferous (Mississippian), Viséan, and certainly including the Late Viséan.

### 4.5.2. Sedimentology

Early sedimentological studies of the Chepor Member were hampered by poor exposure, complex deformation of the rocks and uncertainties in stratigraphic position (e.g. Meor and Lee, 2004). Three recently exposed sections at Sanai Hill B and Hutan Aji, and also some smaller exposures, were used to conduct a
detailed facies analysis (Fig. 4). The three main sections freshly expose unweathered mudstone, which display previously undocumented sedimentary structures that are usually destroyed very rapidly. The rocks of the Chepor Member can be divided into four facies: (1) Mudstone Facies; (2) Graded Sandstone Facies; (3) Clean Sandstone Facies, and; (4) Diamictite Facies.

**Mudstone Facies (Fig. 7A–E):** This was previously designated as massive mudstone facies in Meor and Lee (2004). The mudstone is commonly grey, whitish or red in colour (Fig. 7A). The mudstone generally does not display any features, except for dispersed fossils and fossil fragments and occasional mm- to cm-thick layers of broken fossil fragments. However, fresh exposures display intervals of mm-thick siltstone lamination with normal grading (Fig. 7B). The lamination can be very dense, forming a laminated mudstone. Other fresh exposures display sparse lenticular bedding (sensu Reineck and Wunderlich, 1968), with mm- to cm-thick, cross-laminated sandstone/siltstone ripple lenses in the mudstone. These commonly display load casts.

Thin (less than 10 cm thick), fine grained sandstone beds occur sporadically. These commonly display ripple profiles and cross-laminations, parallel lamination and micro-hummocky cross-stratification. Pebbles are also commonly associated with the mudstone and thin sandstone beds (Fig. 7C). These reach up to 4 cm in diameter, and are commonly composed of quartzite. Some of the pebbles are oriented subvertically, with their long axis perpendicular to bedding. Laminae below the pebbles are downwarped and/or penetrated by the pebble. Laminae above the pebble either onlap or curve above the pebble.

An approximately 30 cm thick interval in the Mudstone Facies of Log 2, Hutan Aji, is composed of a poorly sorted sandy mudstone displaying chaotic deformation (Fig. 7D). The unit displays convoluted bedding and small-scale folding of beds, with large (up to 15 cm long) angular mud clasts floating in the sandy mudstone. Overlying and underlying, cm-thick sandstone beds are also deformed and display load casts.

The mudstone is strongly bioturbated (Ichnofabric Index, abbreviated II, of Droser and Bottjer, 1986 of 5, with II of 1 representing no bioturbation, while 5 meaning strongly bioturbated) by a Chondrites trace fossil assemblage (Fig. 7E). Thin bioturbated intervals composed of possible Planolites are also present. The facies is...
commonly highly fossiliferous, containing a diverse assemblage of small shelly fauna.

**Graded sandstone facies** (Fig. 7F): This includes elements of Facies B in **Meor and Lee** (2004). The beds are several cm–30 cm thick and interbedded between thick mudstone. The facies comprises poorly sorted, fine grained sandstone/silty sandstone, with a sharp erosive base (Fig. 7F). Mud clasts commonly overlie the erosive base. The beds display normal grading. Thicker beds grade upward from fine grained, parallel laminated sandstone, into a thin rippled sandstone interval followed by siltstone/mudstone with rhythmic sandstone lamination, and finally capped by mudstone. The facies is also characterised by the common presence of isolated, rounded to subrounded pebbles floating in the mudstone and sandstone. The pebbles disrupt laminae and beds, forming penetration bottom contacts and onlapping sandstone laminae at top contacts (Thomas and Connell, 1985). Thinner beds also display normal grading from poorly sorted sandstone with mud clasts, directly into mudstone.

**Clean sandstone facies** (Fig. 8): This facies is composed of dm- to m-thick, fine to medium grained, quartzitic sandstone beds. The beds are commonly sharp based and tabular (at least at the outcrop scale, which can be tens of metres wide) with a straight or irregular base, although some beds have a concave-upward base. The beds are commonly interbedded between thick mudstone facies, but can also form stacked successions, with sandstone beds separated only by cm- to dm-thick mudstone. Two main variants of this facies occur in the Chepor Member. The first variant displays parallel lamination associated with symmetrical ripples (Fig. 8A). Some beds display undulating laminae, while some examples resemble hummocky or micro-hummocky cross-stratification (Harms et al., 1975). The second variant of this facies displays a different set of sedimentary structures: cross-bedding and/or thinner, asymmetrical ripple cross-lamination, sometimes also associated with parallel lamination (Fig. 8B and C). Mud drapes line some of the thicker ripple foresets, while mud rip-up clasts sometimes line cross-bed foresets (Fig. 8B and C). Mud rip-up clasts are also present at the base of sandstone beds. The second variant can either display a tabular or scour shaped (concave upward base) geometry.

Both facies variants commonly occur together (Fig. 8D). Again, isolated pebbles are commonly observed floating in the facies (Fig. 9A and B). The pebbles are up to 4 cm in length, subrounded to angular and are composed of quartzite. The pebbles commonly disrupt underlying laminae. However, the pebbles have their long axis oriented parallel to bedding. Soft sediment deformation is also common, with the base of some examples of this facies displaying large scale load casts and ball and pillow structures.

**Diamictite facies** (Fig. 9C and D): Dm- to m-thick beds of dark coloured, poorly sorted sandstone are also present in the Chepor Member. These are more common in the upper part of the Chepor Member succession at Sanai Hill B. The facies comprises angular-subrounded pebbles floating in a muddy sandstone matrix (Fig. 9C and D). Petrographically the rock is a quartzwacke, with grains of feldspar making up less than 5% of the rock. The pebbles are mainly quartzite. The pebble size ranges between 3–15 cm and their long axis is oriented parallel to bedding. The diamictite beds are structureless.

