Higher-resolution biostratigraphy for the Kinta Limestone and an implication for continuous sedimentation in the Paleo-Tethys, Western Belt of Peninsular Malaysia

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Abstract: The paleogeography of the juxtaposed Southeast Asian terranes, derived from the northeastern margins of Gondwana during the Carboniferous to Triassic, resulted in complex basin evolution with massive carbonate deposition on the margins of the Paleo-Tethys. Due to the inherited structural and tectonothermal complexities, discovery of diagnostic microfossils from these carbonates has been problematic. This is particularly the case for the Kinta Limestone, a massive Paleozoic carbonate succession that covers most of the Kinta Valley in the central part of the Western Belt of Peninsular Malaysia. Owing to the complex structural and igneous events, as well as extensive diagenetic alterations, establishing precise age constraints for these carbonates has been challenging. Furthermore, the sedimentation history of these deposits has been masked. Three boreholes, totaling 360 m thickness of core, were drilled at either end of the Kinta Valley on a north-south transect through sections with minimal thermal alteration. The sections are composed chiefly of carbonaceous carbonate mudstone with shale and siltstones beds, in which the carbonates were sampled for microfossils. Five hundred conodont elements were extracted. Nine diagnostic conodont genera and 28 age diagnostic conodont species were identified. The identification of Pseudopolygnathus triangulus and Declinognathodus noduliferus indicated that the successions ranged from Upper Devonian to upper Carboniferous. Further analysis and establishment of stage-level datum that range from the Famennian to Bashkirian (Late Carboniferous) enabled detection of continuous sedimentation and improved age constraints in undated sections of the Kinta Limestone. This higher-resolution conodont biostratigraphy suggests a prevalence of continuous carbonate deposition during the Early Devonian to Late Carboniferous in the Paleo-Tethys. Thus, the identification of diagnostic conodont species for the first time from subsurface data in the area has helped improve the biostratigraphic resolution and establishes depositional continuity of the Kinta Limestone. These data could provide clues to the Paleo-Tethys paleogeographic reconstruction and paleodepositional conditions, and could establish higher temporal resolution correlation than previously attempted.

Key words: Carbonate, conodont, higher-resolution, correlation, paleogeography

1. Introduction

The Devonian to Carboniferous of Southeast Asia was dominated by carbonate deposition from shallow continental to deeper waters of the Paleo-Tethys (Metcalfe, 2002; Jian et al., 2009a, 2009b). Paleogeographic reconstructions of this region (Metcalfe et al., 1990; Metcalfe, 2011, 2013; Searle et al., 2012) have shown, using paleontological, paleobiogeographical, and tectonostratigraphic datasets, that the Paleo-Tethys had huge accommodation space, which probably resulted in the deposition of massive carbonates in the Paleozoic.

The Paleozoic stratigraphic record of Peninsular Malaysia, where many carbonate occurrences have been reported (Figure 1), is not an exception. These deposits encompass marine sedimentary successions ranging from the late Cambrian to early Permian (Foo, 1983; Lee, 2009). Complex tectonostratigraphic events of the Paleo-Tethys basins have been well documented by Metcalfe and Irving (1990), Alavi (1991), Hutchison (1994, 1996, 2007), Metcalfe et al. (2011), and Metcalfe (2013). Thus, these complicated paleodepositional settings may have influenced the distribution and abundance of...
microfossils, which are among the key datasets required to understand the Paleo-Tethys depositional environments, sedimentation histories, and biostratigraphy.

To date, high-resolution conodont biostratigraphy of Peninsular Malaysia has focused mainly on the northwestern part of the Western Stratigraphic Belt as this part of the peninsula contains an almost complete stratigraphic succession of Paleozoic strata (Lee et al., 2004; Cocks et al., 2005; Meor et al., 2005; Lee, 2009; Bashardin et al., 2014), is relatively fossiliferous, and is less affected by metamorphism (Lee, 2009). Conversely, the current biostratigraphy of the Kinta Limestone, which is the main carbonate lithological unit found within the Kinta Valley, in the central part of the Western Belt, is based solely on some poorly preserved uncommon microfossils recovered from outcrop samples within highly metamorphosed sections (Suntharalingam, 1968; Lane, 1979; Lane et al., 1979; Fontaine et al., 1995; Fontaine, 2002; Metcalfe, 2002) (Figure 2).

