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Microbialites and associated facies of the Late Ordovican System in Thailand: palaeoenvironments and palaeogeographic implications

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ABSTRACT

Late Ordovician limestones of the Pa Kae and uppermost Tha Manao Formations (approximately mid-Sandbian to late Katian Stages) of western Sibumasu Terrane in Thailand comprise micritic limestone with abundant bioclasts of fragile fossils, in deep water facies. Both formations have a distinctive Fe-Mn-rich polygonal network vein system containing bioclasts and nodules of micrite. Pa Kae limestones, previously interpreted as rich in microbialites, contain small agglutinated stromatolites but lack calcimicrobes and cements. Unlaminated domes are also present, consistent with the leiolite type of microbial fabrics, other facies are non-microbial micrites. No other microbialite forms were found, despite previous reports of thrombolites and oncolites. The Tha Manao Formation contains no microbialites, evidence that network veins are not genetically related to microbialite growth. The Thai limestones partly overlap, in age and environmental setting, to mid-Sandbian to early Katian Stage Pagoda Formation (Yangtze Platform, south China) which also possesses a network of veins. However, a Pagoda Formation sample examined in comparison reveals its veins' structure to be in place and has instead undergone selective replacement of the micritic host rock by opaque matter while enclosed fossils and exotic intraclasts were unaffected. Some authors view the Pagoda Fm and Thai limestones as non-uniformitarian "time-specific facies". However, they a) do not fully coincide stratigraphically, and b) are each diachronous. Furthermore, other time-constrained unusual facies occur in the rock record (e.g. unique microbialite facies in south China after the end-Permian extinction; Ammonitico Rosso facies of Jurassic to Early Cretaceous in Italy) that are not regarded as being non-uniformitarian. Thus a uniformitarian approach is more appropriate to understand these unusual Ordovician facies, which may relate to early sea-floor partial cementation creating a solid mass that could be fractured to allow pathways of migrating fluids for vein infills to develop.

Key words: Ordovician, stromatolite, Thailand, Pa Kae Formation, Tha Manao Formation, polygonal limestone

1. Introduction and aims

The geography of Thailand comprises the main part of Thailand in the north and a narrow strip of southern Thailand territory, informally called peninsula Thailand, terminating at the border with Malaysia (Fig. 1). Late Ordovician sedimentary rocks in peninsula Thailand and the western area of the main part of Thailand (hereafter called western Thailand) comprise mostly micritic limestones rich in bioclasts, generally interpreted to represent an episode of high sea levels in the Ordovician (Ridd 2011). These rocks are prominent facies in outcrops because of a dark brown curved polygonal vein network of uncertain origin that pervades the rock mass in this part of the Ordovician sequence (Ridd 2011; Burrett et al. 2016). Two formations are well-known to contain the polygonal network: 1) the Pa Kae Formation (late-Sandbian to late Katian, Late Ordovician) of southern part of peninsula Thailand is mostly a distinctive and beautiful red-brown colour and has become one of the symbols of the Satun Geopark (DMR-CCOP-TNCU 2017, Suphakdee 2017); 2) the uppermost part of the Tha Manao Formation occurs in western Thailand is brown/green/grey colour (Bunopas 1983, see also Meesook 2013). The lower part of Tha Manao Formation is Darriwillian, Middle Ordovician (Kruse 1989), but age of the uppermost part is unconfirmed from nautiloid work in progress by other researchers; there are no publications, it may be Late Ordovician, but is possibly as young as earliest Silurian. Nevertheless, it is included in this study because of its visual similarity and likely close stratigraphic level to the Pa Kae Formation.

The Pa Kae Formation limestone is reported as part of regional studies (e.g. Ridd 2011, DMR 2014) and described in detail in the area around Ban Pa Kae village by Wongwanich (1990) in an unpublished PhD thesis and subsequent publications (Wongwanich 2017; Wongwanich et al. 1990) as being comprised of microbialite, in particular stromatolites (together with some thrombolite and oncolite), in facies interpreted as deep water. The process that formed the polygonal vein network distributed throughout the two formations has not been identified, although generally agreed is not due to desiccation because of the deeper water setting and because its structure is not consistent with features required for the process of desiccation cracks which extend only a short distance down into the sediment. Lokier et al. (2017) illustrated modern microbial polygons related to desiccation, that extend only about 5 cm below the surface. An alternative view (Zhou et al. 2016) that the veins represent syneresis cracks is also not sustained because the veins do not resemble syneresis features (e.g. Stow 2005, p78). The vein network helps to define the columnar structure that supports interpretation of stromatolites in the Pa Kae

Formation. However, the work by Wongwanich and co-authors and regional papers listed above are the only available studies of the Pa Kae formation and there is limited assessment of this facies in peer-review literature. The Tha Manao Formation has been less studied (e.g. Kruse 1989, Stait and Burrett, 1984). Therefore the aim of our work is to assess the nature of the polygonal micritic limestones of the Pa Kae and Tha Manao Formations, in order to enhance the understanding of these deposits in facies analyses of Late Ordovician deposits in Thailand, noting that the age of the Tha Manao Formation is not tightly constrained. This work is undertaken against the backdrop of the development of the Satun Geopark (the first in Thailand). Our focus is twofold, on: 1) the relationship of these deposits to interpretations of a microbial origin in deep-water facies; and 2) the structure of the polygonal vein network because of its association with the microbialite deposits in the iconic Pa Kae Formation; the vein network creates a visual impression of stromatolite columns in the field, a component of the reason why these facies are regarded as rich in stromatolites (Wongwanich 1990). Comparisons are made with other unusual limestones containing vein networks in an attempt to constrain the process by which these Thailand limestone structures formed.

2. Materials and methods

A short field visit in July 2018 produced field observations and samples from the Tha Manao Formation NW of Kanchanaburi in western Thailand and the Pa Kae Formation in southern peninsula Thailand (Fig. 1A), noting that sampling was restricted in these protected sites where the facies are very well exposed, so that only critical samples were collected. For the Pa Kae Formation, our study was in different localities from Wongwanich (1990) who worked in the area around Ban Pa Kae village. This paper is therefore based on field observations, polished blocks and thin sections together with comparison with information in existing literature that also includes geochemical data. Table 1 gives coordinates of all sites studied and indicates which figures in this paper illustrate the facies.