**Interpretation**: The fossiliferous mudstone facies is interpreted as mainly suspension fall out deposits in a low energy environment, although the presence of normal graded siltstone intervals represents either gravity flow, distal storm-generated deposits, or a combination of both, i.e. wave-enhanced sediment-gravity flows (Aigner, 1982; Davis et al., 1989; Walker and Plint, 1992; Macquaker et al., 2010). The presence of lenticular bedded intervals is also consistent with occasional current transport and deposition (Swift and Rice, 1984). The abundant shelly fauna, ammonoids, cystosymbid trilobites, and posidonid bivalves are typical for the deeper shelf “Culm Facies” of Europe, where tabulate corals may occur as a minor faunal element. The *Chondrites* dominated trace fossil assemblage is also characteristic of a distal offshore, shelf setting, below fair-weather wave base, but above storm–weather wave base. A possible modern-day analogue is the deeper inner shelf mud of modern day New Zealand (Abbott, 2000), which displays similar facies characteristics such as abundant shelly fauna, structureless, bioturbated mud and intervals of lenticular bedding.

The graded sandstone facies is interpreted as representing gravity-driven turbidites, based on the sharp erosive base, normal grading and incomplete Bouma sequences. The clean sandstone facies represent high energy shallow marine deposits. The first variant displays sedimentary structures characteristic of wave and storm processes (symmetrical ripples, parallel lamination,
The second variant displays current generated sedimentary structures (asymmetrical ripples). The presence of occasional mud drapes and mud clasts in cross-bed foresets suggest significant tidal influence. The facies probably represent storm and tide-generated bars, dunes, shoals or ridges covering extensive areas of a marine shelf (sensu Stride et al., 1982; Desjardins et al., 2012).

Isolated pebbles disrupting bedding and internal lamination in the mudstone and graded sandstone facies are interpreted as dropstones deposited as ice-rafted debris, based on their subvertical position penetrating or downwarping underlying laminae, and the onlapping or curving contact of overlying laminae (Thomas and Connell, 1985).

Pebbles floating in the clean sandstone facies are interpreted as possible wave/current reworked dropstones, as they are oriented sub-parallel to bedding.

The diamictic facies is interpreted as gravity-driven debris flow deposits where matrix strength is the dominant clast-support mechanism. This is based on the absence of internal sedimentary structures, and the matrix-supported pebbles and cobbles and the textural immaturity.

The facies composition of the Chepor Member is consistent with a glacial marine shelf depositional setting. The dominance of mudstone facies containing marine fossils, combined with the rarity of wave-generated facies, indicates a marine shelf setting, below fair-weather wave base. Tidal sand sheets, represented by the cross-stratified sandstone facies, are common and can form extensive bodies on modern day marine shelves (Desjardins et al., 2012).

The presence of wave rippled, laminated and hummocky cross-stratified sandstone beds represent the deposits of waning storms below fair-weather wave base (Harms et al., 1975; Dott and Bourgeois, 1982; Duke, 1985; Leckie and Krystinik, 1989).

In summary, the depositional environment of the lowermost Kubang Pasu Formation is interpreted as a glacial marine shelf system, with glacial dropstones deposited from melting ice rafts and debris flows reedimenting glacial deposits as diamicts in deeper waters. However, this interpretation contrasts with the marine fauna of the Chepor Member, which consists of taxa that are widespread in the deeper warm-water realm of other continents (e.g., Europe, Turkey, North Africa, South China). A plausible interpretation is that icebergs may have drifted into a relatively warmer shallow marine environment and melted, depositing ice-rafted debris (e.g., Metcalfe, 2011b, 2013a).

Sibumasu was a peri-Gondwanan terrane, located a significant distance and at lower latitudes to Gondwanan Australia (Li et al., 2004; Metcalfe, 2013a; Ali et al., 2013; Metcalfe and Aung, in press). The current interpretation is that the dropstones and diamictites originated from ice-rafted sediments deposited by melting icebergs or disintegrating ice sheets that migrated northwards from Gondwana into more temperate waters of Sibumasu during the late Early Carboniferous. The age of the interpreted glacial marine deposits of the Chepor Member is Mississippian (probably Viséan), as dropstone-bearing mudstone facies occur interbedded with mudstone containing the Mississippian fossil assemblage described in this paper (also see Meor and Lee, 2004, 2005, where the same pebbly facies are also observed associated with Weyeraspis, Waribole, Chlupacula, Langgonbole and Posidonia-bearing mudstone). The Langggun Red Beds of Langkawi, which are age equivalent to the Chepor Member in Perlis, also contain isolated pebbles associated with poorly sorted mudstone, which may also be glacial marine deposits (Jones, 1981 and personal observation). However, it is likely that the uppermost diamictite bed in the Sanai Hill B Section (Fig. 4A) is younger (Pennsylvanian), based on its stratigraphic position overlying the fossiliferous beds. Evidence for glaciation occurs mostly later on the supposed neighbouring craton of Western Australia (Mory et al., 2008) but possibly Viséan diamictites occur widely on the adjacent South Tibetan block, where they are thought to have originated from major uplift and alpine type glaciers (Garzanti and Scinnach, 1997).

4.6. Undifferentiated upper Kubang Pasu Formation

Much of the Kubang Pasu Formation overlying the Mississippian Chepor Member remains poorly described, mainly due to poor exposure and absence of diagnostic fossils. Hence, most of the poorly dated succession eastward of the Chepor Member exposures at the Sanai Hills and Hutan Aji is referred to as the undifferentiated upper Kubang Pasu Formation. Generally, it shares many characteristics of the Chepor Member, with thick mudstone of various colours, including red, white, grey, brown and black, interbedded with sandstone, including pebbly diamictites, quartzitic and feldspathic sandstones (Jones, 1981). The Kubang Pasu Formation succession overlying the basal Chepor Member is poorly fossiliferous. Fossil bivalves, brachiopods and crinoid fragments have been reported from intermediate levels of the formation from widely spaced localities. The presence of Pennsylvanian strata is suggested by the occurrence of ammonoid fossils identified as ?Agathiceras sp. and ?Paralegoceras sp. (Jones, 1981), but these specimens have never been described formally. The Singa Formation in Langkawi is the lateral equivalent of the undifferentiated upper Kubang Pasu Formation, and is composed of black mudstone with pebbly horizons interpreted as glacial marine diamictites and interbedded lithic to quartzitic sandstones (Jones, 1981; Stauffer and Lee, 1986).

4.7. Uppermost Kubang Pasu Formation

The uppermost 80 m of the Kubang Pasu Formation is exposed at the foot of the Chuping karst hills, which form several N–S trending ridges in Central Perlis (Jones, 1981). The Kubang Pasu Formation is overlain by the Chuping Limestone. The boundary is gradational, with silicilastic sandstone and mudstone being gradually replaced by limestone upsection. These are the ‘Passage Beds’ of Jones (1981).