Despite the Kinta Limestone and associated siliciclastic lithologies having been affected by multiple alterations such as diagenesis, structural deformation, and metamorphism, important and informative microfossils have still been preserved (Suntharalingam, 1968; Fontaine and Ibrahim, 1995; Haylay et al., 2013). Ingham et al. (1960), Lee (2009), and (Richardson, 1946) documented that the limestone close to the intrusive batholith lacked fossils and is invariably marmorized, implying that paleontological data from outcrops nearer to the granitic intrusion might be affected by structural and thermal events. This has negatively impacted our understanding of the biostratigraphy and deposition history in the Kinta Valley successions and resulted in widely variable age constraints as detailed below. The outcrop-based dating showed that the limestones to the north are mixed Devonian to Carboniferous (Metcalfe, 2002); the limestones further to the southern tip of the valley are middle Devonian to middle Permian (Suntharalingam, 1968). Among the pioneer workers on biostratigraphic studies in the Kinta Valley, Gobbett (1968), who found fusulinacean foraminifera, and Suntharalingam (1968), who identified mollusks and tabulate corals from tinmine outcrops, determined the age of the successions as middle Devonian to middle Permian. Contributions from Fontaine and Ibrahim (1995) also confirmed a Permian age section from western Kampar in the southern part.

Figure 1. Map showing the study area in Peninsular Malaysia, Southeast Asia region. The study area is marked by the red box in western Malaysia.
of the Kinta Valley using *Maklaya* (fusuline). Lane et al. (1979) and Metcalfe (2002) introduced conodont dating from a metamorphosed limestone outcrop in the Kanthan area, which has been dated as mixed Devonian to Carboniferous in age. These studies have advanced the stratigraphic understanding of the Kinta Limestone, as they introduced the usage of microfossils from different geographical localities and they attempted to establish local and regional correlations as well. However, a thorough review of the previous micropaleontological works on the Kinta Limestone showed that these efforts were patchy and all age constraints were made based only on data derived from specific outcrops. Some of them even showed diverse age ranges for groups of microfossils in a single section (Metcalfe, 2002), which may indicate how complex it was to establish constrained paleontological dating of the sedimentary successions let alone understand the depositional history of the succession. The impact of the tectonothermal effects in the late Permian and Early to middle Cretaceous (Harbury et al., 1990) has also affected the reliability of the aragonitic, calcitic, and siliceous microfossils for dating and understanding the depositional

Figure 2. Map of the study area showing the Kinta Valley in the Peninsular Malaysia. Note that drilling locations are in the north (Sungai Siput) and in the south (Malim Nawar).
history in the basin. Thus, the existing paleontological dating has been thwarted by poor preservation and crystallization of the microfossils, which in turn hindered identification of taxa to the species level.

Despite the many attempts to date the Kinta Limestone on the basis of outcrop studies, microfossil distributions in the Kinta Limestone have been much debated due to the associated stratigraphic complexity, and the stratigraphic resolution remains ambiguous. As a result, a new approach is required to examine the Kinta Limestone from fully cored subsurface data to determine the stratigraphic variation and depositional history in the basin. This paper uses conodonts, which are second only to pollen and spores as the most resistant microfossils to metamorphism (Haq et al., 1998), to address the challenges of depositional history, dating, and biofacies variations in the Kinta Limestone. These phosphatic microfossils are the most commonly used biostratigraphic tool for dating late Cambrian to Late Triassic marine rocks (Sweet, 1988; Sweet et al., 2001), which fits the tentative age of the Kinta Limestone. This work presents our preliminary results and interpretations of the conodont biostratigraphy of the Kinta Limestone and its implications for continuous deposition of carbonates in the Paleo-Tethys during the late Paleozoic. This includes resampling classic and new outcrops as well as using new borehole data from the deepest part of the Kinta Limestone succession recognized to date. This study focuses on samples from these vertical boreholes to improve the biostratigraphy and examine the depositional history of the Kinta Limestone.