3. Geological Setting

Ridd (2011) and DMR (2014) provided comprehensive overviews of Thailand Ordovician stratigraphy and its history in peninsula and western Thailand where Palaeozoic rocks are exposed (Fig. 1). Agematsu et al. (2017) gave a valuable summary of the stratigraphy. The rocks studied in this paper lie in the region of complex Cainozoic tectonics of Thailand (Morley et al. 2011), close to the Phuket Slate-Belt Terrane (Ridd and Watkinson 2013) thus affected by tension and strike-slip, for which we see evidence in field observations and samples collected for this study. Burrett and Chaodumrong (2017) gave useful background on Ordovician rocks of Thailand, which belong to the Sibumasu Terrane (Fig. 1A), a narrow microcontinent that extends into present eastern Myanmar and southwestern-most China (Metcalfe 1998) and was a separate continental mass in the Ordovician (Fig. 1B). These literature sources describe the change through the Ordovician sedimentary facies, with an overall sea-level rise, particularly in the Late Ordovician prior to the Hirnantian glaciation regression, so that the facies studied in this paper formed in deeper water conditions, an interpretation consistent with trilobites and conodonts studied by Fortey (1997).

4. Facies, stromatolites and polygonal limestones

Because our work was on two formations widely separated in Thailand, we consider them individually below, followed by discussion.

4.1. Pa Kae Formation of peninsula Thailand

Pa Kae Formation occurs in several sites throughout peninsula Thailand, both on the mainland and islands in the Andaman Sea, crossing the border to Malaysia (Wongwanich 1990). Material collected for this study is from mainland sites of Hin Sarai I, Hin Sarai II, Hin Khao Noi and Ao Noon. Observations were also made at Tha Rae Rocks and information for Khao Daeng Mountain was provided by geologists at the Thailand Department of Mineral Resources. These sites all occur within the Satun Geopark (Fig. 1, Table 1 gives map coordinates). The Pa Kae Formation (Fig. 2) comprises carbonate mudstones and wackestones, a biomicrite rich in bioclasts of thin-shelled organisms, including trilobites, ostracods, molluscs (nautiloids are prominent in outcrop), together with intraclasts of the same material and some exotic limestone clasts, interpreted by Wongwanich (1990, p. 129) to be imported from upslope shallows. Wongwanich (1990) divided the Pa Kae Formation into two parts: the lower 34 m is poorly laminated red limestone, with thin clay partings and poorly developed stromatolitic layers; the upper 32 m is purer carbonate, with less clay and contains more prominent stromatolites with a highly distinctive polygonal vein network. The veins are more cemented than the micritic rock mass and are commonly 20 – 30 cm long in vertical section and 5 -10 mm thick, enclosing nodules of biomicrite, bioclasts and thin veins of Fe-Mn mineral, producing a columnar appearance (Figs. 3; 4A & E). However, the network is also highly variable both in vertical and transverse section (Fig. 4). Nautiloid cephalopods are common in the Pa Kae Formation and may occur entirely within the biomicrite (Fig. 5A) but are commonly in contiguous contact with the network veins (Fig. 5B, D, F). Rarely nautiloids are truncated in contact with the network veins either cut by minor faulting (Fig. 5E) or apparently by replacement by the veins (Fig. 5C), that may themselves be weakness lines of minor slip under pressure in the rock mass.

In detail, the columnar limestones commonly show internal dome-like layers in the field and some polished samples (Fig. 6), resembling stromatolites. In thin section (Fig. 7A-C) the laminated stromatolitic structure is clearly demonstrated, of micrite, intraclasts and bioclasts apparently bound together as agglutinated stromatolite. Careful search of our samples, and in literature, has not revealed any microbial structure; the only evidence of a microbial nature of the rock is the dome-shaped discrete layers that are consistent with agglutination by organic matter (not preserved), perhaps EPS (extracellular polymeric substances) that resulted in grain trapping and construction of a layered sediment (Riding 2000). Wongwanich (1990, Fig. 3.12D) illustrated development of the stromatolites as forming mats that grew into columns. Some samples show areas of micrite lacking stromatolitic layers, but in sharp contact with bioclastic fines, so we regard those patches of micrite as leiolites. Wongwanich (1990) also recorded thrombolites and oncolites, but unfortunately his illustrations are not sufficiently detailed to allow independent assessment, and thus are unconfirmed.

Between the domes, the network veins are complex (Fig. 7D-F in vertical section and Fig. 8 in transverse section). Veins contain multiple very thin (0.01 to 0.2 mm thick) opaque veinlets intermixed with rounded pieces of biomicrite, bioclasts and in some places tension cracks filled with calcite (Fig. 7D) that in enlarged views are shown to be calcite fibres (Fig. 8D), interpreted as growth fibres forming as the cracks opened gradually under tectonic stress. Ridd (2011, Fig. 3.8) described the polygonal network in Pa Kae Fm as a non-calcareous network with clay-filled pressure solution cracks. Wongwanich (1990) referred to the veins as calcareous mudstones and interpreted them as deposited between stromatolite columns. In his Table 7.1 Wongwanich (1990) identified the veins as Fe-Mn mineral and recorded concentrations of Fe and Mn in the veins as approximately 10 times the concentration in the biomicrite between the veins. These agglutinated stromatolites show small-scale vertical change into non-stromatolitic micrite (Fig. 9). Further variation is revealed at Hin Khao Noi where the Pa Kae Fm is gray coloured, and samples reveal a fabric not seen in other sites (Fig. 10) comprising a mottled micrite and micrite nodules in clay-rich matrix. Origin of the nodules is not clear but may be early diagenetic.

Variations of the Pa Kae Formation are shown in the Ao Noon site (Table 1). Fig. 11 shows tectonic displacement of the columnar network veins by differential deformation and bedding plane slip against the rock mass below that has rare network veins. The polygonal limestone in this location is obliquely sheared leaving the columns no longer normal to the bedding surface (Fig. 11B). Of the two samples collected here, the lower sample (Fig. 12) lacks both stromatolite and polygonal limestone, but the upper sample (Fig. 13) contained stromatolite faintly visible on the rock surface, verified in thin section, in an area of tightly polygonal limestone. Tectonic deformation of the Pa Kae formation is revealed in other sites in conjugate joints, reflecting compression in these folded limestones, and clay-rich veins (Fig. 14) due to fracture and injection of clays, presumably from clay-rich horizons but also derived from pressure solution of carbonate content. Figure 14 also shows the leiolitic structure present in some microbialite samples.