The age of the uppermost Kubang Pasu Formation is late Early Permian (Kungurian–Roadian), based on the presence of the fusulind Monodiexodina shiptoni (Basir and Koay, 1990; Ueno, 2003, 2006). The Passage Beds also contain a rich fossil assemblage, including algae, fenestellid bryozoa, brachiopods, and molluscs in the mudstone and siltstone (Jones, 1966). Associated calcareous beds also contain the brachiopod Cancrinella cf. cancrina, again indicative of an Early Permian age (Ishii et al., 1972). Also associated with the brachiopods is the nautiloid Mooreoceras sibumasense (Niko et al., 2005).

A detailed sedimentological and stratigraphic study of the uppermost Kubang Pasu Formation was conducted by Meor et al. (2013b). The uppermost Kubang Pasu Formation can be divided into cycles of metres to tens of metres thick facies successions, that coarsen upward from bioturbated mudstone interbedded with thin siltstone and sandstone (Offshore Facies Association), into interbedded hummocky cross-stratified sandstone and mudstone (Distal Lower Shoreface Facies Association), and finally capped by amalgamated hummocky and swaley cross-stratified sandstone (Proximal Lower Shoreface Facies Association). The facies successions indicate a prograding wave- and storm-influenced coastal depositional system, based on the predominance of wave and storm generated facies (symmetrical ripples, hummocky cross-stratification). The absence of upper shoreface and more terrestrial deposits indicate a more distal location on the marine shelf. A dense monospecific concentration of Monodiexodina fossils forms a ca. 2 m thick bed (Monodiexodina bed) in the uppermost Kubang Pasu Formation.
4.8. Chuping Limestone

The Chuping Limestone forms a series of N-S trending, isolated hills in the middle of Perlis and is also exposed in Langkawi. It is composed of mainly massive, light coloured limestone. The top of the unit has been eroded, but the maximum preserved thickness is around 1000 m in Langkawi and 600 m in Perlis (Jones, 1981).

Fossils are common in the basal beds of the Chuping Limestone. This includes the brachiopods Hamletella cf. alta, Marginifera sp., Derbyia, Squamularia and Martinopsis, the corals Sinopora dendroida, Lophopyllum pendulum and the fusulinids Chusunella sp. and an indeterminate schwagerinid, all indicative of a Permian age (Jones, 1981). Sakagami (1963) reported the presence of bryozoans, including Cyclotrypa, Polyypora, Fistulipora hupehensis indicative of a Kungurian age.

The upper parts of the Chuping Limestone are poorly fossiliferous. Metcalfe (1990a,b) reported the occurrence of the late Triassic (early Norian) conodont Epigondolella abneptis from the unit. Thus, the Chuping Limestone ranges in age from the Permian (Kungurian) to the late Triassic (early Norian).

Sedimentologically, the Chuping Limestone is predominantly composed of light coloured, massive to thickly bedded (dm to m thick) limestone. The lower part of the Chuping Limestone is particularly well bedded, with the beds exposed at Bukit Tungku Lembu comprising stacked, cm- to dm-thick, hummocky cross-stratified grainstone beds (Fig. 10). The limestone is rich in skeletal grains, with minor intraclasts and rare pellets (Rao, 1988). Rao (1988) also reported the presence of angular, polymodal quartz grains accumulating in pockets in the basal limestone. The coarse grained texture and presence of hummocky cross-stratification indicates storm deposition (Harms et al., 1975), and indicates a probable lower shoreface to offshore/shelf depositional environment for the Chuping Limestone (Reinson, 1992). Chert is also common at the base of the Chuping Limestone (Jones, 1981).

Rao (1988) used the sedimentary characteristics and oxygen and carbon isotope values from brachiopods of the Chuping Limestone to interpret a cool-temperate (subpolar) palaeoclimate. The angular quartz grains were interpreted as ice-rafted debris. The $\delta^{18}O$ and $\delta^{13}O$ trend overlaps with values derived from coldwater Early Permian fauna from East Australia (Rao and Green, 1982). Water temperature was estimated to be between 2–13 °C (Rao, 1988).

5. Correlation

An updated stratigraphic correlation for the mid–upper Palaeozoic of the Western Belt, Peninsular Malaysia is presented in Fig. 11.

5.1. Silurian Mempelam Limestone

The Silurian Mempelam Limestone of North Perlis and the Langkawi Islands extends northwards into southern Peninsular Thailand, where it is known as the Kuan Tung Formation (Wongwanich et al., 1990). Both units share the same lithological and faunal characteristics (Cocks et al., 2005). The upper part of both the Mempelam Limestone and Kuan Tung Formation is composed of nodular limestone (Wongwanich et al., 1990).

No record of Silurian age limestone is present east of the Sanai Hills and Hutan Aji outcrops in Perlis. Further south in Kedah, the Mempelam Limestone is replaced by age equivalent black carbonaceous mudstone of the Mahang Formation, where Early Silurian graptolites (Llandovery cyphus to crispus Zones; Upper Wenlock flexilis and lundgreni Zones) have been identified (Burton, 1967; Jones, 1973b). Black carbonaceous mudstone also extends eastwards of the Mahang Formation, into North Perak, where it is known as the Kroh and Grik formations (Burton, 1986; Lee, 2009). Llandovery age graptolites have been reported from the Grik and Kroh formations (Jones, 1973b; Kobayashi, 1984). In southern Perak, Silurian carbonates are again present. The Kanthan Limestone exposed west of Gunung Kangtan, at the northern end of the Kinta Valley, contains Silurian age tabulate corals (Jones, 1973a). The lithology is roughly similar to the Mempelam Limestone, consisting of fine grained, black carbonaceous limestone with argillaceous interbeds, with no macrofossils. The Kuala Lumpur Limestone is exposed further south. Corals indicate a Silurian ( Wenlock and Ludlow) age (Boucot et al., 1966).

Fig. 10. Section at the base of the Chuping Limestone at Bukit Tungku Lembu, composed of beds displaying hummocky cross-stratification. Fig. 11B is a line drawing of Fig. 11A.
5.2. Early Devonian Timah Tasoh Formation

The Early Devonian, black tentaculitid mudstone succession (Timah Tasoh Formation) of Langkawi and Perlis changes into a slightly different succession in the north. The Kuan Tung Formation limestone extends into the Early Devonian (early Emsian) in southern Peninsular Thailand, based on proetid fossils (Fortey, 1989) and conodonts (Long and Burrett, 1989).