1.1. Stratigraphic setting
The Kinta Valley is in the central part of the Western Stratigraphic Belt, where the Kinta Limestone is the major lithological unit covering most of the valley (Figure 2). The Kinta Limestone has previously been dated as extending from the Silurian to Permian (Suntharalingam, 1968; Foo, 1983; Schwartz et al., 1989; Hutchison, 1994; Fontaine and Ibrahim, 1995; Metcalfe, 2002; Haylay et al., 2011, 2012). The flat valley floor of the Kinta Valley is characterized by some prominent remnant karstic limestone hills protruding from thick Quaternary sediments (Batchelor, 1988), which overly the Kinta Limestone (Batchelor, 1988; Kamaludin et al., 1993; Fontaine and Ibrahim, 1995). The thickness of this overburden varies from north to south and it reaches 30 m on average at the drilling location in the Malim Nawar (Figure 2). The subsurface of the Kinta Valley is believed to be underlain by the Kinta Limestone and by Late Triassic to Early Jurassic granitic intrusions (Ingham and Bradford, 1960). The elevated areas in the east and west of the Kinta Valley represent these granitic batholiths (Figure 2). The stratigraphy of the Kinta Valley is represented by the Kinta Limestone, the dominant lithology, with minor intercalation of siliciclastics such as pinching out black shale and silt beds, particularly in the Upper Devonian to lower Carboniferous intervals (Haylay et al., 2015). The Kinta Limestone is bounded on top by an erosional unconformity and the lower boundary is unknown, except for speculative older Precambrian basement complexes. At present the valley is tilting towards the south and the topography is drained to the south along the Kinta River.

2. Materials and methods
In this study, we have carried out an extensive survey of all the accessible outcrops along a north-south transect of the Kinta Valley. These included all major outcrops from Sungai Siput through to Malim Nawar (Figure 2). The detailed fieldwork and survey allowed us to establish that only two limestone hills, near Sungai Siput, would enable us to infer the depositional environments of the Kinta Limestone. These hills are outliers surrounded by siliciclastics; they are both accessible, relatively unaltered by thermal impact, and have exceptionally preserved pockets of limestones retaining primary sedimentary features (Haylay et al., 2014). Two boreholes, SGS-01 and SGS-02, were drilled, retrieving a total of 126.98 m of cores. These boreholes were drilled at ~1 km lateral distance from each other. A third borehole, MNR-03, was then drilled further to the south of the Kinta Valley in Malim Nawar (Figure 2) and retrieved the deepest core, at 232.82 m. This is an area where most of the fossiliferous limestone sites were reported in the literature. The three boreholes resulted in a total of ~360 m of core recovery, which enabled detailed lithofacies (Figures 3–5) and micropaleontological studies of the Kinta Limestone.

The lithofacies from the northern part of the Kinta Valley is mainly dominated by dark to black carbonate mudstone with black shale beds and siltstone intervals, particularly at the base of boreholes SGS-01 and SGS-02 (Figures 3 and 4). The southern section of the Kinta Limestone contains calcitic limestone with minor schistose intervals (Figure 5). The lithofacies from the southern section are relatively coarser than those of the northern section. To investigate the sedimentation history of the Kinta Limestone, establishing high-resolution conodont biostratigraphy was required. A total of 58 samples from cores and outcrops were selected for conodont study. Forty core samples (Figures 3–5) and 18 outcrop samples were processed. Sampling intervals for the cored sections of the boreholes are shown in Figures 3–5, along with the lithostratigraphic logs of the cores. The sampling intervals were set based on the outcrop and core lithofacies description prior to analyses.

Core and chip samples were dissolved for the extraction of conodonts following standard procedures (Jeppsson and Aneshus, 1995, 1999; Jeppsson et al., 1999). Depending
Figure 3. Lithostratigraphic section and sampling intervals of borehole SGS-01. The sampling interval was set based on lithofacies description of the cores.
Figure 4. Lithostratigraphic section and sampling intervals for borehole SGS-02. Note that the sampling was set based on lithofacies characterization.

Figure 5. Lithostratigraphic section and sampling intervals of borehole MNR-03. Note the Quaternary sand unconformably overlaying the Paleozoic carbonate, and sampling was set based on the lithofacies characterization.
on the dominant lithological characteristics (calcaceous or argillaceous), acid leaching for carbonates and treatment with soda were followed. Subsequently, based on the nature of the residues, the conodonts were either manually separated by examining them under a reflected light binocular microscope or separated using heavy liquid (bromoform) separation. This was followed by manually picking the conodonts from enriched or nonenriched insoluble residues under the microscope using a needle and a thin brush, which was accompanied by mounting and cataloging for studying.