4.2. Tha Manao Formation

Tha Manao Formation limestones in western Thailand (Fig. 1A) are located NW of Bangkok and ca. 880 km north of the Satun Geopark area, within the Sibumasu Terrane. The limestone sequence at Ban Tha Kradan site shows vertical development from micritic limestone (Fig. 15A) through a bed comprised of sheared micrites (Fig. 15B) upwards into a biomicrite with a polygonal network of opaque mineral (Fig. 15C-E), very similar to the Pa Kae Formation. However, field examination and thin sections show no microbialites are present (Fig. 16 is a representative example), noting that Meesook (2013, Units T.16-18) referred to these as stromatolite beds, presumably because they resemble the Pa Kae Formation. The uniform fine-grained sediment and bioclast content, including nautiloids, is also consistent with interpretation of a deep-water environment of deposition of the Tha Manao Fm limestones, discussed later.

4.3. Other polygonal limestones

In order to assess the nature of the polygonal vein networks in these facies we searched for comparable examples elsewhere in the geological column; the closest structure (palaeogeographically and stratigraphically) is the Late Ordovician Pagoda Formation of almost the same age in South China (Figures 17 – 19). The Pagoda Formation was described by Zhan and Jin (2007) and Zhan et al. (2016) as a fine-grained limestone, with grey colours in nearer-shore locations but fully purple-coloured in deeper settings; these authors also noted its polygonal vein network is variable and in some places has a structure comparable to the common nodular limestones of the geological record. The Pagoda Formation overlies different formations in different parts of the South China Block (Song et al. 2017), but the Pagoda Formation is distinguished by its polygonal vein structure. Zhan et al. (2016) showed the dark veins are rich in Fe and Si, contrasting the purer carbonate content of the areas between the veins. They regarded the Pagoda Formation as a type of meganodular limestone that formed in the equatorial zone of low wind stress, during a phase of high sea level appropriate for accumulation of fine-grained carbonates. Other well-known cases are nodular limestones of the Lower Ordovician Orthoceras Limestone (Stouge 2004) and the Jurassic - Cretaceous Ammonitico Rosso limestone (Jenkyns 1974), that both have dark veins and are used in transverse sections as decorative building stones.

5. Discussion

There are two principal issues in understanding the polygonal limestones from Thailand described in this paper: 1) the nature and distribution of microbial content; 2) the controlling process on the polygonal network limestone and whether this is related to the presence of microbial carbonate or not.

5.1. Microbial characters

Agglutinated stromatolites and leiolites are common in Earth history (Riding 2000), but reports of associated polygonal limestones seem to be restricted to intertidal settings (see photos in Black 1933, Plate 21; Lokier et al. 2017) and lack the extended vertical veins that are a key feature of the Thai deposits. Also the lack of microbialites in the Tha Manao Formation limestones is evidence that the polygonal limestone formation process is essentially unrelated to the presence of microbialites. Nevertheless, the form of microbial carbonate as stromatolite domes creates variations of lithological consistency in the rock mass, that may be expected to have influenced the pattern of polygonal limestones in those places, where veins developed around the microbial patches, rather than through them, as a local control. A similar effect is evident in network veins associated with nautiloids, because the veins in almost all cases go around the margins of nautiloids and only rarely interrupts their structure (see Fig. 5, a feature noted also by Zhan et al. 2016, p356, for the Pagoda Formation in China). Thus we view the heterogeneity of the limestone caused by microbial patches and by nautiloids as having only a local effect on the arrangement of network veins and therefore the recognition of distribution of stromatolites cannot be on the basis of polygonal veins. Zhan et al. (2016, Fig. 4F) interpreted iron oxide-coated irregular areas within the Pagoda Fm as oxidation of pyrite coatings on clasts. Similar structures are present in our samples from Pa Kae Fm (Figs. 7, 13 & 14) but we consider them to be intraclasts. Pyrite coatings on grains would need a mechanism to form below the redox boundary in the sediment, raising the question of why pyrite crystals are rare in the rock; such clasts may instead be mineralized in deeper waters under low sedimentation rates, a feature discussed by Wongwanich (1990). We presume the Thai limestones were deposited under oxygenated conditions because there is no evidence of low-oxygen depositional features. Wongwanich (1990 p.152) interpreted a fully oxygenated sea floor and used oxygen isotopes to argue a water depth of 175-290 m (Wongwanich 1990, p.162). Interpreted borings are also illustrated by Zhan et al. (2016, Fig. 4E); similar features are also present in the Pa Kae Formation (Fig. 7). However, borings are not usually so irregular, and although they could be clasts, they are very irregular, and may be clasts modified by localized pressure solution, noting that pressure solution is common in some of the Pa Kae Formation and would be expected in limestones subject to tectonic environments.

The fine-grained nature of the limestones of our samples, together with fossil assemblages, is consistent with prior interpretations of deep shelf environments for these facies. The micritic content, with fossils, and some exotic limestone clasts (Fig. 13, see also Wongwanich 1990, p129) indicates input of material into the deep environments, from shallower environments, including deposition of bioclasts of pelagic fossils. Other cases of deep-water stromatolites are not common in the geological record. George (1999) reported deepwater Frasnian stromatolites from the Canning Basin, which are also constructed of only sediment, lacking calcimicrobes and cements (Annette George, personal communication to SK, 2018). George (1999) viewed these stromatolites as forming in conditions of very low sedimentation rate, a feature that may explain the vertical changes of stromatolites in the Pa Kae Formation, illustrated here in Figures 9, 13 and 20. Thus local vertical transition from stromatolitic to non-stromatolitic sediments in our samples of the Pa Kae Formation may be caused by increase in sedimentation that prevented microbial tissue from acting to bind the sediment and create stromatolitic layers. The post Frasnian-Famennian extinction deeper water microbial facies in the Canning Basin are calcimicrobe-constructed (Stephens and Sumner 2003), very different from sediment-based microbialites studied here. Modern deeper shelf stromatolites in the Arabian Gulf are interpreted as related to methane seeps (Himmler et al. 2018) and more complex large deep-water microbial mounds of the Early Jurassic of Argentina were also interpreted as associated with methane seeps (Gomez-Perez 2003). Mesoproterozoic deep-water stromatolites were interpreted by Bartley et al. (2014) as reflecting a combination of stromatolite growth and redox changes. Overall, the closest examples to the Thailand microbialites illustrated here are the Devonian deep shelf Frasnian stromatolites from the Canning Basin and are interpreted here to have been subject to similar controls. Wongwanich (1990, 2017) provided a 3-dimensional block diagram reconstruction of the carbonate ramp system of the Thung Song Group in Thailand, that places the Pa Kae Formation in deeper water.