The overlying Pa Samed Formation is also age-equivalent to the Timah Tasoh Formation. It is also composed of black tentaculitid-bearing mudstone (Wongwanich et al., 1990). Fossils indicate an earliest Emsian age for the Pa Samed Formation (Boucot et al., 1999; Agematsu et al., 2006). The faunal assemblage of the Pa Samed Formation is similar to the Timah Tasoh Formation, and includes tentaculitids such as Nowakia acuaria, Styliolina, Metastyliolina, the graptolite Monograptus, the trilobite Plagiolaria and also brachiopods including Plectodonta (P.) forteyi, all of which are present in the Timah Tasoh Formation (Meor and Lee, 2005; Meor et al., 2013a). The Timah Tasoh Formation grades laterally into black mudstone and slate of the Mahang Formation in East Perlis (Basir et al., 2010). The Timah Tasoh Formation is also correlated to the upper part of the Mahang Formation, southwards in Kedah. Lochkovian praehercynicus and hercynicus Zone graptolites have been recorded from the Mahang Formation by Jones (1973b). Jones (1973b) also reported the occurrence of Monograptus sp. cf. yukonensis associated with the tentaculitids Nowakia and Styliolina, from shales of the Mahang Formation in Central Kedah. The faunal assemblage resembles that of the Timah Tasoh Formation, with the presence of Monograptus cf. yukonensis indicating a late Pragian or earliest Emsian age. Black mudstone extends further eastward from Kedah, into North Perak, in the form of the Grik and Kroh formations. The tentaculitids Styliolina and Nowakia cf. acuaria have been reported from the Kroh Formation, indicating an Early Devonian age (Burton, 1986). Kobayashi and Hamada (1972) also reported an Emsian fossil assemblage composed of tentaculitids, brachiopods and blind trilobites from the Kroh Formation.

Further south, in Central Perak, the argillaceous Mahang Formation is replaced by carbonates. Lane et al. (1979) described Emsian gronbergi Zone conodonts from the Kanthan Limestone north of Ipoh. The dark grey to black Kajang Schist overlying the Kuala Lumpur Limestone in Kuala Lumpur has been interpreted to be Late Silurian to Devonian in age (Yin, 1976), and may be a metamorphosed lateral extension of the Early Devonian mudstone facies in the south.

5.3. Late Devonian Sanai Limestone

Definite Late Devonian rocks are only known from two areas in western Peninsular Malaysia: (1) the latest Frasnian to early Famennian Sanai Limestone in Perlis, and; (2) carbonates around Kinta Valley, near Ipoh, Central Perak. The carbonates around Ipoh preserve a virtually continuous succession from the Emsian to the Middle Frasnian (Gobbett, 1966; Jones, 1973a; Lane et al., 1979; Lee, 2009). Frasnian rocks in the Kinta Valley are represented by the lower part of the Kanthan Limestone (Lane et al., 1979). Both
the Sanai and Kanthan limestones share the same general facies characteristics, being mainly composed of dark, fine grained, bedded limestone.

5.4. Tournaissian Telaga Jatoh Formation

The Late Tournaissian Telaga Jatoh Formation at the base of the Kubang Pasu Formation is relatively thin and forms small outcrops. However, it is widespread in distribution, with exposures in Perlis and Kedah. The chert beds do not extend westwards into Langkawi. Siliceous shale and radiolarian chert containing conodonts spanning the Tournaissian–Viséan transition have been reported from Ko Yo, Songkla in Peninsular Thailand (Igo, 1973). Late Tournaissian (lower part of Scalognathus anchoralis Zone) conodonts have also been reported from limestone and mudstone beds of the Taungnyo Group near Loi Kaw, Myanmar (Metcalf and Aung, in press). Tournaissian chert is also absent from the Kinta Valley area further south. The Late Tournaissian is preserved in the Kanthan Limestone as limestone beds containing conodonts of the Scalognathus anchoralis Zone unconformably overlying Late Devonian (Middle Frasian) limestone beds containing conodonts of the south. The Late Tournaisian is preserved in the Kanthan Limestone as limestone beds containing conodonts of the Scalognathus anchoralis Zone unconformably overlying Late Devonian (Middle Frasian) beds (Metcalf, 1983, 2002). Tournaissian aged chert beds are also observed underlying beds of the Kenny Hill Formation in Dengkil, Selangor (Zaiton and Basir, 2003).

5.5. Carboniferous Chepor Member

The Carboniferous (Viséan and possibly younger) Chepor Member of the Kubang Pasu Formation is also widely distributed, forming the lower part of the Kubang Pasu Formation in Perlis and Kedah (Meor and Lee, 2005). Rocks of similar lithology, facies characteristics and faunal assemblage are also exposed westwards in Langkawi, where they are known as the Langgun Red Beds (Kobayashi and Hamada, 1973). Similar rocks in southern Peninsular Thailand are known as the Kuan Klang Formation. The Kuan Klang Formation is also composed of light coloured and red fossiliferous mudstone with arkosic sandstone beds (DMR, 2004; Ridd, 2009). Fossil taxa shared by both the Chepor Member and Klang Klang Formation include the bivalve Posidonia (“Posidonomya”), the trilobite Langgonbole vulgaris and chonetid brachiopods (Ridd, 2009). In Central Perak, age equivalent strata are represented again by carbonates. The Kuan On Beds of the Kinta Valley comprises carbonaceous shaly limestone with oolitic intervals (Sintharalingam, 1968). The Kuan On Beds contain a Mississippian faunal assemblage, including Siphonophlylla sp. Viséan corals have also been reported from thick bedded sandy limestone exposed west of Kampar (Jones, 1966). In the Kanthan Limestone, Viséan beds containing conodonts of the Lochheidae commutata Zone unconformably overlie Late Tournaissian beds (Metcalf, 2002). Siliciclastics overlying the black tentaculitid mudstone of the Pa Samed Formation in Satun contain Serpukhovian–Bashkirian (Arnsbergian–Yeadonian substages) goniatites (Wongwanich et al., 2004). These beds were assigned to the Pa Samed Formation, but are referred to as part of the Kuan Klang Formation by DMR (2004) and Ridd (2009). These can probably be correlated with the upper part of the Chepor Member, although Serpukhovian–Bashkirian fossils have not been reported from the unit. The only Late Viséan ammonoid fauna of southern peninsular Thailand, with a possible member of the Goniatiididae and prolocanitids (Promitites), was described by Reed (1920) from the eastern coast near Songkhla (see Fujikawa and Ishibashi, 2000) and needs revision. The Kenny Hill Formation exposed in Selangor roughly resembles the Kubang Pasu Formation, being mainly composed of interbedded mudstone and quartzitic sandstone (Lee, 2009). Unfortunately, the Kenny Hill Formation is poorly fossiliferous and does not display abundant sedimentary structures. The beds overlying the Tournaissian chert at Dengkil, Selangor (Zaiton and Basir, 2003) are probably age equivalent to the Chepor Member.

