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The occurrence of *Paleodictyon* in shallow-marine deposits of the Upper Cretaceous Mikasa Formation, Hokkaido Island, northern Japan: Implications for spatiotemporal variation of the *Nereites* ichnofacies

Kazuki Kikuchi

Department of Geology and Mineralogy, Graduate School of Science, Kyoto University, Kitashirakawaoiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan

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ABSTRACT

The trace fossil *Paleodictyon* is characterized by a regular hexagonal network and has been widely considered to be a characteristic of the *Nereites* ichnofacies, indicative of a deep-marine environment. Recently, however, some researchers have reported *Paleodictyon* occurrences in relatively shallow settings, leading to suggestions that the habitat of these burrowers was not restricted to deep-marine environments. A new occurrence of this trace fossil is presented in this study from a shallow-marine succession of Upper Cretaceous deposits in northern Japan. Paleobathymetric and temporal variations in the habitat range of shallow-marine examples of this ichnotaxon are also discussed based on a compilation of previous works. The new *Paleodictyon* specimens discussed here are from the lowermost part of the Mikasa Formation within the Yezo Group, interpreted as a deposit representing the lower shoreface through to the inner shelf transitional zone. This paper presents the first record of a shallow-marine *Paleodictyon* from the Pacific region; combined with data from previous studies, records suggest that shallow-marine *Paleodictyon* are observable from Paleozoic-to-Mesozoic shelf deposits, although no reliable records of their occurrences have so far been reported from the Cenozoic. Increasing bioturbation intensity and predation pressure during the Mesozoic and Cenozoic may have been significant factors preventing the preservation of this ichnogenus in post-Mesozoic shallow-marine settings. The *Paleodictyon*-bearing interval of the Mikasa Formation also preserves evidence for low-intensity bioturbation, which may account for preservation of the traces in this case.

1. Introduction

The trace fossil *Paleodictyon* Meneghini in Murchison, 1850 is a characteristic member of the *Nereites* ichnofacies (Seilacher, 1967) that is characterized by a regular hexagonal network on the base of sandstone beds. These trace fossils have been regarded as indicators of deep-marine oligotrophic environments (e.g. Seilacher, 1977; Miller III, 1991; Wetzel and Uchman, 1998), and are common in deep-marine turbidite successions (e.g. Seilacher, 1977; Uchman, 1995; Uchman et al., 2004; Heard and Pickering, 2008; Cummings and Hodgson, 2011; Phillips et al., 2011; Callow et al., 2013). A number of structures similar to *Paleodictyon* have also been described from the modern seafloor below 3000 m water-depth (Rona and Merrill, 1978; Ekdale, 1980; Gaillard, 1991; Rona et al., 2009).

The process of graphoglyptid preservation (Seilacher, 1977) including *Paleodictyon* is thought to take place as follows: (1) Burrows were formed primarily in fine-grained deposits near to the sea-floor; (2) erosional processes, including turbidity currents, eroded this surface to expose the burrows, and; (3) burrows were cast by subsequent deposition of sand (Seilacher, 1977). Although Seilacher (1977) argued that the formation of graphoglyptids took place in deep-marine turbidite successions, inner-to-outer shelf settings can also potentially satisfy these conditions as they can comprise alternating beds of storm sandstones and fair weather mudstones.

A number of researchers have reported occurrences of *Paleodictyon* from deposits shallower than the continental slope (see Fürsich et al., 2007 and references therein), even though these trace fossils have most often been considered characteristic ichnofossils of deep-sea environments (Seilacher, 1977). Fürsich et al. (2007) noted the presence of *Paleodictyon* in Triassic and Jurassic shallow-marine deposits from Iran, and these traces have also been reported from similar deposits in coastal areas of the Atlantic and Indian Ocean (see Fürsich et al., 2007). No occurrences of shallow-marine *Paleodictyon* have so far been reported from the Pacific region.

