

Characteristic Trace Fossils from Shoreface to Offshore Environments of an Oligocene Succession, Northeastern Taiwan

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ABSTRACT

Well-exposed Oligocene strata of the Hsuehshan Range in Taiwan were deposited in the Hsuehshan Trough along the eastern Eurasia continental margin. The Hsuehshan Trough was a restricted epeiric basin confined by a series of horsts. The Oligocene succession records a deepening-upward to shallowing-upward sequence of deltaic deposystems associated with fluvial and shallow marine environments. These environments ranged from wave-dominated delta-plain through storm-dominated delta-slope to regressive tide-dominated delta-front environments. The fining-upward to coarsening-upward sequence can be divided into five lithofacies and five ichnocoenoses. Ichnocoenoses characterized by *Ophiomorpha*, *Cylindrichnus*, *Teichichnus*, *Scolicia*, and *Zoophycos* were defined on the basis of assemblages, degree of bioturbation, diversity, and abundance.

The Lower Oligocene deposits exhibit a fining-upward trend and upward increases trend in bioturbation and abundance of deposit-feeding structures. Accompanying these changes is a transition from *Ophiomorpha*, *Cylindrichnus*, *Teichichnus*, *Scolicia* to *Zoophycos* ichnocoenoses, which also suggests a transgressive system from delta-plain to prodelta-slope environment. The sequential variation in lithofacies and ichnofossil assemblages coincides with changes in Early Oligocene sea level. The Upper Oligocene deposits show a shallowing-upward succession that suggests an evolution from a storm-dominated prodelta slope to a tide-dominated delta plain. The ichnofossil assemblages show a transition from *Scolicia*, *Teichichnus* to *Ophiomorpha* ichnocoenoses that are suggestive of regressive systems. The sequential trends documented in the Late Oligocene deposits of northeastern Taiwan are not consistent with global sea-level fluc-

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tuations and therefore, tectonic processes are invoked to have controlled local basin conditions. In general, the sequential variations documented in the Oligocene strata probably were controlled by paleoceanographic conditions that were closely linked to tectonic processes and longer-term, first-order sea-level fluctuations.

(Key words: Trace fossil, Oligocene, Hsuehshan Range, Sea-level fluctuation)

1. INTRODUCTION

Oligocene fluvial and shallow marine deposits containing a diverse assemblage of body fossils as well as physical and biogenic structures are widely exposed in the Hsuehshan Range, Taiwan (Fig. 1). The study area, located along the northeastern coast of Taiwan, has excellent exposures of Oligocene strata that provide an opportunity for detailed sedimentological analysis of deposystems and ichnofacies. Strata are composed of shoreface to offshore marine wave,

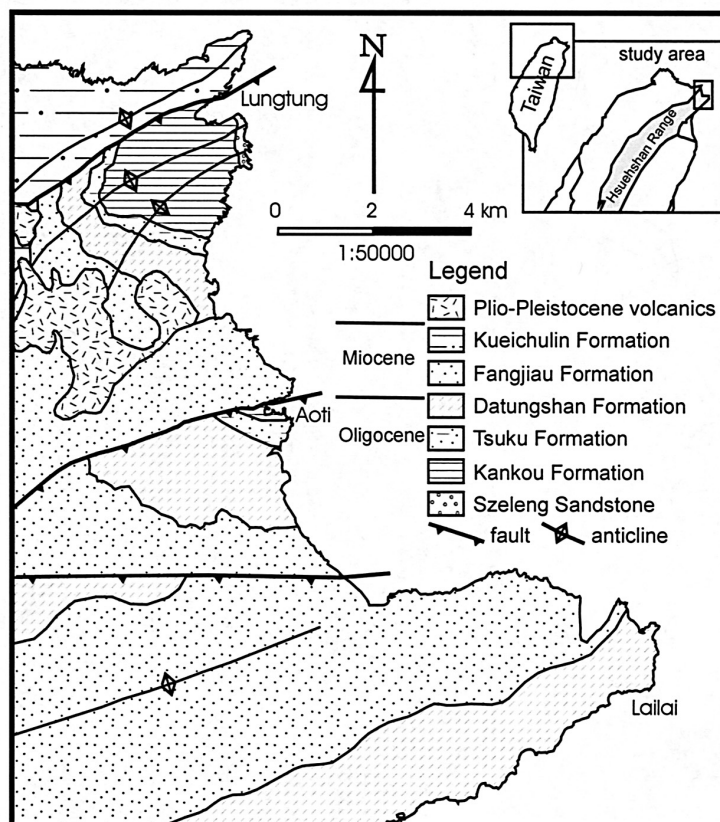


Fig. 1. Geologic map of the northeastern coast of Taiwan.

tide, and storm deposits that record transgressive and regressive events. Few previous studies have focused on the reconstruction of these depositional environments. By analyzing both sedimentary structures and trace fossils, a more accurate reconstruction of both syndepositional and post-depositional environmental conditions is possible. Sedimentary structures alone, however, do not allow sedimentologists to recognize the post-depositional history of sedimentary rocks. In the last three decades, paleontologists and sedimentologists increasingly have refined the use of ichnofossils as paleoenvironmental indicators. The combination of ichnology with sedimentology has improved environmental interpretations for factors such as bathymetry, salinity, oxygenation, and relative rates of deposition (Frey and Howard 1985; Wignall and Myers 1988). The Oligocene succession of northeastern Taiwan, which contains several different lithofacies and well-defined ichnofacies, ideally is suited for delineating sedimentological environments because of the excellent exposures. In this study, new sedimentologic and biologic data along with ichnofossil assemblages are used to reconstruct the depositional environments of the eastern Eurasia continental margin during the Oligocene.

2. GEOLOGIC SETTING

Paleogene rocks are broadly distributed throughout Taiwan, where widespread thick Cenozoic deposits unconformably overlie late Mesozoic basement (Yuan et al. 1985). At the beginning of the late Cretaceous, the region in what is now Taiwan underwent extension associated with the opening of the South China Sea (Teng 1992). Extensional deformation resulted in the formation of numerous half-graben basins that were filled with sediments derived from southeast Mainland China during Eocene to Miocene. The Paleogene deposits of the Hsuehshan Range and offshore in the Taiwan Strait are estimated to be more than 4000 m thick. These strata were deposited in fluvial and marine environments, ranging from an alluvial- and wave-dominated delta plain through a storm-dominated prodelta slope to a tide-dominated delta front. The thick, shallow-marine deposits indicate active subsidence during deposition.

The post-middle Miocene geologic history of Taiwan was heavily affected by convergent tectonics due to the collision between the Luzon volcanic arc and the Eurasian continent. Regional shortening associated with collisional deformation led to uplift of Paleogene strata and produced the excellent exposures in the Hsuehshan Range. Foraminifera biostratigraphy (Huang and Cheng 1983) and paleoecology of molluscan fauna (Lee 1983) provide a stratigraphic framework.