5.6. Carbo-Permian, undifferentiated and uppermost Kubang Pasu Formation

The undifferentiated Kubang Pasu Formation can be correlated to the Singa Formation in Langkawi (Jones, 1981). However, the Singa Formation is muddier, darker coloured and contains more abundant evidence of cold waters and glaciation, including dropstones, diamictites and cold water brachiopods (Stauffer and Lee, 1986; Mohd Shafeea Leman, 1996). Rocks similar to the Singa Formation are thicker and more widely exposed in southern Peninsular Thailand, where they are known as the Khaeng Krachan Group, and have also been interpreted as glacial marine deposits (Aimpawan et al., 2009; Ridd, 2009). Fossil brachiopods from the upper part of both the Singa Formation and Kaeng Krachan Group indicate an Early Permian (late Asselian–Early Sakmarian) age (Waterhouse, 1982; Shi and Archbold, 1995; Mohd Shafeea Leman, 1996). The undifferentiated Kubang Pasu Formation can be correlated southwards to carbonates of the Nam Loong and H.S. Lee beds in the Kinta Valley, which contain Early Permian (Sakmarian–Artinskian) brachiopods. Conodonts characteristic of the Neogondolella bisselli-Sweetognathus whitei Zone (late Wolfcampian, now Artinskian) have been reported from the northern end of the Kanthan Limestone (Metcalf, 1981).

The uppermost Kubang Pasu Formation, which is Kungurian in age, based on the presence of the Monodiodexidina bed, can be easily correlated with the uppermost part of the Kaeng Krachan (Khoa Phra Formation), which also contains the Kungurian age Monodiodexidina (Ingavat and Douglas, 1981) and lower Kungurian (Bolarian) ammonoids, especially Neoceorphites in association with Mikhukhoceras (Fujikawa et al., 2005).

5.7. Chuping Limestone

Late Permian to Late Triassic age limestone located east and south of the Chuping Limestone have been previously referred to as the Kodiang Limestone, but they are now considered part of the Chuping Limestone (Metcalf, 1981; Lee, 2009).

The Permian part of the Chuping Limestone can be correlated to the chert unit (previously Chert Member of Burton, 1973) of the Semanggol Formation which is exposed further south in East Kedah (Teoh, 1992; Basir and Zaiton, 2007). The chert unit comprises alternating chert, mudstone, siltstone and rhythmic bedded sandstone–mudstone interbeds and matrix-supported conglomerate interpreted as turbidites, debrisites and basinal deposits (Basir and Zaiton, 2007). Radiolarians, conodonts and bivalves give an age range from late Early Permian to Mid–Triassic (Spiller and Metcalf, 1995; Sashida et al., 1995; Basir, 1997; Spiller, 2002; Basir and Zaiton, 2007). Further south, the H.S. Lee Beds of the Kinta Limestone contains a fauna indicative of the Pseudofusulina ambiguza Zone, equivalent to the lower part of the Leonardian (Now Kungurian) (Gobbert, 1973).

The Permian Chuping Limestone extends northwards into Peninsular Thailand, where it is known as the Ratburi Limestone (Ueno and Charoentitirat, 2011). The Ratburi Limestone contains foraminifera indicating a latest Early Permian to probably Late Permian (Kungurian–Wuchapingian) age (Ueno, 2000, 2003; Ueno et al., 2000). It is also composed of massive to bedded limestone, with chert nodules/layers near the base and is locally dolomitised.

6. The Devonian–Carboniferous boundary in Northwest Peninsular Malaysia

The Devonian–Carboniferous successions in Northwest Peninsular Malaysia and also throughout the whole Western Belt
of Peninsular Malaysia is incomplete. At Sanai Hill A, Perlis, Emsian tentaculitid mudstone is directly overlain by Viséan mudstone and sandstone. At Sanai Hill B, the Emsian tentaculitid mudstone is directly overlain by Famenian limestone. Further north, at Sanai Hill C, the contact is between Emsian tentaculitid mudstone and overlying Viséan mudstone and sandstone. Mapping of the Sanai Hills indicates that the boundary between Devonian and Carboniferous rocks is represented by a fault contact (Meor and Lee, 2002, 2005 and this paper). This explains the missing sections, the variations in the stratigraphic gap between adjacent hills and the pinching of the Tournaisian Telaga Jatoh Formation chert beds below the Kubang Pasu Formation. A fault contact is also identified between Emsian Timah Tasoh Formation and overlying Viséan Kubang Pasu Formation at Hutan Aji. Interestingly, most of the Devonian record is also missing throughout most of the Western Belt of Peninsular Malaysia. The Devonian stratigraphic gap throughout the whole Western Belt strongly suggests the presence of an unconformity.

A Mid-Palaeozoic Unconformity has been proposed for the Western Belt of Peninsular Malaysia by numerous workers in the past. Koopmans (1965) interpreted a Mid-Palaeozoic orogeny based on differences in deformation, regional metamorphism and granite intrusion between the lower and upper Palaeozoic Successions in Northwest Peninsular Malaysia. Jones (1973a) placed the unconformity between the Early Devonian Timah Tasoh Formation and the overlying Chepor Member/Langgun Red Beds (now known to be of definite Carboniferous age). Metcalfe (1983, 2002) also described an unconformity between Late Devonian and Late Tournaisian beds in the Kanthan Limestone. The Late Tournaisian beds contain abundant, reworked, Tournaisian and Late Devonian Tournaisian conodonts in beds overlying the Mid-Palaeozoic (Meor and Lee, 2002, 2005 and this paper). This explains the missing sections, the variations in the stratigraphic gap between adjacent hills and the pinching of the Tournaisian Telaga Jatoh Formation chert beds below the Kubang Pasu Formation. A fault contact is also identified between Emsian Timah Tasoh Formation and overlying Viséan Kubang Pasu Formation at Hutan Aji. Interestingly, most of the Devonian record is also missing throughout most of the Western Belt of Peninsular Malaysia. The Devonian stratigraphic gap throughout the whole Western Belt strongly suggests the presence of an unconformity.