5.2. Polygonal vein network limestone

Huang et al. (2018), in a paper written in Chinese, interpreted the texture of the carbonate forming the Pagoda Formation as having a gel consistency, leading to the unusual veins. Although Huang et al. (2018) in their English abstract do not explain how the gel may have formed, the notion of gels in carbonate rocks has been applied to mud mounds in the rock record, for example Mississippian Waulsortian mounds (Rodriguez-Martinez 2011) and Frasnian mud mounds (Boulvain 2001). However, such gels are normally invoked to explain why mud mounds had such steeply sloping sides, and are often considered to be microbial, although physical evidence of microbial origin is lacking. Whether a gel consistency is applicable or not to both the Thailand limestones and Pagoda Formation is an area of future research, but a key point of interest regarding the polygonal vein networks is potentially relevant: the presence of raised levels of Fe and Si associated with lower $^{\text{delta13}}$C values in the Pagoda Formation veins (Zhan et al. 2016, Fig. 7) and the Fe-Mn-rich veins in the Pa Kae

Formation (Wongwanich 1990). There is a need to explain how these raised mineral levels occur in the veins. Zhan et al. (2016) interpreted the Pagoda Fm as forming nodules by early recrystallisation of an initially homogenous micritic mass, therefore the accumulation of Fe in the veins is due to early diagenetic separation. This is related to an established interpreted mechanism of early recrystallisation of aragonite muds, developed by Munnecke and Samtleben (1996) to explain limestone-mudstone rhythmic sediments and is a widely applied model. We note that the model reconstruction diagram in Zhan et al. (2016, Fig. 6) has an incomplete caption, so that Fig. 6 of their paper is not fully explained. However, in the Thailand Pa Kae Fm, the veins occur directly between stromatolite columns; this arrangement creates a problem of explaining how an early diagenetic nodule-forming mechanism would work in the Thailand limestones because the stromatolites' structure is very well preserved; how can the limestone reorganize itself to form nodules, moving the Fe into spaces between the nodules, when those nodules are stromatolites that are in a very good state of preservation? Wongwanich (1990, p151) also noted that the Pa Kae limestone is not extensively recrystallized. There is no reason to believe that the stromatolites are nodular limestones formed by migration of carbonate within the rock mass, because they have a sedimentary layering that is reasonably interpreted as having a microbial origin.

Although pressure solution affected Thailand and Pagoda formation limestones, we do not interpret pressure solution as the cause of formation of the polygonal vein networks because of their inconsistency with pressure solution fabrics. Also, thin section evidence presented in this paper does not support an interpretation of pressure solution to concentrate Fe, Mn and Si in veins. The higher levels of clay with Fe-Mn mineral could be explained by import into the limestone along weakness lines, but that explanation would need physical gaps to develop as polygons in the limestone. It is possible instead that the polygons do represent early alteration of the limestone, and later tectonic activity exploited weakness in the limestone to allow permeation of mineral-rich groundwaters into the limestone to form the polygons (Figs 3 & 4). Tectonic activity has certainly played a part in the overall history of the Pa Kae and Tha Manao polygonal networks, because tensional cracks and fibrous calcite infills (Figs. 8D & 16) are evidence of post-lithification extension, as an overprint on pre-existing veins. In the Pagoda Fm, the good preservation of bioclasts and exotic limestone clasts within veins (Fig. 19) is evidence that the micritic sediment of this formation was unstable when it was deposited and may have undergone very early transformation (presumably from an original aragonitic composition) along narrow zones. Despite the interpretation of early diagenetic migration of carbonate to form nodules, invoked by Zhan et al. (2016), figures 18 and 19 of this paper provide evidence of in-place recrystallisation of the lithified limestone, where it is ***replaced*** by opaque minerals, and that is not the same as the model developed by Munnecke and Samtleben (1996) for early carbonate migration in clay-rich limestones. However, the cause of narrow zone alteration remains problematic, unlikely to be burrows, as Zhan et al. (2016) also argued. In the Thai limestones, the possibility of tectonic fracturing of a delicate rock fabric in an area close to major tectonic belts is likely because of the veins and clear movement in the fractures. Nevertheless, the tectonic fractures must be later features, and in any case it is difficult to apply the idea of tectonic fracturing as a formation process of the Pagoda Fm network because it lacks fractures and lacks a regional tectonic stress regime in the stable craton of south China (which, if it had existed, would be expected to fracture the formations below and above the Pagoda Formation, noting that they are not fractured). If the limestones had a gel-like consistency and were under tension, then the possibility of weakening along narrow zones might have promoted diagenetic change in those zones, with import of minerals via diagenetic fluids, in preference to wholesale alteration of the rock. We stress, however, that this explanation is made tentatively because it is difficult to understand how minerals could permeate the *ca* 30 m thickness of polygonal limestone in the Pa Kae Formation and the variable thickness of the Pagoda Fm (up to 90 m, Zhan et al. 2016, Table 1).