In spite of reported occurrences from shallow-marine settings, *Paleodictyon* is considered characteristic of deep-marine environments, probably because occurrences in the former are significantly rarer than in the latter. There are two main explanations for the rare occurrence of

E-mail address: kikuchi@kueps.kyoto-u.ac.jp.

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these fossils in shallow-marine settings; non-preservation of *Paleodictyon* and/or non-presence of the producer. Fürsich et al. (2007) explained the infrequent occurrence of *Paleodictyon* in shallow-marine deposits based on a lower preservation potential via observations and suggested that these burrowers did not just live in deep-marine environments; thus, frequent erosion of the seafloor by storm- or wave-generated flows could have impaired the preservation of this ichnotaxon. At the same time, bioturbation intensity might also have prevented the preservation of graphoglyptids, including *Paleodictyon* (Seilacher, 1977, 2007), while changes in bioturbation intensity due to evolutionary events might also have affected the temporal and/or paleobathymetric range of *Paleodictyon* in shallow-marine settings. The abundance of this ichnofossil in deep-marine environments may therefore simply reflect the habitat preferences of these burrowers even though they are able to tolerate shallow-marine environments.

Documenting the geographic and temporal distribution of *Paloedictyon* is a key to understanding the reasons that underlie the rare occurrences of this ichnotaxon in shallow-marine environments. As examples of physical disturbance, such as erosion by storm waves, appear to be independent of geographic or temporal situation, the distribution of *Paleodictyon* can be expected to be uniform if physical disturbance lead to a decrease in preservation potential in shallow-marine settings. In contrast, if geographic or temporal bias in distribution can be detected, then bioturbation activities and/or habitat preferences can be considered as causes for rare shallow-marine *Paleodictyon* occurrences.

New occurrences of *Paleodictyon* are presented in this paper from shallow-marine deposits of the Upper Cretaceous Mikasa Formation within the Yezo Group on Hokkaido Island, northern Japan. This paper therefore describes the first records of shallow-marine *Paleodictyon* from the Pacific region; on the basis of this discovery, the geographic, temporal and paleobathymetric distribution of this ichnotaxon are further investigated in order to understand the possible factors that underlie the rare occurrences of these fossils in shallow-marine environments. Additional data on previous research other than that discussed by Fürsich et al. (2007) are also presented in this paper. The aims of this study were therefore to (1): describe *Paleodictyon* from the Mikasa Formation and its occurrence interval; (2) illustrate the paleobathymetric and temporal distribution of shallow-marine *Paleodictyon* over geological time, and; (3) discuss the relationship between shallow-marine occurrences of *Paleodictyon* and paleoecological changes over geological time.

2. Geological setting

2.1. The Yezo Group and the Mikasa Formation

The Aptian-to-Maastrichtian Yezo Group outcrops across central Hokkaido in northern Japan (Fig. 1), conformably overlies the Upper Jurassic-to-Barremian Sorachi Group, and is capped by the Middle-to-Upper Eocene Ishikari Group and the Upper Eocene-to-Lower Oligocene Poronai Group (Takashima et al., 2004; Fig. 2). The type section of the Yezo Group ranges between 8000 m and 10,000 m in thickness within the Oyubari area (Takashima et al., 2004), and has been interpreted as a sequence of deposits that filled a N-S trending forearc basin that was elongated from the southern part of Sakhalin Island to the area of northeastern Tohoku (Ando, 2003, 2005). The Yezo Group mainly comprises continental slope facies, especially mudstone and turbidite sandstone beds, while sandstone-dominated shallow-marine facies are mainly exposed in the western area (Takashima et al., 2004). This group has been subdivided into nine formations on the basis of lithofacies differences (Takashima et al., 2004; Fig. 2).