7. Depositional history

A revised depositional history of the Western Belt of Peninsular Malaysia is summarised here, based on current data. The interpretations are based on the generally accepted view that the Western Belt is part of a Gondwana-derived continental fragment called Sibumasu, which was located outboard of Gondwanan Australia during the Early to Mid-Palaeozoic (Metcalfe, 2011a,b, 2013a,b).

7.1. Late Silurian

There was widespread deposition of pelagic carbonates in the area of present day Northwest Peninsular Malaysia and southern Peninsular Thailand area during the Late Silurian (Mempelam Limestone and Kuan Tung Formation). The deposits probably represent the distal margins of a carbonate platform associated with the peri-Gondwana continental shelf. The basin deepened towards the present day east and south, represented by deposition of black mudstone of the Mahang, Grik and Kroh formations in present day East Perlis, Kedah and North Perak. Another carbonate platform was present further south in present day Central Perak and Kuala Lumpur (the Kanthan Limestone and the Kuala Lumpur Limestone).

7.2. Early Devonian

Carbonate development persisted during the Early Devonian in present day southern Peninsular Thailand and South Perak (upper Kuan Tung Formation and Kinta Limestone units). During the earliest Devonian (Lochkovian), transgression in the areas of present day Northwest Peninsular Malaysia and Selangor resulted in gradual drowning of the carbonate platform and deposition of black mudstone (as marked by the gradational boundary between Mempelam Limestone and Timah Tasoh Formation in Perlis and Langkawi). Transgression occurred later in southern Peninsular Thailand, with carbonates of the Kuan Tung Formation being replaced by the Pa Samed Formation during the Emsian. However, a carbonate platform still persisted during the Early Devonian in the Kinta Valley area (Kanthan Limestone).

Black mudstone deposition also persisted in East Perlis and Kedah (Mahan, Grik and Kroh formations), and also possibly in Selangor (Kajang Schist). Boucot et al. (1995) estimated a water depth of between 150–200 m for the basin, based on the benthic faunal assemblage. The black mudstone indicates dysoxic/anoxic waters brought on by sluggish circulation. There is a general
eastward trend in eye reduction in trilobites associated with the black mudstone, from Northwest Peninsular Malaysia to North Perak. The phacopid Plagiolaria poothai, which is present in the Timah Tasoh and Pa Samed formations, is atheloptic (reduce eyed) (Crônier and Fortey, 2006). The Kroh Formation, further eastward, contains a mixture of blind and degenerate eyed trilobites (Kobayashi and Hamada, 1972). This is consistent with eastward deepening of the basin, with the North Perak black mudstone representing the deepest part of the basin. Blindness in trilobites may coincide with transgression and basin deepening (Crônier and Fortey, 2006) but adaptation to infaunal life style can be equally important (e.g., Berkowski, 1991; Becker and Schreiber, 1994). These Early Devonian black mudstone deposits with a characteristic tentaculitid and monograptid fauna formed an elongate, outer shelf/continental margin belt extending from West Yunnan to Peninsular Malaysia (Meor et al., 2013a).

7.3. Middle–Late Devonian

The latest Early to Late Devonian record is missing from most of the Palaeozoic successions of the Western Belt. This probably marks a major rifting event, resulting in erosion and non-deposition associated with fault block tilting and uplift. Erosion and/or non-deposition started in Northwest Peninsular Malaysia, probably during the Mid- or earliest Late Devonian. However, there was concurrent, continuous deposition in the Central Perak area. Carbonate development still persisted until the early Middle Frasnian in the present day Ipoh area. The diverse fossil assemblage from the Givetian Thye On Beds limestone indicates a shallower, more proximal part of the carbonate platform. Erosion and/or non-deposition occurred later in Central Perak, i.e. during the Famennian or earliest Tournaisian. The differences in timing of erosion and/or non-deposition indicates active rifting, with different fault blocks experiencing different rates of uplift and subsidence.

7.4. Carboniferous

Continued rifting resulted in rapid subsidence with associated widespread transgression during the latest Tournaisian. High plankton productivity led to deposition of radiolarian ooze on the outer shelf and slope (Albilella deflandrei and indensis Zones, Basir and Zaiton, 2011b). Rapid subsidence resulted in significant creation of accommodation space in rift basins. The differential relief between uplifted fault blocks and adjacent subsided basins produced an increase in sediment supply, and the basin was filled by a thick syn-rift succession of post-Tournaisian clastic deposits. The post-Tournaisian Carboniferous deposits in Sibumasu represent a mainly muddy shelf depositional environment with extensive sheets/ridges of wave, storm, tidal current and gravity flow-modified and deposited sands. In Northwest Peninsular Malaysia, the shelf deposits include evidence of distal, glacial marine influence. Dropstone intervals associated with interbedded mudstone containing a Viséan age fauna and occasional daimictites in the Carboniferous succession of Northwest Peninsular Malaysia probably indicate deposition of ice-rafted sediment by melting icebergs originating from Gondwana, which indicates Carboniferous (Viséan and younger) glaciation. The oldest glacial deposits from Australia are latest Viséan in age (Eyles et al., 2002; Mory et al., 2008; Fielding et al., 2008). The siliciclastic succession coarsens upward in Northwest Peninsular Malaysia, indicating progradation from the Mississippian to Pennsylvanian. Widespread glaciation of Northwest Australia during the Pennsylvanian affected the offshore region represented by Sibumasu, where ice-rafterd debris was deposited as dropstones, while other glacially-derived material were transported into the deeper parts of the basin by debris flows.