5.3 Time-specific facies

The abundance of polygonal network structure within the Katian (Late Ordovician) limestones of the Pagoda Fm across the south China region and the Sandbian-Katian Thailand limestones of Pa Kae and Tha Manao Formations is extraordinary. Polygonal limestones also occur in the Linwe Formation of southern Shan state in eastern Myanmar (Bender 1983, Fig. 37b), also part of the Sibumasu Terrane (Khin Zaw et al. 2017), but the age of the Linwe Formation is attributed differently by authors. Myint Lwin Thein (1973, page 149) reviewed earlier work that attributed the Linwe Formation to either Upper Ordovician or Early Silurian. Udchachon et al. (2017, Fig. 8) indicated a Katian age, thus correlatable with the Pa Kae Formation, but Bender (1983) and Cai et al. (2017) state that the Linwe Formation is Lower Silurian. This variety of opinion has parallels in determining the age of the Tha Manao Formation in Thailand discussed above, and demonstrate that more research is needed to fully constrain the ages of these facies. Despite the issues regarding age precision, the concept of a time-specific facies to account for these unusual polygonal limestones is favoured by some authors (e.g. Zhan et al. 2016; Burrett and Chaodumrong 2017, p19) to try to account for the conditions under which polygonal networks in limestones could form. The global Guttenberg Isotope of Carbon Excursion (GICE) is present within the Pagoda Formation and in Malaysia (Bergström et al. 2009a, 2009b, 2010); and Munnecke et al. (2011) demonstrated several carbon isotope excursions in the Katian. Overall, carbon isotope results show that the region was influenced by the (unknown) oceanographic controls on the isotopes, yet the unusual polygonal limestone facies in Thailand, Myanmar and China is geographically limited in the Sibumasu and South China blocks. We draw attention to the problem that a time-specific facies is a reflection of some change in physical and chemical conditions on Earth's surface that presumably has a stimulus, but that stimulus has not been identified, but implies a non-uniformitarian origin. The underlying danger of invoking a time-specific facies is because it seems to require special processes to interpret the processes of formation of facies. Nevertheless, even if there was a non-uniformitarian time-specific process that controlled formation of polygonal networks in the late Ordovician limestones in Thailand, south China and Myanmar, there is still a need to explain the process, which Zhan et al. (2016) attempt, using arguments which are actually uniformitarian! In our opinion, a non-uniformitarian approach is neither needed nor appropriate to investigate how these facies formed. Instead, an explanation that addresses the physical properties and changes in the sediment is more likely to lead to a satisfactory understanding. We make a brief comparison with other unusual time-restricted sedimentary units in the geological record:

1) calcimicrobe framestone that developed across South China directly after the end-Permian extinction is composed of a structure that doesn't occur anywhere else in the rock record (Kershaw et al. 2018), and is also almost entirely a place-specific facies (Kershaw, 2015), because the calcimicrobe framestone is so far known in only one other location, recently discovered in Iran (Maaleki-Moghadam et al. 2019).

2) Another example, that has aspects in common with the Thai Ordovician limestones, is the Ammonitico Rosso red nodular limestone facies which was widespread in the Tethyan

region from Callovian (late Middle Jurassic) times (e.g. Kandemir and Yilmaz 2009) but disappeared from the rock record at the end of the Berriasian Stage (lowermost Cretaceous) (Cecca et al. 1992). Jenkyns (1974) noted the condensed nature of the Ammonitico Rosso and drew attention to the fact that fossils do not cross the dark veins between micrite nodules, as we have illustrated in Fig. 5 for the Pa Kae Formation and Zhan et al. (2016) recorded for the Pagoda Formation. Jenkyns (1974) further considered that the nodules of the Ammonitico Rosso rock were quite possibly discrete objects on the sea floor, thus formed very early in the history of the rock, which is also a possible explanation for the large dark-coloured clasts in the Pa Kae Formation (Figs. 7, 8, 9, 12, 13, 14 and the interpretations by Wongwanich 1990). The Ammonitico Rosso Facies is widely attributed to having formed in pelagic environments (both basins and tectonic highs) in active tectonic settings (e.g. Coimbra et al. 2009), but conditions appropriate for its formation ceased to operate from Early Cretaceous times, and it has not reappeared in the rock record anywhere in the world. The middle Jurassic appearance and Early Cretaceous disappearance of the Ammonitico Rosso facies is therefore a process control.

3) the "*Orthoceras*" limestone of Lower Ordovician age in the Baltic region is well-exposed on Öland island and regarded as a cool water deposit (Stouge 2004). It is a nodular limestone which in transverse section shows areas of elongate veins that partly resemble the Thai limestones and Pagoda Formation, noting that it is older.

Literature search for Late Ordovician facies that resemble either the Thailand limestones studied in this paper, or the Pagoda Formation or Linwe Formation, have not discovered any published descriptions of similar facies in the Sandbian-Katian time globally, despite copious work, particularly in Scandinavia (e.g. Cherns and Wheeley 2007) and North America (e.g. Frey, 1995) (Fig. 1). Thus for the Late Ordovician limestones studied here, it would be more appropriate for the concept of "time-specific facies" be replaced by "unusual process-specific facies" that is an acknowledgement of uniformitarianism but also of processes that are not fully understood.

5.4. Palaeogeography and oceanography

A final consideration is the palaeogeographic position of Sibumasu Terrane during the Late Ordovician, and also relevant is the latitude of the South China block, and its proximity to Sibumasu. Continental reconstruction before the time of Pangaea is problematic, and numerous reconstructions of continental positions place these ancient continents in different locations. In Fig. 1 we used that of Scotese (2015) which places Sibumasu in northern mid-latitudes, and south China north of the equator in low latitude. Zhan et al. (2016) used a reconstruction that places south China approximately on the equator, which is important for their oceanographic interpretation of equatorial doldrums with hurricane-free zones for the deposition of the Pagoda Formation in reduced energy settings. In a survey of Palaeozoic nautiloids, Histon (2012) used a palaeogeographic latitude of 30 degrees south for her description of the Pagoda Formation. Han et al. (2015) placed south China at 19.5 degrees south of the equator, making the key point that it was in the tropics during the Late Ordovician. The problem of determining the true location of these continental masses in the Late Ordovician therefore has a critical impact on the applicability of models to explain their sedimentology, noting that the Scotese (2015) reconstruction used in our Fig. 1 places south China at about 20 degrees north, also within the tropics. Nevertheless, we agree with Wongwanich (1990) for the Pa Kae Formation, and with Zhan et al. (2016) and Zhang et al. (2018) for the Pagoda Formation, that these late Ordovician limestones are deep shelf deposits, and are best described overall as having a nodular character, with early diagenesis as a major aspect of their formation.