The Mikasa Formation outcrops within the Mikasa area, in the central region of Yezo Group distribution (Fig. 1). This sequence is contemporaneous with the Saku Formation which is exposed in the eastern area, and conformably overlies the Hikagenosawa Formation (Fig. 2). The Mikasa Formation is characterized by sandstone-dominated facies that include a series of beds that exhibit hummocky and trough cross-stratification with intercalated intensely bioturbated sandy mudstones (Ando, 1990a, 1990b; Takashima et al., 2004). Two or three coarsening-upward successions are observable within this succession which can be interpreted as third-order depositional sequences (Ando, 1990a, 1990b, 1997). The depositional environment of the Mikasa Formation varies from outer shelf in the lower part of the interval to river channel towards the top (Ando, 1990a). Ammonoid and inoceramid fossil zones indicate that this formation ranges in age between the Cenomanian and Turonian (Ando, 1990a; Takashima et al., 2004).

2.2. Lithofacies of the Paleodictyon-bearing interval

The ichnogenus *Paleodictyon* occurs within the lower part of the Mikasa Formation which outcrops along the Ponbetsu River (Fig. 1). This interval is composed of alternating sandstone and mudstone beds (Fig. 3A); units of the former within this sequence are fine-grained and range in thickness between 2 cm and 30 cm. The surfaces of these beds are sharp and planar, the upper surfaces wavy. Normal or inverse grading cannot be seen. These sandstone beds commonly exhibit parallel and wave ripple laminations as well as hummocky cross-stratification (Figs. 3, 4A). The ichnospecies *Phycosiphon incertum* is observable on the bottom surfaces of some sandstone beds in addition to *Paleodictyon*, and these intercalated mudstone beds are between 1 cm and 10 cm in thickness. Parallel laminations are also rarely seen in these mudstone beds.

The succession that includes *Paleodictyon* transitions from thin-to-thick upwards; the lowermost part of this interval, which overlies the boundary between the Hikagenosawa and the Mikasa formations, is composed of alternating beds of thick-bedded hummocky cross-stratified sandstone and thin-bedded siltstone. These sandstone beds thin upwards in the middle part of the succession, and the uppermost part of the *Paleodictyon*-bearing interval is conformably overlain by thick-bedded hummocky cross-stratified sandstone beds (Fig. 1B).

This interval within the Mikasa Formation is interpreted as deposits of lower shoreface-to-offshore transitional environments (Clifton, 2006; Plint, 2010). The wave ripple lamination and hummocky cross-stratification within the sandstone beds indicate that this interval was deposited in a shallow-marine environment, under both fair-weather and storm wave-influenced conditions. The parallel lamination associated with hummocky cross-stratification and/or wave ripple lamination can be interpreted as having been generated during the early stage of sediment settling around the peak of the storm (Plint, 2010), while sedimentary structures that indicate a unidirectional flow origin, like current ripple lamination, appear to be absent. These sedimentological characteristics imply that the deposits within this interval are indicative of deposition within a lower shoreface-to-offshore transitional environment (Clifton, 2006; Plint, 2010). It is noteworthy that Ando (1990a) interpreted the hummocky cross-stratified sandstone which overlies this interval as an inner shelf-to-lower shoreface deposit. This depositional facies transition supports the interpretation that the interval containing *Paleodictyon* is shallow-marine in origin.

3. Ichnotaxonomy of Mikasa *Paleodictyon*

Three specimens of *Paleodictyon* (specimens A, B, and C) from the Mikasa Formation were investigated in this study (Fig. 4B–D). *Paleodictyon* is an ichnofossil that comprises three dimensional networks that are themselves composed of regular-to-irregular hexagonal meshes and vertical outlets (Uchman, 1995). These structures are string-like sandstone hypolief; the morphology of this ichnotaxon is generally expressed in terms of the maximum diagonal length of these hexagonal meshes (mesh size) and the mean width of the string-like positive hyporelief (string diameter) (Uchman, 1995). The specimens of *Paleodictyon* presented in this study were found on the bases of two