Interestingly, carbonate deposition re-commenced in the Central Perak area at least during the Late Tournaisian (Metcalfe, 2002). An unconformity between Tournaisian and Viséan beds in the Kanthan Limestone marks a local erosional event, probably associated with local fault block movement. Carbonate deposition again re-commenced during the latest Viséan and in the middle Bashkirian (Westphalian A, Lane et al., 1979; Metcalfe, 2002). In general, carbonate development was again interrupted during the Pennsylvania and replaced by deposition of siliciclastics.

7.5. Early Permian (Sakmarian–Artinskian)

There was still widespread glaciation on Gondwana, with ice rafting and gravity flows depositing glacial debris on the marine shelf represented by Northwest Peninsular Malaysia. Continued rifting associated with separation of Sibumasu from Gondwana during this period resulted in thick accumulations of glacial marine deposits (Aimpawan et al., 2009; Ridd, 2009). Carbonate development still persisted in the Central Perak area during the Early Permian. Brachiopods from the limestone indicate cold temperate conditions (Shi and Waterhouse, 1991).

7.6. Early Permian (Kungurian)

The depositional environment of Northwest Peninsular Malaya changed from glacial marine, outer shelf during the Sakmarian to Artinskian, to shallow marine inner shelf during the Kungurian. The shelf was wave- and storm-influenced, with extensive shoreface sands and offshore shoals. Again, carbonates still persisted in Central Perak. Clastic supply gradually diminished during the Permian, ending in extensive shelf carbonate development during the Late Permian. This probably represents a post-rift phase associated again with Sibumasu separation (Meor et al., 2013b).

8. Conclusions

- The mid- to upper Palaeozoic stratigraphy of Northwest Peninsular Malaysia is divided into 5 formations: (1) Early Devonian (late Pragian or earliest Emsian) black mudstone of the Timah Tasoh Formation; (2) Late Devonian (latest Frasnian–early Famennian) Sanai Limestone; (3) Mississippian (Tournaisian) chert of the Telaga Jatoh Formation; (4) Carboniferous–Permian sandstone and mudstone of the Kubang Pasu Formation, and; (5) Permian Chuping Limestone.
- Two ammonoids are reported from the Chepor Member of the Kubang Pasu Formation in Pauh, East Perlis: (1) Goniatiites sp., and; (2) Praedaraelites tuntungensis sp. nov. The presence of Praedaraelites tuntungensis suggests a Viséan age for the Chepor Member, Kubang Pasu Formation.
- Detailed facies analysis of the Chepor Member, Kubang Pasu Formation, indicates a marine shelf depositional environment with storm and tide-generated bars, dunes, shoals or ridges. Isolated pebbles associated with mudstone containing a Mississippian (most probably Viséan) fossil assemblage and an overlying daimictite (Viséan or probably Pennsylvanian in age) are interpreted as glacial marine deposits. This indicates probable Viséan glaciation.
- A Mid-Palaeozoic Unconformity can be traced throughout the Sibumasu-derived Western Belt of Peninsular Malaysia. The unconformity is represented by a stratigraphic gap between mainly Devonian and Carboniferous rocks. It is possible that the unconformity marks initiation of rifting on Sibumasu, which eventually lead to the separation of Sibumasu from Australian Gondwana during the Early Permian. Variability in the age of the unconformity and the range of the stratigraphic gap suggests a complex tectonic evolution involving both rift and basin development.
graphic gap probably indicates different rates of uplift and subsidence associated with the initiation of localised rift basins (e.g. Ridd, 2009).

Acknowledgements

This work has been part of a long term study to understand the Palaeozoic stratigraphy of Peninsular Malaysia, initiated by Prof. Lee Chai Peng of the University of Malaya, and his guidance and drive during the past 10 years is greatly appreciated by the first author. This study was supported financially by University of Malaya research grants BK020-2011 and RU011-2013. Critical comments by two anonymous reviewers and Prof. Aj. Barber greatly improved the initial manuscript. Mahfuza Zulkarnain, Muhammad Arif Fitri Ahmad, Muhammad Zahid Zamanshah, Ahmad Sheeqal Abdul Samad, Abdul Kadir Ahmad Akhri and Kherman Mahali are acknowledged for their assistance in the field.

Appendix A. Systematic palaeontology

The description and identification of the ammonoids presented here was by R.T. Becker. All specimens described here are deposited in the Geology Department, University of Malaya. Abbreviations: \( dm = \) diameter, \( wh = \) whorl height, \( uw = \) umbilical width, \(WER = \) whorl expansion rate, \( E = \) external lobe(s), \( A = \) adventitious flank lobe, \( L = \) lateral lobe, \( U = \) umbilical lobes.

Order GONIATITIDAE Hyatt, 1884
Suborder GONIATITIDAE Hyatt, 1884
Superfamily GONIATITACEA de Haan, 1825
Family GONIATITIDAE de Haan, 1825
Genus GONIATITES de Haan, 1825

?Goniatites sp.

A.1. Material

One specimen (UMBTP001) from the Chepor Member, Kubang Pasu Formation at Bukit Tuntung, Pauh, East Perlis, an incomplete, somewhat distorted and partly corroded internal mould (Fig. 5).

A.2. Description

Conch diameter 27 mm, umbilical width ca. 13–14% \( dm \), with traces of spiral ornament. Relatively narrow ventral lobe with more or less straight sides in the lower part but diverging above a minor inflexion and towards the strongly sharpened apex of the asymmetric, very high ventral saddle (Fig. 5C). Reliable width–depth ratios cannot be given. Median saddles pointed, narrow and rather low (clearly less than half as high as the ventral saddle). Adventitious flank lobe trifid, with marked concave inflexions on both lobe sides. Inner flank saddle asymmetrically rounded, lower than the ventral saddle.