Katian limestones in some locations have been regarded as having been deposited during conditions of changed climate conditions. A well-known example is the Katian-age Boda Limestone in Sweden, that gave its name to the Boda Event (Fortey and Cocks 2005; Cherns and Wheeley 2007). Fortey and Cocks (2005) interpreted the Boda Event as a warm water phase, but Cherns and Wheeley (2007) reinterpreted that as a cool water phase. A problem of these contrasting interpretations is that they are based on different lines of evidence; Fortey and Cocks (2005) used fossil assemblages, while Cherns and Wheeley (2007) used sedimentary signals for their model. The Boda Event is present in limestones in low-latitude continents of Baltica, Avalonia and Laurentia (Cherns and Wheeley 2007; Fig. 1). Wongwanich (1990, pages 156-160) argued for a cool water setting for the Pa Kae Formation, that lies within the Boda Event. Jin et al. (2018) interpreted cool water for the Pagoda Formation. Apart from the contrasting interpretations of warm vs cool conditions, an interesting problem that emerges from these interpretations is to know the sea-surface temperatures at low-latitude locations during this time, in the Ordovician world of raised $C0_2$, noting that determination of tropical cooling at the Last Glacial Maximum, only *ca*. 20

ky, has resulted in a variety of estimates (compare estimates of *ca* 2-6°C cooling in the tropical Atlantic and 8°C cooling in tropical Pacific Oceans by Trend-Staid and Prell 2002; *ca* 6°C overall tropical cooling by Schneider von Deimling et al. 2006; *ca* 4.5°C overall tropical cooling by Peltier and Solheim 2004; 4-7°C tropical cooling of the air over landmasses, 26°C cooling over the Laurentide Ice Sheet and overall global cooling of 4.3°C by Bush and Philander 1999; *ca* 4°C global cooling by Annan and Hargreaves 2013). A further key issue is stratigraphy; the Thailand polygonal limestones range from lowermost Katian to near the end of the Katian, while the Pagoda Limestone is within upper Sanbian to Lower Katian. The Boda Event is middle to Upper Katian, and thus post-dates the Pagoda Limestone. Consequently the climatic changes in these later pre-Hirnantian rocks cannot currently be matched to the stratigraphic ranges of either the Thailand polygonal limestones or the Pagoda Formation, so there is no real basis for an explanation of climate changes to have influenced their formation.

Conclusions

1. Late Ordovician Pa Kae limestones of peninsula Thailand contain microbialites of agglutinated stromatolites (laminated) and leiolites (vaguely structured, neither laminated nor clotted); they are made of micritic sediment rich in intraclasts and bioclasts but lack cements and calcimicrobes, so are interpreted here as agglutinated microbialites. Literature reports of thrombolites and oncolites are unconfirmed.
2. Tha Manao Formation of western Thailand is also composed of micritic limestone containing bioclasts, but lacks microbialites.
3. The interpretation of deep shelf setting of both formations, made by other authors, is consistent with observations in field, polished samples and thin sections in this study. The microbialites of Pa Kae Formation likely grew under conditions of very low sedimentation rates.
4. The presence of unusual polygon vein networks in both Tha Manao and Pa Kae limestones is attributed to early diagenetic change, in comparison with other unusual vein-bearing limestones, in particular the Pagoda Formation of approximately the same age in south China. Our results are consistent with previous interpretations that these

unusual structures constitute a form of nodular limestone. The strong contrast in composition and geochemistry between the vein infills and the limestone between veins is interpreted here as evidence of early partial lithification, followed by fracturing of the limestone, succeeded by migration of mineral-precipitating fluids through fractures. The stratigraphic limitation of the polygonal limestones may relate to gel-like consistency of these limestones when deposited, that future investigations may be able to identify.

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Figure captions

Fig. 1 A. Map of Thailand showing location of study sites (see Table 1 for detailed coordinates) and terranes in the southeast Asia region; the study area is located within Sibumasu Terrane, added from Ridd (2011, Fig. 3.1). **B.** Palaeogeographic reconstruction of location of Sibumasu during the Late Ordovician Period, redrawn from Scotese (2015, map for 460 Ma, the nearest map to the age of the Late Ordovician in his reconstructions). Note that other reconstructions provide some differences in latitude and orientation of Sibumasu and South China plates, discussed in the text as may be expected in reconstructions of Lower Palaeozoic continent positions

Fig. 2 Summary log of Late Ordovician to Early Silurian, based on peninsula Thailand, compiled from Wongwanich (1990. Fig. 3.13) and Burrett et al. (2016, Fig. 2). The Pa Kae Formation that contains the stromatolites and polygonal vein networks illustrated in this paper ranges from latest Sandbian to latest Katian, and is approximately co-eval with the Tha Manao Formation, discussed in the text. The Guttenberg Isotope of Carbon Excursion (GICE) approximate stratigraphic distribution is indicated, based on Bergström et al. (2009a, Fig. 1)

Fig. 3 Typical appearance of Late Ordovician (Katian) Pa Kae Formation limestone, shown here in vertical outcrop section, with polygonal network of harder iron-rich dark brown material enclosing red-brown micrite, the latter in some parts forms columnar shapes similar to columnar stromatolites. Inset shows weather-protected outcrop. Hin Sarai I site, Satun Geopark, peninsula Thailand

Fig. 4 Variations of polygonal network of dark-brown iron-rich material in outcrop of Pa Kae Formation limestone, Hin Sarai I site, Satun Geopark, peninsula Thailand. **A.** Vertical section showing network comprises major vertical sheets with subsidiary irregular sheets that are largely horizontally orientated. **B & C.** Vertical section detail of irregular network sheets. **D.** Transverse section showing polygonal structure of network. **E.** Loose block showing transverse section in lower part of photo and vertical section in upper part, revealing the three-dimensional appearance of the polygonal network (way up of this block unknown). Throughout all these images, the red-brown limestone within the polygonal network is biomicrite. A-D: smallest divisions in white scale are mm