Study and identification of the picked conodont materials required imaging through a scanning electron microscope (SEM). For this purpose, representative specimens were selected from the collection (Figures 6 and 7). The samples were mounted in a row of different positions in which all the important structures of the conodonts could be seen. These were then sprayed with a thin layer of gold and placed in the SEM for imaging. Sample selection, preparation, and description were done at Universiti Teknologi PETRONAS, Perak, Malaysia. Dissolution, extraction, and identification of the conodonts were carried out at Lomonosov Moscow State University, Moscow, Russia.

3. Results

3.1. Conodont abundance

The majority of processed samples produced a good quantity and quality of conodonts suitable for identification to species level. The conodonts showed variable abundance in the two studied localities of the Kinta Limestone. Out of the 40 core samples, 20 of them were taken from borehole MNR-03 in the southern part of the Kinta Valley; six of these 20 samples were found barren. The remaining 20 were taken from boreholes SGS-01 and SGS-02 in the Sungai Siput section at the northern part of the valley. The proportion of the conodonts recovered from the northern part of the Kinta Limestone covers 80% of the total. The conodonts from the southern part of the Kinta Valley cover 20% of the total recovery. The samples taken from the northern part of the Kinta Limestone contain 24 conodont species and samples from the southern part of the Kinta Valley contain four conodont species, which have been identified from more than 60 conodont elements. The dark to black carbonaceous carbonate mudstone from the Sungai Siput section of the Kinta Limestone is richer in conodonts than the light gray calcitic limestone from the southern section. Even though a thicker section was recovered in the southern part of the Kinta Valley, MNR-03, it was found to be relatively poor in conodont speciation and abundance, only containing four species. In addition to this, the marmorized carbonate lithofacies to the east and west of the Kinta Valley were found barren.

3.2. Conodont biostratigraphy

The conodonts recovered from the northern and southern localities of the Kinta Limestone range from the Early Devonian to Late Carboniferous. Conodont taxa and their abundances are summarized in Tables 1–3. These conodont data allowed us to subdivide the Kinta Limestone into stage levels of dating resolution. The conodont species Polygnathus communis communis (Branson et al., 1933), Pseudopolygnathus dentilineatus (Branson et al., 1933), Palmatolepis cf. gracilis sigmaoidalis (Ziegler, 1962), Spathognathodus crassidentatus (Branson et al., 1933), Pseudopolygnathus cf. triangulus pinnatus (Voges, 1959), Siphonodella obsoleta (Hass, 1959), Siphonodella crenulata (Cooper, 1939), Polygnathus inornatus inornatus (Branson et al., 1933), Polygnathus bischoffi (Rhodes et al., 1969), Pseudopolygnathus triangulus pinnatus (Voges, 1959), Pseudopolygnathus aff. fusiformis (Branson et al., 1933), Pseudopolygnathus multistriatus (Mehl et al., 1947), Clydagnostus cavusformis (Rhodes et al., 1969), Bispaphodus stabilis (Branson et al., 1933), Siphonodella cf. quadruplicata (Branson et al., 1933), Gnathodus punctatus (Cooper, 1939), Pseudopolygnathus cf. triangulus triangulus (Voges, 1959), Polygnathus inornatus inornatus (Branson et al., 1933), Gnathodus cf. semiglaber (Bischoff, 1957), and Pinacognathus fornicatus (Ji et al., 1984) are common in the samples from SGS-01 and SGS-02, indicating Famennian to Tournaian age carbonate deposits. The conodont species Declinognathodus noduliferus noduliferus (Ellison, 1941), Declinognathodus noduliferus inaequalis (Higgins, 1975), Declinognathodus noduliferus japonicus (Igo et al., 1964), and Declinognathodus cf. noduliferus noduliferus (Ellison et al., 1941) are mainly extracted from the samples of borehole MNR-03, suggesting Bashkirian age deposits. These data, using the age-diagnostic conodont species such as the Pseudopolygnathus triangulus triangulus and Declinognathodus noduliferus noduliferus, indicate a continuous succession of the Kinta Limestone from the north to the south of the Kinta Valley. Representative SEM images of the age-diagnostic conodonts are shown in Figures 6 and 7, while the conodont biostratigraphy along with the standard chronostratigraphy and short-term Phanerozoic sea-level curve for the specific time interval mentioned above are indicated in Figures 8 and 9, respectively.