A.3. Discussion

The specimen is too poorly preserved to allow a clear generic assignment. The combination of the sharply pointed ventral saddle with a rather narrow ventral lobe and small median saddle suggest a species of Goniatites. The markedly trifid A-lobe is more typical of slightly younger genera, such as Lusitanoceras, Neogoniatites, or Dombarites (s.l.). However, their median saddles are higher. There are some advanced Goniatites species, such as Gon. spinifer from Germany, Gon. stenumbilicatus from Spain, Gon. cryophilicus from the Urals, and Gon. multirratus from the American Midcontinent, and Gon. tympanus and Gon. gerberi from Morocco, that have similar A-lobes. Very similar forms also occur in Xinjiang (Northwest China, Liang and Wang, 1991). The combination of a low median saddle with an advanced A-lobe are typical for Gon. evelinae from the eastern Anti-Atlas (Klug et al., 2006), Gon. constructus from Xinjiang (Liang and Wang, 1991), and for the more involute Gon. deceptus from Utah (Korn and Titus, 2011). In other Goniatitidae, e.g., Hibernicoceras, Goniattiella, Kalagilagites, and Paraglyphioceras, the ventral saddle is not as sharp (e.g., Korn, 1988). Arnsbergites and Junggarites have a slightly higher median saddle and much weaker outer inflexions of the A-lobe. The latter feature is also missing in Hypergoniatiidae, which is additionally characterised by high adult whorls. Other differences between genera of the Goniatitidae, such as the early conch ontogeny, cannot be applied to the new Malayan specimen.

A.4. Age

The characteristic sutures place the specimen in the Late Viséan. According to Korn (1997b) median saddles that are not half as high as the ventral saddle are typical for his Upper Viséan A (Korn and Horn, 1997), ca. the lower third of the Late Viséan. Advanced species of Goniatites, for example the Moroccan Gon. gerberi Assemblage (Korn et al., 2007), indicate a level near the Asbian/Brigantian transition (Korn et al., 2004, Fig. 8; Korn and Titus, 2011, Fig. 11).

Order PROLECANITIDAE Miller and Furnish, 1954
Superfamily PROLECANITACEA Hyatt, 1884
Family DARAELITIDAE Chernov, 1907
Genus PRAEDARAELITES Schindewolf, 1934
Praedaraelites tuntungensis sp. nov.

A.5. Material

Specimens with clearly visible partial sutures include the small (ca. 7 mm diameter) paratype UMBTP004, the incomplete holotype UMBTP002a-b (two counterparts), and the ventral whorl fragment of paratype UMBTP003. Additional, more complete paratypes but without good sutures are the juveniles GSGS 12001–2, KB12001, and UMBTP006, and the median-sized paratypes UMBTP005007 and 008A (Fig. 6).

A.6. Derivation of name

After the type-locality Bukit Tuntung.

A.7. Diagnosis

A subevolute (uw/dm = ca. 0.42–0.45) species of Praedaraelites with fast expanding (WER = 2.2–2.4), high whorls (wh/dm = ca. 0.31–0.36) that hardly overlap and with little change of shell geometry through ontogeny. E-lobes small, of equal length, median saddles small, only ca. 1/3 as high as the narrow, constricted ventral saddles, which are only ca. half as high as the dominant, constricted L-A-saddle. A-, L-, and U2-lobes serrate, small U3-lobe near the umbilical seam.

A.8. Description

All specimens are squashed flat and partly distorted (e.g., paratypes UMBTP007 and KB12001. The maximum conch diameter of the holotype is estimated at ca. 48.5 mm. At ca. 12 mm wh it shows four flank lobes, the outer three of which are distinctly serrate, with five or six denticles. All flank saddles are constricted at middle height and they become smaller towards...
the umbilicus whilst the width and depth of the lobes increase towards the venter. The small U₂-lobe just outside the umbilical seam is not well visible but appears to be undivided on the holotype counterpart. Paratype UMBTP003 shows that the small E-lobes are not serraté and of equal length, but all deeper than the wide and strongly serraté A-lobe. This gives a distinctive stepwise pattern of the ventral suture.

Shell parameters taken from the more complete specimens (1.5–17 mm dm) suggest that there is not much ontogenetic change. Paratype UMBTP005 allows the best insights into the relatively regular coiling, with whorl height near 1/3 of dm, very small imprint zone, and umbilical width near 43 % dm. Due to the squashed preservation, WER is only estimated to lie between ca. 2.2 and 2.4. Paratype GSA12001 indicates gently rounded flanks, at least until 10 mm dm.

A.9. Discussion

The specimens from Bukit Tuntung are clearly a new species, which can be named despite the overall poor, squashed preservation. Currently there are 26 species names in Praedaraelites s.l. (see compilation in Korn and Titus, 2011) but none of these display the combination of non-serrate ventral lobes and strongly serrate adventitious, lateral and first umbilical lobes. The equal length of the ventral lobes prove that the new form is a typical Praedaraelites and not Rotocanites, which is elevated here from subgenus to full genus level. Based on the addition of outer U₄-lobes in both genera/subgenera, it may be possible to further subdivide the group.

All species described from South China (Ruan, 1981) possess only one (quadratus) or two (virius, apiculus, acutus, involutus) serrate flank lobes (the A- and L-lobes). Therefore, as the European (Praed. culmiensis, postculmiensis, pyrenacis), North American (Praed. loeblichi), North African (Praed. culmiensis), and Novaya Zemlya (Praed. sobolevi) species, they are morphologically simpler. Praed. densus and Praed. medius described from Xinjiang by Li and Wang (1991) have three serraté flank lobes but also a serraté second ventral lobe and a non-serraté third U-lobe outside the umbilical seam. Therefore, they are morphologically more advanced. The most advanced Serpukhovian Praed. aktubensis from the Urals combines serraté E-lobes with lobe serration or proliferation at the umbilical seam.

Daraelitids are long known from SE Asia, based on a still poorly known species described by Fromaget (1931) from “Middle Laos” as Daraelites praecursor. Only at maturity it shows serraté of the A-lobe. Therefore, it is much less advanced than the new Malaysian form and occupies a rather ancestral position within Praedaraelites.

A.10. Age

The genus ranges from the Upper Viséan to Serpukhovian. In Germany, England, Ireland, Portugal, and NE Morocco, the morphologically simpler Praed. culmiensis occurs in the Late Viséan B sensu Korn and Horn (1997; e.g., Korn, 1988, 1997a). But in the Antler Foreland Basin of western North America, the similarly less advanced Praed. loeblichi enters much lower in the Late Viséan (Korn and Titus, 2011). The mentioned Novaya Zemlya, South Chinese and advanced Xinjiang species come from the top of the Viséan. Rootocanites inflatus, which has reached a very similar level of suture complication within the group, was found within a more than 150 m thick interval of the Goniiites Genozoan (Nalinskaya Formation), which suggests an early to middle part of the Upper Viséan (Li and Wang, 1991). With respect to the moderately advanced sutures, the new Malaysian form should be from median parts within the range of the genus.