3. SEDIMENTARY STRUCTURES AND TRACE FOSSILS

The study area is ~20 km long and bordered by a narrow coastal erosional-platform that corresponds to the northern tip of the Hsuehshan Range (Fig. 1). Underlying these rocks are folded Oligocene-Miocene strata that were subdivided by Tang and Yang (1976) into the Szeleng, Kankou, Tsuku, Datungshan, and Fangjiao Formations. The deepening-upward to shallowing-upward succession consisting of conglomerate, sandstone, rhythmic sandstone/shale and intensely bioturbated sandstone characterize these strata. These rocks are about 1700 m

thick, and have been deformed and slightly metamorphosed. As documented below, the succession can be divided into six facies associations, which are broadly interpreted to have been deposited along a shoreface to offshore gradient.

Trace fossils are abundant within the widespread outcrops of the Oligocene succession. The ichnofacies study presented here is combined with sedimentary structure, paleontological, and chemical data to better reconstruct the depositional environments (Moslow and Pemberton 1988; Frey et al. 1990). This study only deals briefly with ethologic description, and places more emphasis on integrating the characteristics of bioturbation, ichnodiversity, trace fossil abundance, and sedimentary structures. As indicated previously, there is an intimate relationship between trace fossils and lithofacies and allows recognition of five ichnocoenoses.

3.1 *Ophiomorpha* Ichnocoenosis

Lithologically, ichnocoenosis occurs in pebbly sandstone and sandstone associations. The pebbly-sandstone association of the lower Szeleng Sandstone comprises thick-bedded, moderately to well-sorted, coarse-grained sandstone and pebbly sandstone with large-scale cross-laminae, parallel-laminae (Fig. 2), and, less commonly, swaley and symmetrical megariipples. Swaley cross-stratification reflects storm-dominated deposition above fair-weather wave base that developed as large-scale composite sandwaves (Leckie and Walker 1982; Colquhoun 1995). Individual beds are about 0.5 to 1.0 m thick, exhibiting basal bounding surfaces marked by a lag of winnowed pebbles. The erosional bases display gently undulatory surfaces with maximum relief of 0.5 m. The near-shore environment is dominated by fair-weather deposits interrupted occasionally by erosive surfaces formed by the effect of storms (Rossetti 1997). Throughout, lithofacies consists mainly of unidirectional cross-laminae. The sedimentary structures reflect wave influence that indicates intense reworking of fair-weather deposits during storms. Variations in facies association reflect the positions of the sections with respect to a nearshore-shoreface environment (Mueller and Dimroth 1987; Tai and Teng 1994).

The sandstone association of the Fangjiao Formation is characterized by thick-bedded, well-sorted sandstone, alternating with rhythmic beds that show herringbone cross-stratification (Fig. 3), wavy, and flaser structures. Unidirectional trough cross-laminae are pervasive throughout the sandstone, with individual sets being 0.3 to 1 m thick. Mudstone drapes on foresets suggest tidal influence (Richards 1994; Corcoran et al. 1998). In rare cases, sandstones show cross-laminae in a direction opposite to the dominant flow direction. Ripple-laminated sands with well-developed mud drapes interbedded with lenticular- and flaser-bedded deposits are common. Sparse lags contain abundant mud clasts and rare plant debris, usually found in the troughs of erosion surfaces. The erosional surfaces may have a basal lag of shale pebbles, which are interpreted as tide-dominated channel-fill deposits (Savrda et al. 1998). The sandstone facies represents deposition in a subtidal-intertidal environment.

Only a few trace fossils occur in this lithofacies, which is dominated by physical sedimentary structures (Fig. 4). Sedimentary structures indicate that relatively high-energy conditions prevailed during frequent erosion and deposition on a marine substrate within a littoral-sublittoral zone. Trace fossils are usually sparse in the sandstone and pebbly sandstone beds, but abundant in a few of the sandstone beds (Fig. 5). All preserved trace fossils are vertical burrows;



Fig. 2. Thick-bedded sandstones show planar cross- and parallel-laminae structures. Scale bar = 20 cm.

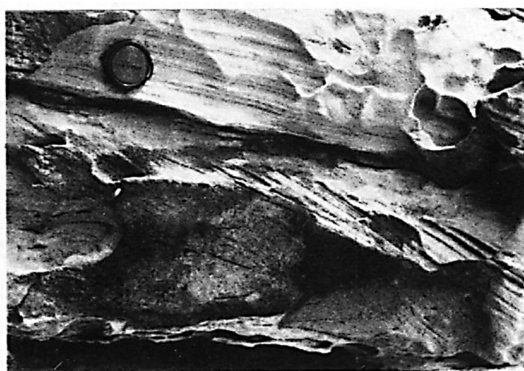


Fig. 3. Thick-bedded sandstones show trough cross-laminae, herringbone cross-laminae and parallel-laminae structures. Lens cap = 6.5 cm.

no shallow-tier tracks or trails were recognized. The *Ophiomorpha* ichnocoenosis is associated mainly with large-scale cross- and parallel-laminated structures in which *Ophiomorpha nodosa* (Fig. 6a) and *Skolithos* isp. are present. The configuration of *Ophiomorpha* isp. has been used as an environmental indicator. Predominant vertical elements reflect high-energy conditions, whereas domination by horizontal elements is more likely associated with low-energy environments (Frey and Mayou 1971; Jones and Pemberton 1989). Here, *Ophiomorpha nodosa* is a prominent and striking vertical structure that commonly forms a low-abundance and -diversity ichnoassemblage (Figs. 7, 8) preserved in thick-bedded sandstones. The producers of both *Ophiomorpha* and *Skolithos* are interpreted as a stress-tolerant suspension feeder that was well adapted to nearshore environments. The fluctuating periods of deposition and erosion in the littoral-sublittoral zone resulted in the absence of shallow tiers (Bromley, 1990; Bromley and Asgaard, 1991). The *Ophiomorpha* ichnocoenosis is interpreted to reflect a well-