4. Discussion

4.1. Stratigraphy and age constraint for the Kinta Limestone

Using borehole data from pockets of relatively unaltered carbonate lithologies at either end of the Kinta Valley (Sungai Siput in the north and Malim Nawar in the south), within the heavily metamorphosed Kinta Limestone, has enabled us to establish precise high-resolution
Figure 6. The scale bar represents 100 µm. Marker conodont species’ SEM images. The name of the species of the marker conodonts is as follows: 1 = Siphonodella cf. quadruplicata (Branson & Mehl, 1934), sample B-1-5, upper view; 2 = Siphonodella obsoleta (Hass, 1959), sample B-1-7, upper view; 3 = Siphonodella crenulata (Cooper, 1939), sample B-2-7, upper view; 4 = Palmatolepis cf. gracilis sigmoidalis (Ziegler, 1962), sample B-1-1, upper view; 5 = Siphonodella crenulata (Cooper, 1939), sample B-1-3, upper view; 6 = Polygnathus communis communis (Branson & Mehl, 1934), sample B-2-2; 6a = upper view, 6b = lower view; 7 = Polygnathus bischoffi (Rhodes, Austin & Druce, 1969), sample B-1-6, upper view; 8 = Polygnathus inornatus inornatus (Branson & Mehl, 1934), sample B-1-3; 8a = lower view, 8b = upper view; 9 = Gnathodus semiglaber (Bischoff, 1957), sample B-1-6, upper view; 10 = Gnathodus punctatus (Cooper, 1939), sample B-1-6, upper view; 11 = Pseudopolygnathus triangulus (Voges, 1959), sample B-1-3, upper view; 12, 13 = Declinognathodus noduliferus noduliferus (Ellison & Graves, 1941), sample B-3-3, upper view.
biostratigraphy and constrained the age range for the Kinta Limestone. The preserved sedimentological features in the relatively unaltered carbonate lithofacies enabled us to establish suitable study locations. The carbonate lithofacies from the northern part of the Kinta Valley are found to be interbedded with shale beds maintaining sharp bedding contacts, lamination, and syndepositional structures such as frequent slumps and contorted beds. In addition to preserved sedimentary structures at the drilling locations, similar slump-like features crop out in the caves east of Ipoh, such as Tambun and Kek Lok Tong (Kadir et al., 2011; Pierson et al., 2011). These features have been found extending from the surface to the subsurface part of the Kinta Limestone and we have been able to intercept a continuous limestone succession with intercalation of shale and siltstone intervals along the vertical wells from the Sungai Siput area. Conversely, in the southern section at Malim Nawar, the carbonate lithofacies is mainly calcitic limestone with short intervals of schistose material and has lost almost all of its sedimentary heterogeneity. Despite this loss of primary sedimentary features, the southern well has proven that, in addition to the towering limestone karstic hills, which are mainly aligned in the western foothill of the Main Range granite in the Kinta Valley (Figure 2), the Kinta Limestone continuously underlies the Quaternary deposits. It is well known that carbonate production is partly controlled by water depth and optimum bathymetry, where the rise of sea level is not going to threaten the survival of the carbonate producing organisms (Kendall et al., 1981). Examination of the geochemical and mineralogical analyses of the lithofacies, which creates sharp contact planes within carbonate successions, showed that there was little mixing of the carbonate and siliciclastics during their deposition (Haylay et al., 2012, 2014), indicating a change in depositional environments within the Kinta Limestone. These differing lithologies along the strike from the north to the south of the Kinta Valley have prompted questions of whether these are due to lateral small-scale facies changes or actually represent temporal changes in the carbonate succession.