Fig. 5 Nautiloids in the Pa Kae Formation limestone, showing variable relationship with the dark-brown polygonal network, all photos from the Satun Geopark, peninsula Thailand. **A.** Nautiloid lies entirely within the micritic limestone, not touched by the network sheets (Tha Rae Rocks site). **B.** Cross section of plane-spiral nautiloid completely enclosed within polygonal network material. **C.** Transverse section of orthoconic nautiloid showing alteration of its margin with network veins in direct contact with altered portion (B & C from Hin Sarai I site). **D.** Orthoconic nautiloid from a display in Satun Geopark reception building, showing nautiloid completely enclosed in a thick layer of network material. **E.** Nautiloid truncated (yellow arrow) against network veins (Tha Rae Rocks site). **F.** Curved nautiloid completely enclosed by network material in a loose block at Khao Daeng Mountain, in Satun Geopark (photo by Ms Thapanee Pengtha, Department of Mineral Resources, Thailand)

Fig. 6 Details of stromatolitic columnar limestone and polygonal network, Hin Sarai I site. **A & B.** Vertical section outcrop views of columns with domal laminations revealed in thin sections as stromatolites (Fig. 7). **C.** Polished vertical section of sample of stromatolites from nearby outcrop showing domal structure separated by polygonal network material. **D & E.** Transverse section views of outcrop and a polished sample collected from nearby outcrop

Fig. 7 Vertical thin section views of Pa Kae Formation stromatolites from outcrop near to Hin Sarai I site. **A.** Whole thin section photo showing parts of two domes and intervening network material; note the somewhat irregular nature of the network material. The well-defined laminated domes in the lower part pass upward into very faintly laminated micrite at the top that is more reminiscent of leiolite texture. **B.** Enlargement of area of yellow box in A, showing laminated micrite of the stromatolites, rich in bioclasts plus intraclasts. **C.** Detail of stromatolite, where layers are faintly shown, and reveal the dense accumulation of bioclasts in the micrite. The stromatolites do not contain any identifiable microbes and are interpreted as agglutinated stromatolites, whereby sediment is bound by organic matter that left no remains. **D.** Detail of network material, comprising opaque matter of presumed Fe-Mn mineral (Wongwanich 1990). Amongst the dark matter are partially rounded fragments of biomicrite; note the small white zones lateral to the biomicrite fragments, which are tension fractures, showing separation of the biomicrite from the Fe-Mn veins and filled with calcite, shown in detail in Fig. 8D. **E & F.** More details of network material between domes of stromatolite, showing a chaotic mix of dark matter, bioclasts and partially rounded fragments of biomicrite

Fig. 8 Transverse thin section views of Pa Kae Formation stromatolites from outcrop near to Hin Sarai I site. **A.** Whole thin section photo showing patchy biomicrite of parts of two stromatolite columns in transverse section, separated by dark matter of the polygonal network. **B.** Detail of TS of stromatolite from another thin section, showing biomicrite containing rounded intraclasts of micrite. **C & D.** Details of polygon network sheets, from two other thin sections showing the network comprises a mixture of biomicrite and tracers of dark matter, plus cement. D shows the cement areas have orientated crystals (yellow arrows) interpreted as growth fibres in a tensional tectonic setting, discussed in the text

Fig. 9 Vertical thin section views of Pa Kae Formation stromatolites from outcrop near to Hin Sarai I site. **A.** Whole thin section photo of domal stromatolite showing defined stromatolite irregular top surface, overlain by unlaminated biomicrite. At the bottom of the photo, the micrite is poorly laminated; a network vein is present on the left-hand side of the photo, adjacent to the stromatolite. Irregular subhorizontal lines of dark matter are interpreted as stylolites. The central part of the photo, with defined laminated structure, is lighter coloured than unlaminated and poorly laminated upper and lower parts, which may be related to reduced sedimentation rate in the stromatolite; see text for discussion. **B - D.** Detail of top surface of stromatolite showing its top is not sharp, but instead passes up into non-laminated micrite without a break

Fig. 10 Vertical section of polished sample and thin sections of biomicrite at Hin Khao Noi site. Material illustrated comes from layers of Pa Kae Formation, which is normally a red-brown colour, but this site preserved the rock in dark grey, for reasons unknown. **A.** Polished sample of biomicrite with lower part containing subcircular structures and the upper part appears concretionary. **B.** Thin section from another sample showing a subcircular structure, composed of biomicrite. **C.** Detail from area indicated in A, but from an adjacent thin section, showing the subcircular structure is fundamentally the same as the sediment outside it. **D.** Detail from area indicated in A, but from an adjacent thin section, showing the biomicrite interlayered with clay-rich micrite, forming a concretionary area

Fig. 11 Field views of vertical sections of Pa Kae Formation limestones at Ao Noon Bay, Satun Geopark, peninsula Thailand. The limestones dip at about 30 deg, but reorientated to horizontal in these photographs. **A.** Limestone shows variation of occurrence of network polygons, with the lower two thirds of the picture having little network structure, while the upper third has a dense network. The sharp contact between these two areas is interpreted as due to bedding plane slip during folding. Locations of Figs. 12 and 13 are indicated by red squares. **B.** Enlargement of polygonal network showing oblique orientation, interpreted as deformation during folding, indicating the polygonal network formed prior to folding, discussed in the text

Fig. 12 A & B. Vertical section of polished sample (A) and thin section (B) views of lower part of outcrop in Fig. 11, showing non-stromatolitic biomicrite, riven with stylolites (dark irregular lines in both photographs) presumed to have developed during burial and deformation of the rock. **C & D.** Enlargements of a different thin section from B, showing details of non-microbial micrite, rich in thin bioclasts

Fig. 13 Vertical polished sample and thin section views of upper part of outcrop in Fig. 11, showing stromatolitic biomicrite. **A & B.** Polished sample and general view of thin section; lower part of sample has two stromatolite domes, upper part has one, separated by a non-stromatolitic layer. **C.** Detail of two stromatolite domes and network polygon structure that has rounded clasts of biomicrite embedded in the dark matter. Note one grey-coloured exotic clast (yellow arrow). **D.** Detail of stromatolite layers composed of micrite, intraclasts and bioclasts. **E.** Detail of area between the lower two stromatolites and upper stromatolite showing sediment is made of biomicrite with intraclasts plus one grey-coloured exotic clast (yellow arrow). In lower part of photo is an irregular horizon possibly due to erosion of stromatolite top