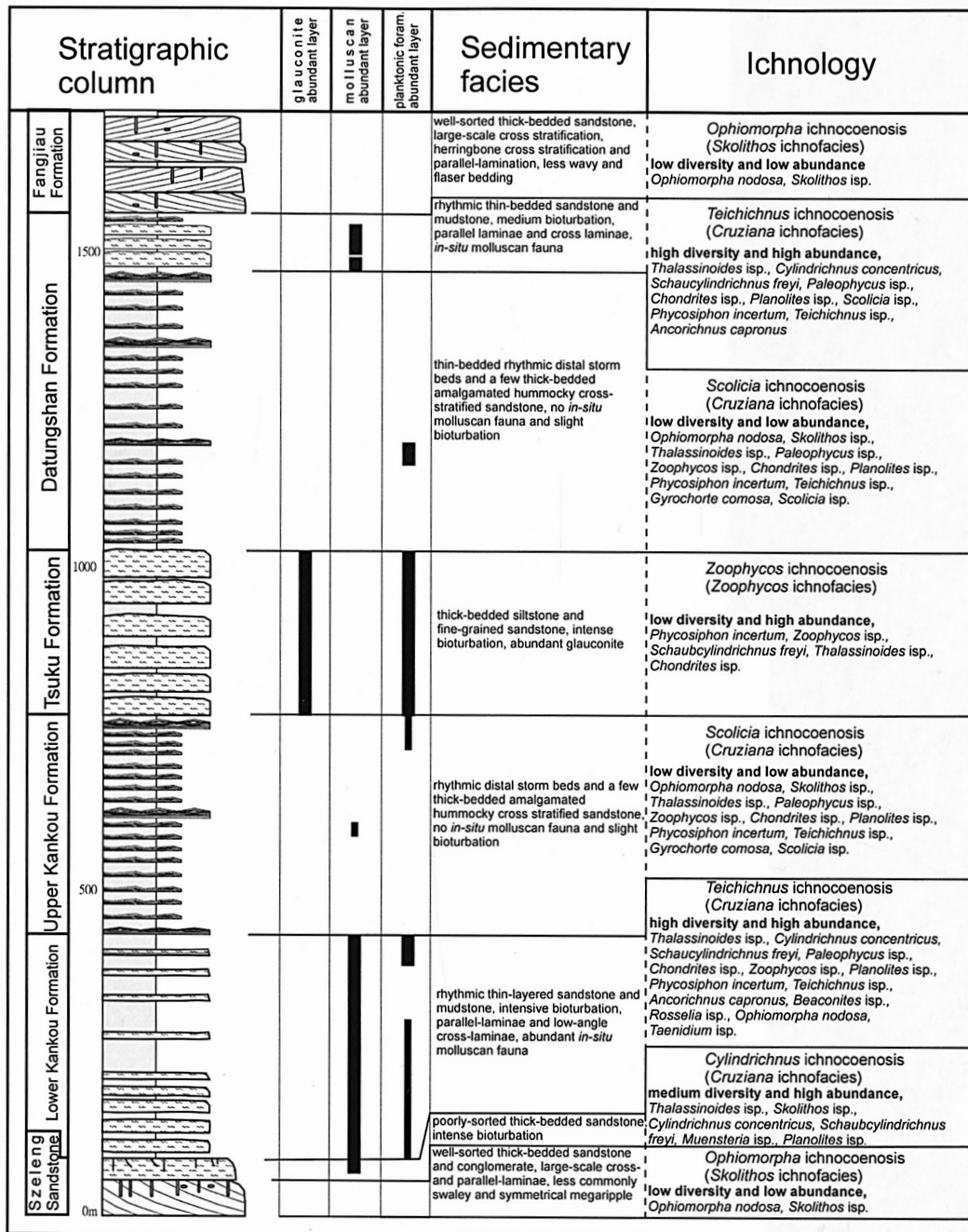


Fig. 4. Sedimentological log of Oligocene formations at northeastern coast section shows sedimentary facies, molluscan, planktonic foram and glauconite data and compared to ichnologic composition.

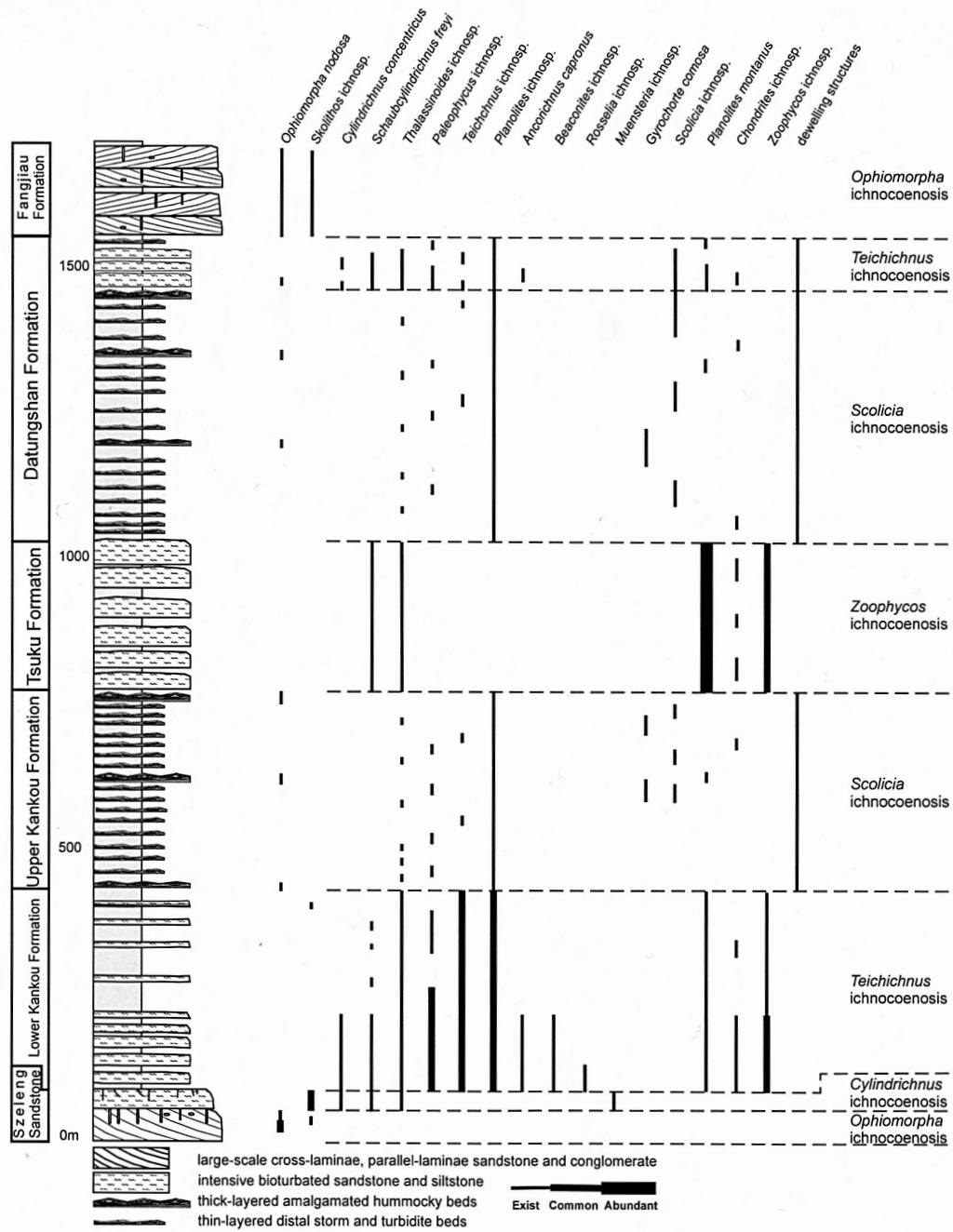


Fig. 5. Trace fossil composition of ichnocoenoses in the Oligocene formations.