### Table 1. Conodont elements from SGS-01.

<table>
<thead>
<tr>
<th>Sections</th>
<th>Sungai Siput (SGS-01)</th>
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<tr>
<td>Conodont taxa</td>
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<tr>
<td>Samples</td>
<td>B-1-1</td>
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<tr>
<td>Polygnathus communis communis (Branson &amp; Mehl, 1934)</td>
<td>10</td>
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<tr>
<td>Pseudopolygnathus dentilineatus (E.R. Branson, 1934)</td>
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<tr>
<td>Palmatolepis cf. gracilis sigmoidalis (Ziegler, 1962)</td>
<td>1</td>
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<tr>
<td>Spathognathodus crassidentatus (Branson &amp; Mehl, 1934)</td>
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<td>Pseudopolygnathus cf. triangulus pinnatus (Voges, 1959)</td>
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<td>Siphonodella obsoleta (Hass, 1959)</td>
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<td>Siphonodella crenulata (Cooper, 1939)</td>
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<tr>
<td>Polygnathus inornatus inornatus (Branson &amp; Mehl, 1934)</td>
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<tr>
<td>Polygnathus bischoffi (Rhodes et al., 1969)</td>
<td>3</td>
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<tr>
<td>Pseudopolygnathus triangulus pinnatus (Voges, 1959) (8)</td>
<td>8</td>
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<tr>
<td>Pseudopolygnathus aff. fusiformis (Branson et al., 1933)</td>
<td>1</td>
</tr>
<tr>
<td>Pseudopolygnathus multistriatus (Mehl &amp; Thomas, 1947)</td>
<td>1</td>
</tr>
<tr>
<td>Clydagnostus caviformis (Rhodes et al., 1969)</td>
<td>5</td>
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<tr>
<td>Bispathodus stabilis (Branson et al., 1933)</td>
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<tr>
<td>Siphonodella cf. quadruplicata (Branson et al., 1933)</td>
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<td>Gnathodus punctatus (Cooper, 1939) (4)</td>
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<td>Pseudopolygnathus cf. triangulus triangulus (Voges, 1959)</td>
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<tr>
<td>Polygnathus inornatus inornatus (Branson et al., 1933)</td>
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<td>Gnathodus cf. semiglaber (Bischoff, 1957)</td>
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<td>Pinacognathus fornaticus (Ji et al., 1984)</td>
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This question was hampered in previous studies by lack of outcrop, as well as the highly altered nature of the sequences and the challenging physiography of the karstic hills. In this study, we have collected new data from cored vertical wells penetrating to a depth of 232.82 m of carbonate succession, allowing determination of the age of the...
Figure 7. The scale bar represents 100 µm. Marker conodont species' SEM images. The name of the species of the marker conodonts is as follows: 1, 2 = Clydognathus cavasformis (Rhodes, Austin & Druce, 1969), sample B-1-3, 1a = upper view, 1b = lateral view, sample B-1-3= lateral view; 3, 4 = Bispathodus stabilis (Branson & Mehl, 1934), sample B-1-3, 3a = upper view, 3b = lateral view, sample B-2-7 = lateral view; 5 = Spathognathodus sp., sample B-2-5 = lateral view; 6 = Bispathodus aculeatus plumulus (Rhodes, Austin & Druce, 1969), sample B-2-7 = lateral view; 7 = Declinognathodus noduliferus inaequalis (Higgins, 1975), sample B-3-3 = upper view; 8 = Pinacognathus fornicatus (Li, Xiong & Wu, 1985), sample B-1-8 = upper view; 9 = Pseudopolygnathus triangulus triangulus (Voges, 1959), sample B-1-3 = upper view; 10 = Polygnathus lacinatus asymmetricus (Rhodes, Austin & Druce, 1969), sample B-2-5, 10a = upper view, 10b = lower view; 11 = Pseudopolygnathus dentlineatus (E.R. Branson, 1934), sample B-1-1, 11a = upper view, 11b = lower view, 12 = Declinognathodus noduliferus japonicus (Igo & Koike, 1964), sample B-3-15 = upper view.
Figure 8. Conodont biostratigraphy in the Kinta Limestone. Marker genera have been identified and these conodonts are plotted with their first appearance and indicate a potential zonation in the Upper Devonian–lower Carboniferous.
Figure 9. Lithostratigraphy, sea level, and conodont biostratigraphy of the three studied sections from the Kinta Limestone. Note that the sections have the same vertical scale; the sea-level curve (modified after Haq and Schutter, 2008) is rising to the left and falling to the right. The barren zone is indicated for the deepest borehole, MNR-03.
sections using well-preserved conodont species extracted from the core samples. The paleontological dating of these sections has enabled us to extrapolate surface data, which are patchy and scattered, to the continuous subsurface and thus estimate the thickness and depositional history of the Kinta Limestone. This has provided us with an opportunity to correlate three sections using paleontological dating at a resolution never previously applied to this succession.