Fig. 14 Vertical section views of Pa Kae Formation biomicrite from outcrop near Hin Sarai I site, with tectonic breakage and post-lithification movement. **A.** Biomicrite is poorly laminated, and is interpreted here as leilolite. Yellow arrow highlights a patch rich in bioclasts adjacent to leiolite mass with sharp contact. Note intraclasts with opaque rims; Wongwanich (1990) interpreted these to be sea-floor clasts that acquired an opaque rim; it might have parallels in the Ammonitico Rosso as discussed in the text. Separation within the rock is shown by calcite-filled tension cracks (green arrows). **B.** Detail of broken micrite with laminated clay-rich zones between pieces of micrite

Fig. 15 Variations of likely Late Ordovician limestones at Ban Tha Kradan site near Kanchanaburi, in NW Thailand. **A.** Bedded fossiliferous micrites in lower part of section (Unit T.10 of Meesook, 2013). (Thick white lines are heavy machinery scratches on the rock when the site was developed). **B.** Vertical thin section of sheared micrites in the middle of the section below the polygonal limestone. **C.** Polygonal vein network limestone in an exposure of the Tha Manao Formation in three dimensions, showing vertical section on left and transverse section on right, illustrating the polygon network (Units T16-18 of Meesook, 2013). **D.** Vertical section of limestone showing polygon network comprises vertical sheets. **E.** Detail of transverse section of polygonal vein network in micritic limestone

Fig. 16 Details of polygonal vein networks in Tha Manao Formation limestone at Ban Tha Kradan site near Kanchanaburi, in NW Thailand. **A.** Field view of vertical section showing vertical sheets of polygon network (this photo is an enlargement of Fig. 16D. **B.** VS of thin section (stained on right side with ARS and K ferricyanide) showing narrow zones of fine layers of polygon network. **C & D.** Details of biomicrite limestone and polygon network structure. In Figs. B – D, there is no evidence of microbial structure. **E.** Detail of another thin section showing intermixed biomicrite and dark layers. Cement fibres in tension fractures within the polygon network are highlighted by red arrows

Fig. 17 A – C. Pagoda Fm, Katian of S. China, polished decorative tiles from the entrance hall of Datong Buddhist temple site, Shanxi Province, northern China; origin and stratigraphic level of the illustrated samples are unknown. These are all transverse sections. The photos show the polygonal network has some resemblance to the co-eval micrites in Thailand, but thin sections in Figs. 18 & 19 show there are notable differences from Pa Kae Fm limestones

Fig. 18 Transverse thin section details of Pagoda Fm limestone from a decorative tile acquired by SK in 1996 in southern Sichuan Province; its origin and horizon are unknown. **A.** Biomicrite with linear dark zones that are sharp-bounded in some places and diffuse in others (noted by Zhan et al. 2016). **B.** Detail of yellow box in A, showing an area of contact between the light grey biomicrite and darker polygon vein network material. The lower left half of this photo shows the grey limestone present within the vein has diffuse contact with surrounding dark material and is presented here as evidence that the grey limestone was recrystallised to the dark material, yet the enclosed fossil fragments were not recrystallised, discussed in the text. In the centre of the photo, within the dark material, the circular arrangement of shells is evidence of soft-sediment burrowing. **C.** Transverse section detail of another thin section showing an enlarged view of the diffuse contact between grey micrite and dark material, with preservation of fossil shells

Fig. 19 Vertical thin section details of Pagoda Fm limestone, from the same sample as in Fig. 18. **A.** shows zones of alteration into dark material. **B.** Within that zone an exotic packstone clast has been less affected by alteration processes than the grey micrite and was presumably more lithified. **C.** Another thin section showing three more exotic clasts (red arrows) one within the grey micrite and the other two within the dark alteration zones; the latter are not altered in contrast to the biomicrite. **D & E.** Vertical section details of another thin section of Pagoda Fm limestone showing a prominent packstone exotic clast entirely within the dark material of the alteration zones in polygonal network. The exotic clast is almost unaltered in contrast to pervasive recrystallisation of the grey biomicrite

Fig. 20 Vertical section summary reconstruction of Pa Kae Formation facies, derived from field, hand specimen and thin section studies in this paper. **1.** Layered biomicrite lacking microbial structures. **2.** Stromatolitic domes of agglutinated biomicrite with intraclasts. **3.** Termination of stromatolite dome with curved top. **4.** Leiolite dome, composed of in-situ lithified (or at least hardened) biomicrite, buried in non-microbial biomicrite **(5)**. **6.** Post-depositional veins, as part of the polygonal vein network. The sequence 1-4 can be explained by variations in sedimentation rate, so that rate is higher in 1, lower in 2 to allow microbial biofilms to agglutinate the sediment. Sedimentation rate is interpreted to have increased briefly at 3 to terminate stromatolite growth, then fell to very low levels in 4 to allow growth of leiolite dome without laminations. Sedimentation rate then may have increased sharply in 5, or perhaps after a hiatus, to bury the leiolite dome. Finally, post-depositional veins formed in 6, that are possibly related to inherent weaknesses in the limestone, discussed in the text

Table 1 List of sites with geographic coordinates and illustrations in this paper

Site name and illustration	**Coordinates**
Kanchanaburi area: Ban Tha Kradan, Figs. 15 & 16	N 14˚27’9.68”; E 99˚7’48.67”

Satun Geopark office (museum), Fig. 5D	N 7˚5’26.25”; E 99˚46’5.81”
Satun Geopark: Hin Sarai I, Figs. 3, 4, 5, 6, 7, 8, 9, 14	N 6˚58’41.41”; E 99˚46’54.16”
Satun Geopark: Hin Sarai II, Fig. 13	N 6˚58’36.69”; E 99˚46’31.68”
Satun Geopark: Hin Khao Noi, Fig. 10	N 6˚58’30.98”; E 99˚46’19.75”
Satun Geopark: Ao Noon, sea cliff, Figs. 11, 12	N 6˚56’8.81”; E 99˚45’46.67”
Satun Geopark: Tha Rae Rocks, Figs. 5A	N 6˚56’31.44”; E 99˚46’35.64”
Satun Geopark: Khao Deang Mountain, Fig. 5F	N 6˚54’34.89”; E 99˚46’41.07”