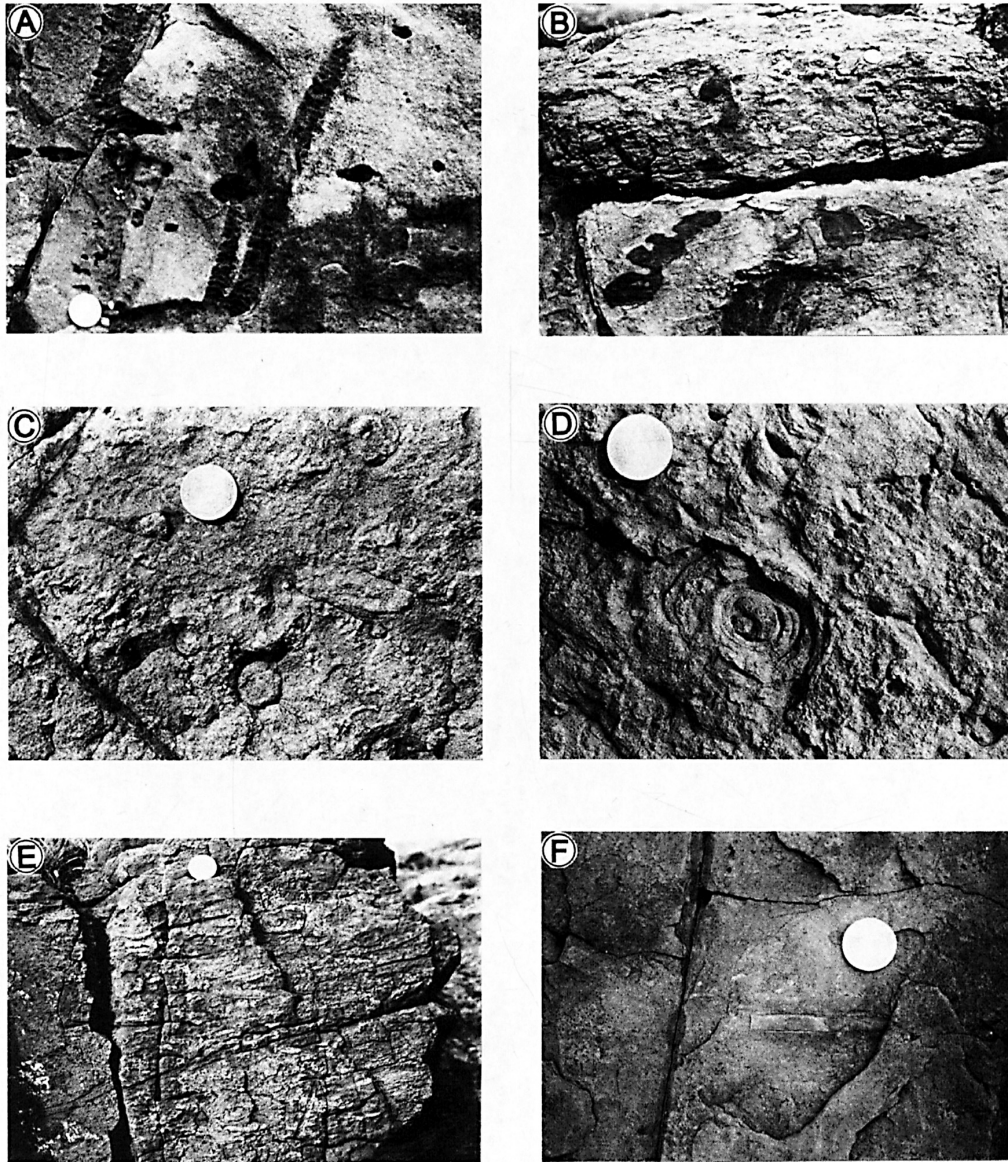


Fig. 6. (a) Vertical section view of *Ophiomorpha nodosa* from the lower Szeleng Sandstone. (b) The sandstone displays as poorly sorted and structureless with a high degree of bioturbation. (c) Bedding plane view of *Skolithos* isp. from the upper Szeleng Sandstone. (d) *Cylindrichnus concentricus* from the upper Szeleng Sandstone. (e) Bioturbated sandstone often obscures sedimentary structures by abundant deposit-feeders. (f) *Paleophycus* isp. from the lower Kankou Formation. Coin = 2.6 cm.