We have recovered, for the first time, sizable quantities of phosphatic conodont microfossil elements, which being identified to species level provide a much higher temporal resolution for the subsurface part of the Kinta Limestone than previously established. These microfossil data have been associated to the lithological variations, which have been deduced from the relict textures and preserved sedimentary structures, to reveal temporal, and to a much lesser extent spatial, variations within the lithofacies. We have found considerable variation in the conodont abundance, species diversity, and apparent lithofacies association between the two northern sections (which show little spatial variation) and the southern section, which are comparable to the differing lithofacies discussed above. The studied sections of the Kinta Limestone have shown variation in many attributes, including texture, organic content, and extent of thermal alterations (Haylay et al., 2014; Haylay Tsegab et al., 2015). Sediment thickness for the two cored sections measured in the shortened, more condensed, northern part of the valley at Sungai Siput is 126.98 m and represents Lower Devonian to lower Carboniferous (Mississippian) lithofacies, whereas the sediment thickness recovered from the southern part of the valley at Malim Nawar is more than 232.82 m, mainly representing upper Carboniferous (Pennsylvanian) age sediments. These ages show that the sections, which are about 80 km apart, can now be correlated using the cooccurrence of established conodont datum of *Polygnathus inornatus rostratus* and *Declinognathodus nodiliferus nodiliferus*. The composite stratigraphic section (Figure 8) demonstrates definitively that the Kinta Limestone has a chronostratigraphic range from at least the Lower Devonian to upper Carboniferous, while the total age range based on previous studies of the formation were much wider, possibly ranging from the Silurian to Permian (Suntharalingam, 1968). Crucially, this study now establishes high-resolution dating for the previously undated Sungai Siput section, indicating that the Kinta Limestone is older in the north, growing younger towards the south, with much younger upper Carboniferous to Permian sequences lying south of Kampar (Suntharalingam, 1968; Fontaine and Ibrahim, 1995).

### 4.2. Sedimentation history in the Paleo-Tethys

In terms of relative thickness and depositional history, over 80% of the conodont elements recovered in this study come from the shorter and older successions in the north. Despite the smaller section drilled, this still covers a total chronostratigraphic age of Famennian (Upper Devonian) to Serpukhovian (Upper Mississippian), thus indicating that this section is condensed due to a variable or lower rate of sedimentation during the Late Devonian to late Carboniferous. The compacted sediments from the late Devonian to early Carboniferous sections are characterized by the carbonaceous dark gray to black limestone interbedded with black shale beds. The succession is devoid of benthic faunas and combined with the characteristic slump structures, dominance of fine-grained lithofacies, and bedded cherts (Haylay et al., 2014) is indicative of a deep basinal deposit with low depositional rates. By contrast, the section at Malim Nawar is much thicker and covers a shorter time interval, indicating more rapid deposition of thicker, shallower water carbonates during the middle to Late Carboniferous, with the occurrence of shallow benthic macrofossils and forams. This indicates that the Kinta Limestone had a variable depositional history, with the deeper, darker more organic-rich pelagic carbonates (black limestones) and black shale beds with a lower deposition rate of the late Devonian to early Carboniferous giving way to the thicker, more calcitic limestones of the Bashkirian to mid-late Carboniferous. These variations are clearly temporal, but may also have some relevance to the paleodepositional conditions of the studied successions. Thus, we can infer bathymetric variation in the paleo-basin during the deposition of these successions, with the conodont-rich older sections deposited in a relatively deeper setting than the younger, conodont-poor, shallower depositional successions in the southern part of the valley.