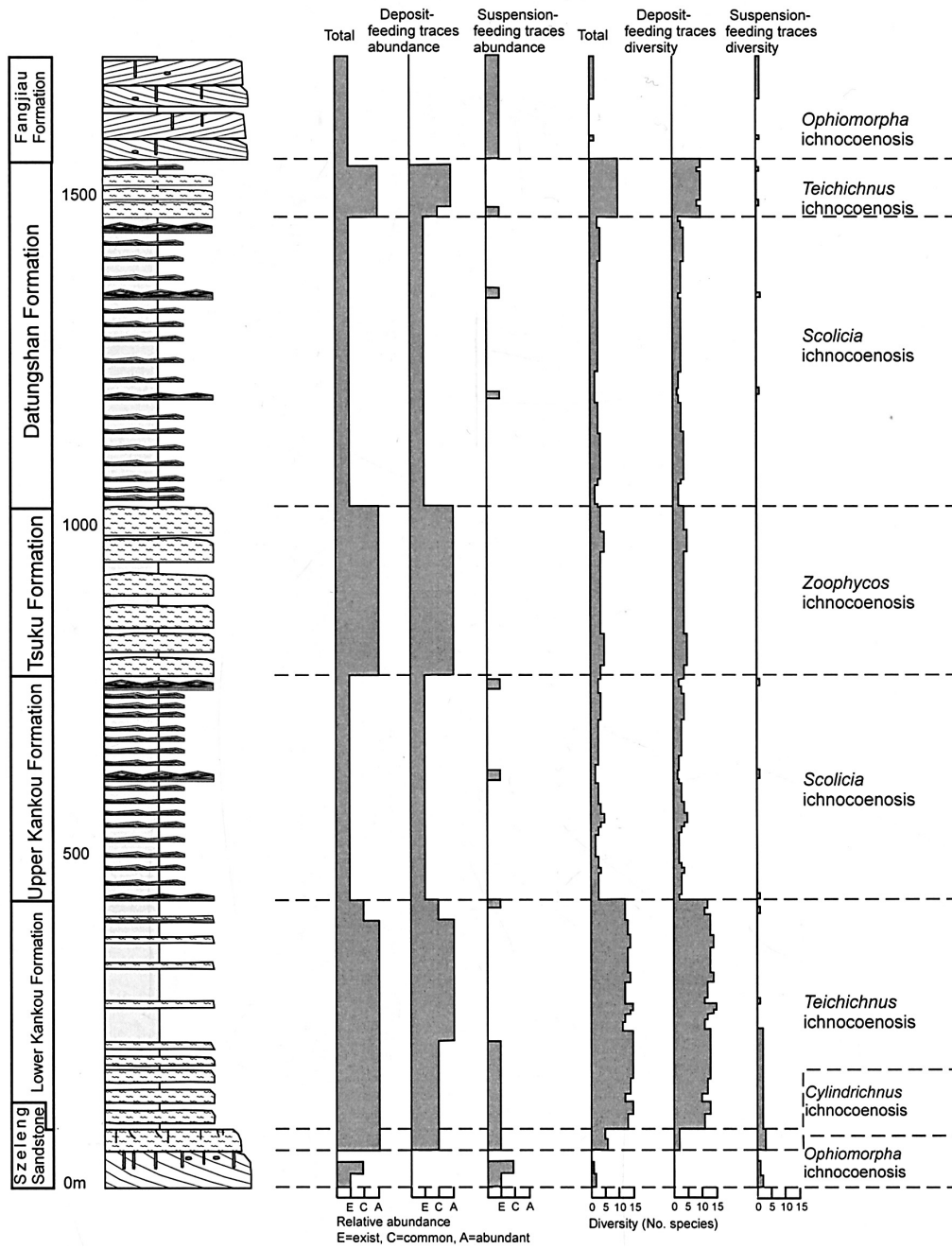


Fig. 7. Diversity (number of species) and abundance of trace fossils in various types of lithofacies.

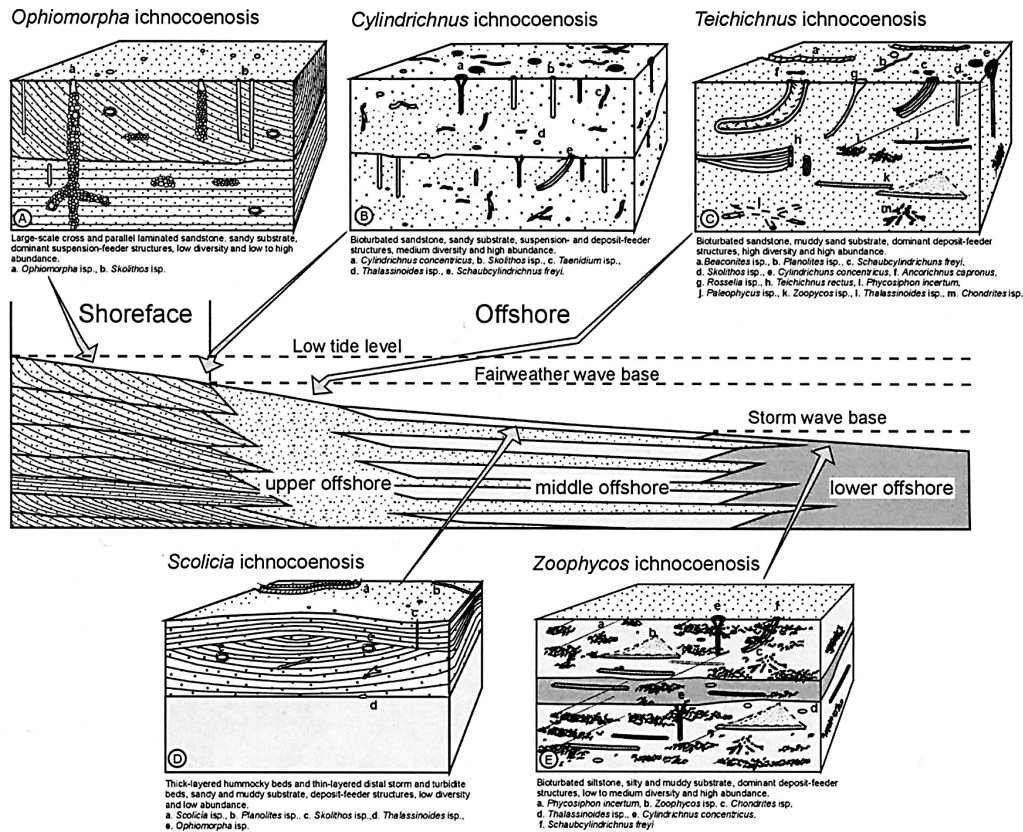


Fig. 8. Ichnofacies model of the Oligocene formations, showing the distribution of the sedimentary facies and ichnocoenoses. Reconstruction of (a) *Ophiomorpha* ichnocoenosis; (b) *Cylindrichnus* ichnocoenosis; (c) *Teichichnus* ichnocoenosis; (d) *Scolicia* ichnocoenosis; and (e) *Zoophycos* ichnocoenosis. Not to scale.

aerated, high-energy environment with abundant suspended food, probably above fair-weather wave base. Such an ichnocoenosis is similar to Seilacher's (1964) "Skolithos ichnofacies", which is often interpreted to represent high-energy wave- and tide-dominated, littoral-sublittoral environments.

3.2 *Cylindrichnus* Ichnocoenosis

The sediments containing the *Cylindrichnus* ichnocoenosis consist of intensely bioturbated thick-bedded (0.5 - 1.0 m) sandstone (Figs. 4, 6b). The bioturbated sandstone of the upper

Szeleng Sandstone is medium- to coarse-grained and poorly sorted, having abundant invertebrate detritus. Biogenic structures are composed mainly of vertical burrows. Thick-bedded sandstone, probably caused by intense bioturbation, may have originally been interbedded sandstone and shale. In other words, benthos modified the substrate under waning energy conditions after sediments were initially deposited. The bioturbated sandstone often is interbedded with cross- and parallel-laminated sandstone in other sections (Chen 1986), and has been interpreted as the product of deposition just below fair-weather wavebase (Howard 1972; Chen 1986) or within lower-shoreface environments (Howard and Frey 1984). The lithofacies and biogenic structures point to a general environment between shoreface and offshore.

The *Cylindrichnus* ichnocoenosis consists of abundant and diverse ichnofossils in bioturbated sandstones. The most common ichnofossils are *Skolithos* isp. (Fig. 6c), *Thalassinoides* isp., *Cylindrichnus concentricus* (Fig. 6d), *Schaubcylindrichnus freyi*, *Taenidium* isp., and *Planolites* isp. (Fig. 5). These traces are mainly domicinia of suspension feeders, represented by *Skolithos* isp., *Cylindrichnus concentricus* and *Schaubcylindrichnus freyi*. The feeding burrows of deposit feeders are represented by *Thalassinoides* isp., and *Planolites* isp. The ichnoassemblage contains mainly domicinial vertical burrows, indicating that bottom-water circulation was sufficient to fully oxygenate the seafloor. In general, suspension-feeders show a slight propensity for coarser-grained sediments (Fursich 1975) under an alternating high- to low-energy environment. Following a storm, abundant benthos colonized the substrate that previously was bioturbated thoroughly during the post-storm periods. The next storm event ensued before the benthos was able to completely bioturbate the previously deposited storm sediment. Howard (1972) interpreted such an ichnocoenosis as representing alternating periods of storm and fair-weather conditions in an environment at or just below the fair-weather wavebase. The *Cylindrichnus* ichnocoenosis, therefore, is interpreted to be constituted by medium-diversity and high-abundance ichnofossil assemblages within an individual bed (Figs. 7, 8), which is represented by the *Cruziana* ichnofacies close to the fair-weather wave base (MacEachern et al. 1999; Fursich and Pandey 1999).

3.3 *Teichichnus* Ichnocoenosis

Feeding burrows characterize rhythmic thick-bedded sandstones and mudstones having gradational contacts; and bioturbation (Fig. 6e) obscures physical sedimentary structures (Figs. 4, 5 and 7). Nevertheless, it is still possible to find a few sedimentary structures present, including parallel-laminae, low-angle cross-laminae, and molluscan-detritus lags. These types of sedimentary structures are suggestive of storm deposits. Bioturbated sandstones are commonly thin-bedded and amalgamated in part and usually have bioturbated tops and lower parts that retain parallel and low-angle cross-laminae.

The thick-bedded mudstones in this ichnocoenosis are bioturbated thoroughly and contain abundant *in situ* molluscan fauna of mostly a shallow marine affinity (Lee 1983). Molluscs generally occupy a position at or beneath the seafloor, and indicate an oxygenated environment. Much of the molluscan detritus along the sandstone bases was deposited originally as storm-deposited lags, rather than as storm current deposits. The intensely bioturbated

sandstones are postulated to be storm-emplaced. Hence, this ichnocoenosis is interpreted as having been deposited below the fair-weather wavebase in the upper offshore environment. Nevertheless modification of molluscan detritus exhibited a random orientation of shell fragments; and these features are interpreted as the result of subsequent bioturbation (Fursich and Pandey 1999).

The *Teichichnus* ichnocoenosis is characterized by completely bioturbated sandstones and mudstones containing diverse and abundant, well-preserved trace fossils (Fig. 8) including *Thalassinoides* isp., *Cylindrichnus concentricus*, *Schaubcylindrichnus freyi*, *Paleophycus* isp., *Chondrites* isp., *Zoophycos* isp., *Planolites* isp., *Phycosiphon incertum*, *Teichichnus rectus*, *Ancorichnus capronus*, *Rosselia* isp., *Ophiomorpha nodosa*, and *Taenidium* isp. (Figs. 4, 5). Although individual identification and quantitative analysis are not straightforward, *Thalassinoides* isp., *Cylindrichnus concentricus*, *Paleophycus* isp. (Fig. 6f), *Schaubcylindrichnus freyi* (Fig. 9a), *Planolites* isp., and *Teichichnus rectus* (Fig. 9b) are most common. *Zoophycos* isp. is locally common also. This association consists mainly of horizontal trace fossils presumably produced by deposit feeders, and a few oblique and vertical burrows considered to be the work of suspension feeders. Other vertical burrows in this ichnoassemblage, such as *Ophiomorpha nodosa* and *Skolithos* isp., rarely are observed through the entire ichnocoenosis. *Ophiomorpha nodosa* and *Skolithos* isp. commonly occur in storm beds, representing dwelling structures of suspension feeders during waning energy conditions related to storm events. Abundant benthic fauna destroys the low-angle undulatory parallel-laminated sandstone in the post-storm depositional stage that is interpreted to reflect upper-offshore deposits (MacEachern et al. 1999). The *Teichichnus* ichnocoenosis is a high-diversity and low- to high-abundance assemblage of trace fossils that characterize the *Cruziana* ichnofacies in the upper offshore (Howard and Frey 1984).

Zoophycos isp. is well preserved and more visible in completely bioturbated deposits of mixed-layer tiers. *Zoophycos* isp., produced by a deep deposit feeder, is emplaced within the deeper substrate in connection with an oxygenated seafloor and a coherent substrate (Olivero and Gaillard 1996). Appearance of a deeper tier of *Zoophycos* activity probably has obliterated the original deposit-feeder burrows. The substrate commonly ranges from fully oxygenated regions in shallow tiers into oxygen-deficient environments in deeper tiers. However, a few of the subhorizontal trace fossils such as, *Taenidium* isp., *Thalassinoides* isp., *Planolites* isp., and *Teichichnus rectus*, superimpose *Zoophycos* spreiten in bioturbated sandstone. The above ichnoassemblage, except *Zoophycos* isp., probably represents a dysaerobic environment. Possibly, erosion of the seafloor by storm events created a temporary aerobic environment during the post-storm that was hospitable to a few deposit-feeders.

3.4 *Scolicia* Ichnocoenosis

The *Scolicia* ichnocoenosis, ranging in thickness at individual beds from 1 m to a few centimeters, is composed mainly of rhythmic sandstone and shale, about 5 - 15 cm in individual sandstone bed thickness. These sandstones are predominantly thin-bedded storm-generated sandstone (Fig. 9c) and a few are thick-bedded amalgamated hummocky beds. Various sedimentary structures have been identified in current ripples, parallel laminae, small-scale