Our data are useful for constraining a depositional model of the Kinta Limestone and the paleobiogeographical evolution of the region. As the Sibumasu terrain began to converge with the Indochina terrane, the deep basinal deposits of the Late Devonian to early Carboniferous, with a lower rate of deposition and characteristic slump structures, gave way to the thicker, shallower carbonates of the Late Carboniferous to Permian. Globally, the Devonian to Carboniferous time is marked by widespread carbonate platforms (Schlager, 2003; Markello et al., 2008). In the Paleo-Tethys, massive carbonate deposits, of which the Kinta Limestone is a part, have been reported (Şengör, 1984; Hutchison, 2007). The Early Devonian to early Carboniferous (Mississippian) was characterized by continuous sea-level rise (Haq et al., 2008), which reached a maximum in the Bashkirian (late Carboniferous). This maximum sea-level rise corresponds to the time at which the studied part of the Kinta Limestone was deposited, with the dark gray to black carbonaceous Late Devonian to early Carboniferous lithofacies giving way to thick...
calcitic limestones in the Bashkirian. At Sungai Siput, preserved beddings and laminations suggest deposition in a relatively deep, low-energy environment, suggesting the development of anoxic conditions in the deeper part of the paleo-basin and thus possibly more favorable conditions for the preservation of conodonts. Similar studies in relation to the abundance and diversity of conodonts and other marine microfossils showed that conodonts recovered from lithofacies in association with black shale beds indicate the paleo-basin water depth and possibly paleo-hydrographic conditions (Fähraeus et al., 1975; Klapper et al., 1978; Lindström, 1984; Aldridge, 1986). The compendium of marine microfossils (Sepkoski, 2002) noted that the conodonts showed a decreasing trend in diversity and abundance from the Devonian to the Carboniferous, which is consistent with our data from the Kinta Limestone. These data also fit with the end-Devonian mass extinction event, with high Devonian diversity leading up to it and then low diversity in the Carboniferous.

Studies in the Paleo-Tethys indicated that it was characterized by continuous deposition of sedimentation until the Neo-Tethys (Gaetani et al., 1991). The closure of the Paleo-Tethys was in the Middle Triassic (Sone et al., 2008), implying that there was accommodation space for a continuous deposition of sedimentary successions in the paleo-basin. Moreover, the global sea level for the Phanerozoic (Haq and Schutter, 2008) was on the rise from the Devonian to lower Carboniferous. Carbonate-producing organisms were at their peak during those periods (Markello et al., 2008) and hence a huge volume of carbonate sediment is expected in these conditions, favoring the possibility of deposition of the voluminous Kinta Limestone. Studies have indicated that the paleolatitude of the Paleo-Tethys during this time was tropical (Stauffer, 1974), which is another important factor for carbonate sedimentation, with many modern carbonate analogs being limited to low-latitude geographic locations of the Earth.

High-resolution conodont biostratigraphy of the Kinta Limestone confirms the significant chronostratigraphic range of the formation, with no apparent breaks in sedimentation. Crucially, we demonstrate that sedimentation was not consistent and these rates are comparable with other temporal observations within the Paleo-Tethys basin. Our conclusions are, however, limited to the Late Devonian to late Carboniferous and there may be breaks in sedimentation in older or younger sequences not encountered in this study. Other studies have shown comparable continuous successions of Middle Devonian to lower Permian in the Kinta Valley (Suntharalingam, 1968; Foo, 1983; Hutchison, 1994; Fontaine and Ibrahim, 1995), without an apparent sedimentation break. These studies, however, reached their conclusions without the detailed subsurface biostratigraphic framework used in this study, which enabled more precise age determination and sedimentation data to be established. In contrast to this study, the previous studies were only able to constrain the bottom and top of the succession using macrofossil data, while we have been able to reveal details of the depositional history of the Kinta Limestone. In order to constrain the entire succession, we would need to penetrate deeper into the older sequences at Sungai Siput, as our existing boreholes did not reach the underlying oldest sedimentary succession. Similarly, we would also prospect for younger drill sections south of Kampar in the Late Carboniferous to Permian sequences. This research may encourage the revisiting of similar successions in the Paleo-Tethys for useful clues for potential petroleum exploration target in the Southeast Asia region.

In conclusion, improved high-resolution dating of the Kinta Limestone using conodont biostratigraphy from three newly cored well sections in relatively unaltered sediments has, for the first time, conclusively constrained the age of part of the Paleozoic carbonate successions in the central part of the Western Belt of Peninsular Malaysia. This has enabled measurement of a continuous succession of Upper Devonian to upper Carboniferous (Pennsylvanian) strata. Results indicate continuous but variable rates of deposition during the Late Devonian to Late Carboniferous in the Paleo-Tethys basin of Peninsular Malaysia. The research also indicated sedimentological and temporal variations related to changing local paleodepositional conditions, and the extent of oxygenation within the paleo-basins was reflected in the marked variation of sedimentation in the late Paleozoic Paleo-Tethys basin.

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