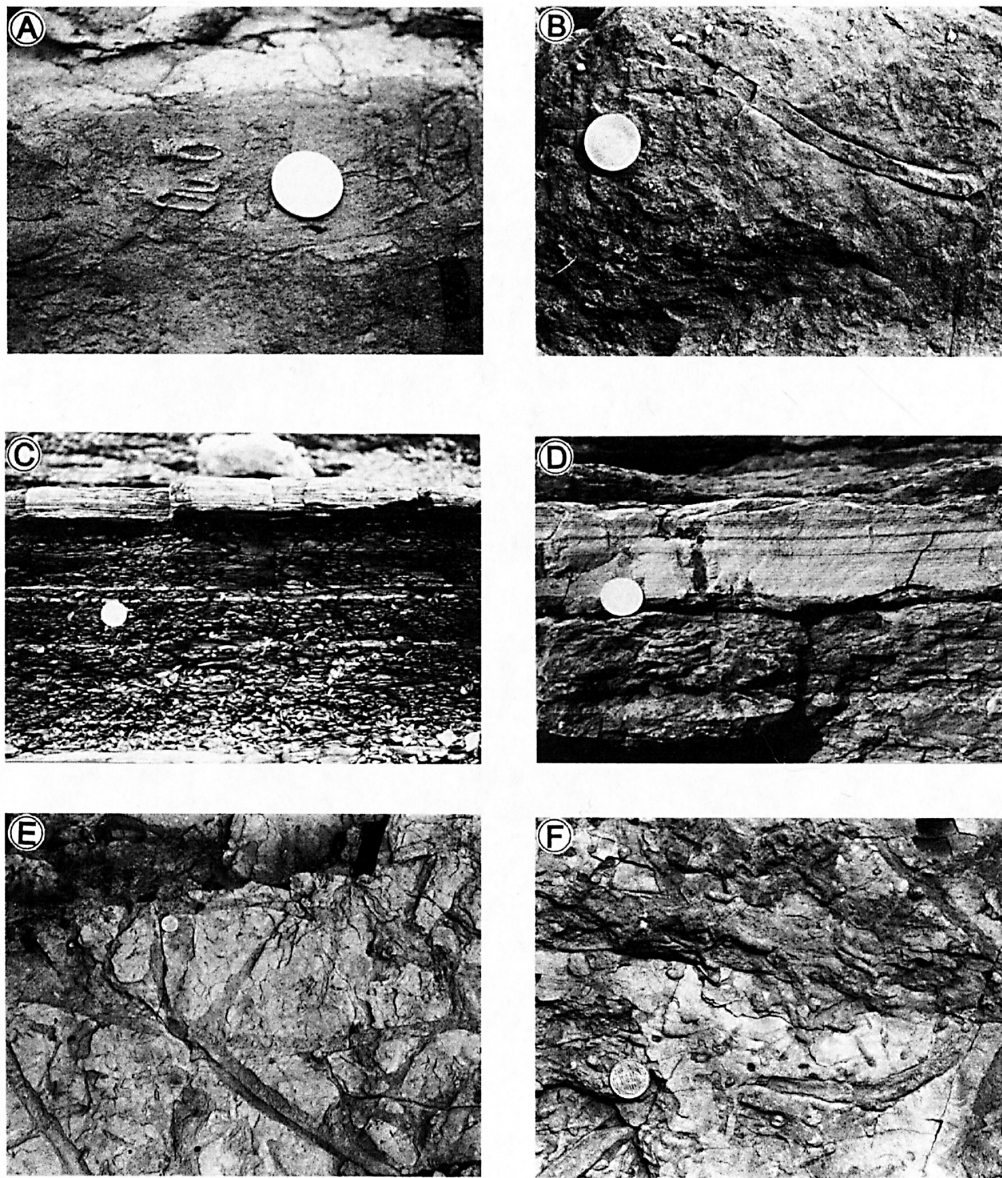


Fig. 9. (a) *Schaubcylindrichnus freyi* from the lower Kankou Formation. (b) *Teichichnus rectus* from the lower Kankou Formation; (c) *Scolicia* ichnocoenosis displays thin-bedded distal storm sandstone; (d) Thin-bedded storm beds show the parallel laminae and undirectional small-scale cross stratification; (e) *Thalassinoides* isp. from the upper Kankou Formation; (f) *Paleophycus* isp. from the upper Kankou Formation. Coin = 2.6 cm.

cross-laminae (Fig. 9d), and hummocky cross-stratification. The tops of thinner beds show straight-crested oscillation ripples and linguoid current ripples, demonstrating flow conditions in waning storms (Pfluger 1999). These beds have sharp and flat bases that are generally continuous across an outcrop, but some pinch out locally. The above sedimentary features indicate a storm origin. This lithofacies is interpreted as distal storm beds and turbidites that have been reworked by storm-induced traction currents (Johnson and Baldwin 1996). The ratio of sandstone to shale is low, and the amount of bioturbation is low. Thick-bedded amalgamated hummocky storm beds occur in medium-grained sandstone and are characterized by parallel-laminae, cross-stratification, and sharp bases. Hummocky undulations exhibit spacing of 1 - 3 m. The generally accepted interpretation for hummocky storm beds is that they are produced by storm-induced traction and oscillatory currents (Duke 1985; Southard et al. 1990). This lithofacies association was probably deposited in shallow water below fair-weather wavebase but above storm wavebase (Cheel and Leckie 1993).

The *Scolicia* ichnocoenosis, usually devoid of molluscan body fossils, is associated with slightly bioturbated structures (Fig. 8) containing low diversity and low abundant assemblages (Fig. 7). More commonly individual biogenic structures can be recognized; most of these appear to be deposit-feeding structures. This ichnocoenosis typically displays sparse trace fossils in individual storm beds. The most common ichnofossils are *Ophiomorpha nodosa*, *Skolithos* isp., *Thalassinoides* isp. (Fig. 9e), *Paleophycus* isp. (Fig. 9f), *Zoophycos* isp., *Chondrites* isp., *Phycosiphon incertum*, *Planolites* isp. (Fig. 10a), *Teichichnus* isp., *Gyrochorte comosa* (Fig. 10b), *Scolicia* isp. (Fig. 10c), and dwelling structures (Figs. 4, 5). In the *Scolicia* ichnocoenosis, rhythmic sandstones and shales were deposited episodically by storms in an offshore environment with alternatingly high- and low-energy conditions. Sandstones also contain sparse *Ophiomorpha nodosa*, *Skolithos* isp., and other feeding and dwelling structures produced by suspension feeders formed during waning-energy conditions related to storm events. The sandstones regularly preserve *Planolites* isp., *Scolicia* isp., and dwelling structures on the top, and sparse *Paleophycus* isp. and *Thalassinoides* isp. at the base. This ichnoassemblage consists mainly of horizontal and oblique burrows of deposit feeders, indicating low-energy environments during post-storm deposition. This environmental interpretation is supported by the low-diversity and low-abundance trace fossil assemblage in an individual bed (Figs. 7, 8), which is characteristic of the *Cruziana* ichnofacies of the middle offshore (Howard and Frey 1984). The sandstone in this ichnocoenosis, however, resulted in a deposition under oxygen-deficient conditions that reflect periodic oxygenation episodes. The shale with very thin siltstone laminae a few millimeters thick, as a whole, rarely shows bioturbation and is devoid of molluscan fauna. Obviously, dysaerobic to anaerobic conditions existed in the post-storm depositional environment.

3.5 *Zoophycos* Ichnocoenosis

The *Zoophycos* ichnocoenosis occurs mainly as alternative 0.4 - 1.0 m thick-bedded bioturbated and structureless siltstones (Fig. 10d). In addition, slight grading and lag deposits are, for example, interpreted as storm-generated deposits in an offshore environment. In addition, this ichnocoenosis is intercalated with several horizons rich in glauconitic minerals and rela-

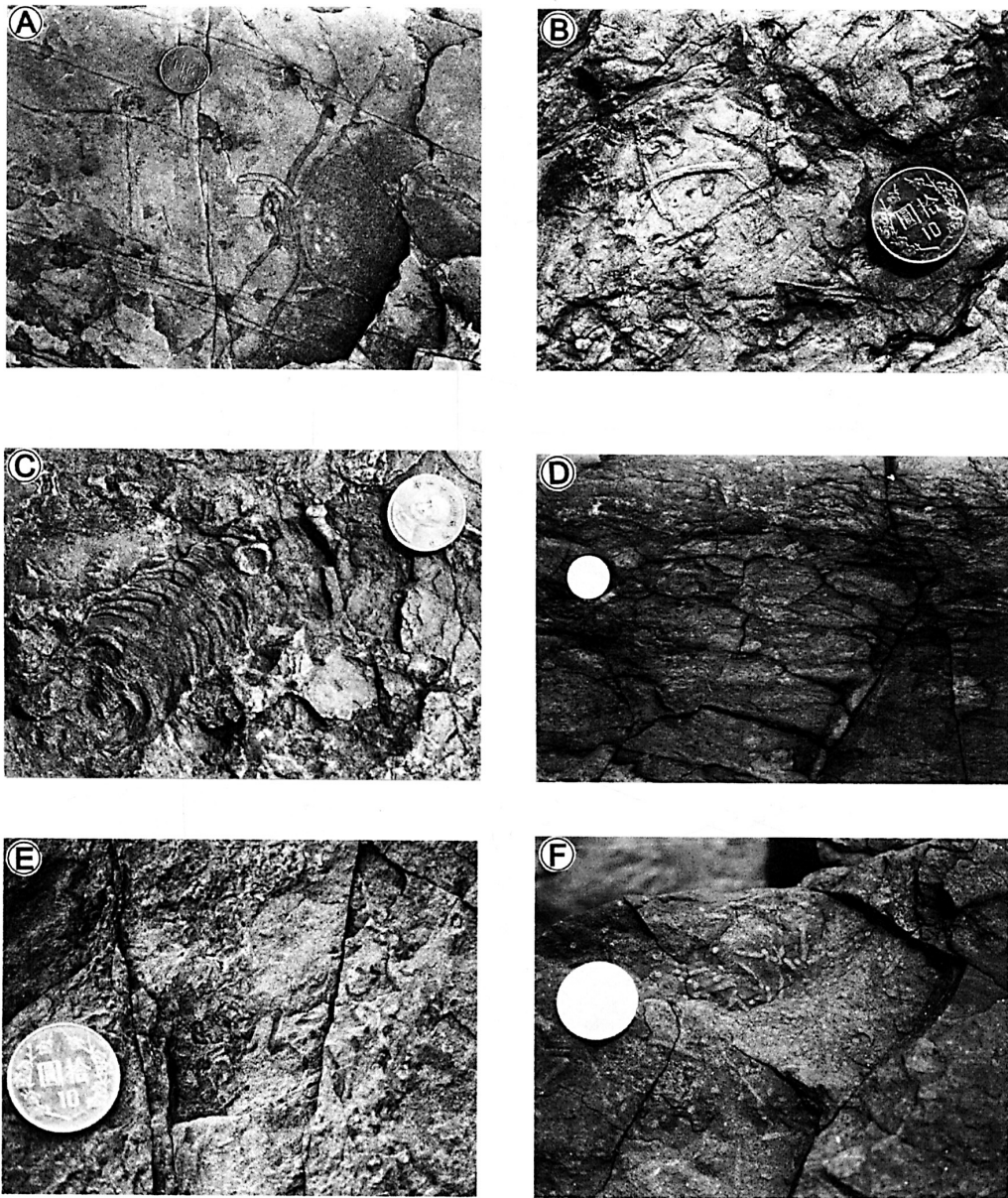


Fig. 10. (a) *Planolites* isp. from the upper Kankou Formation. (b) *Gyrochorte comosa* from the upper Kankou Formation; (c) *Scolicia* isp. from the upper Kankou Formation; (d) *Zoophycos* ichnocoenosis displays bioturbated beds mixed with thin-bedded siltstone; (e) *Phycosiphon incertum* from the Tsuku Formation; (f) *Chondrites* isp. from the Tsuku Formation. Coin = 2.6 cm.

tively deep-water benthic and planktonic foraminiferal assemblages (Huang and Cheng 1983; Tai and Teng 1994). Glauconite generally forms at the sediment-water interface and indicates slightly reducing conditions and lower sedimentation rates (Van Houten and Purucker 1984; Lin and Lin 1993; Burkhalter 1995). The lithofacies, therefore, may reflect dysaerobic conditions and lower sedimentation rates in post-storm environments.

The *Zoophycos* ichnocoenosis comprises a low-diversity assemblage of trace fossils consisting of *Phycosiphon incertum* (Fig. 10e), *Chondrites* isp. (Fig. 10f), *Zoophycos* isp. (Figs. 11, 12), *Thalassinoides* isp., *Schaubcylindrichnus freyi*, and *Cylindrichnus concentricus* (Figs. 4, 5). The ichnocoenosis is dominated by *Phycosiphon incertum* and *Zoophycos* isp., which are characterized by high abundance in an individual bed (Figs. 7, 8). Strongly bioturbated siltstones especially are characterized by an abundance of *Phycosiphon incertum*. *Phycosiphon incertum* consists of an unbranched, unlined, sinuous, subhorizontal, tiny, densely spaced and packed tunnel (Frey and Howard 1985; Ekdale and Lewis 1991; Miller and Vokes 1998), which is commonly confused with branching *Chondrites* isp. It represents the activity of a deposit-feeder at various tier depths and at variable water depths from lower shoreface to bathyal (Wetzel and Bromley 1994). *Thalassinoides* isp., *Cylindrichnus concentricus*, and *Schaubcylindrichnus freyi* occur in low abundance and are distributed sparsely in bioturbated siltstones. They are disturbed and superimposed by *Phycosiphon incertum* and *Zoophycos* isp., which represent opportunistic colonization during waning-energy conditions related to storm events. They provide a record of the activity of the earliest colonizers. A rapid deoxygenating event at the cost of aerobic to dysaerobic conditions during the post-storm event can be recognized based on their crosscutting relationships. In cases of high burrow density, the *Zoophycos* ichnocoenosis is composed of plentiful *Phycosiphon incertum* and *Zoophycos* isp. within glauconite-bearing beds that probably indicate dysaerobic post-storm conditions on the seafloor. Therefore, it is likely that *Phycosiphon incertum* in this case probably possessed a behavior to adapt to oxygen deficient conditions. This ichnocoenosis is not dissimilar to the *Zoophycos* ichnofacies, which is often interpreted to represent the normal low-energy environment below storm-wave base (Howard and Frey 1984; Bromley 1990).

4. DISCUSSIONS

The Early Oligocene deposits, as deduced from sedimentology, represent a transgressive sequence from the shoreface to lower offshore environment. Trace fossil associations from this succession can be divided into five ichnocoenoses in three ichnofacies. The distinguishing features of the ichnoassemblages are representative of the transition from the *Skolithos* ichnofacies to *Zoophycos* ichnofacies. The ichnocoenoses vary in ascending order from *Ophiomorpha*, *Cylindrichnus*, *Teichichnus*, *Scolicia* to *Zoophycos* ichnocoenoses.

The trace fossils in the succession generally are distinct and well preserved. Dominant suspension-feeder trace fossils such as *Ophiomorpha nodosa*, *Skolithos* isp., and *Cylindrichnus concentricus* are in the order of decreasing abundance (Fig. 5), probably reflecting decreasing seafloor water energy. In addition, the degree to which sediments have been bioturbated is also an indicator of physical energy and aeration of the environment. Bioturbated structures



Fig. 11. Vertical section view of *Zoophycos* isp. Coin = 2.6 cm.



Fig. 12. Bedding plane view of *Zoophycos* isp. Coin = 6.5 cm.

commonly increase from shoreface to offshore environments due to increasing benthos. This is especially true for the upper offshore and below fair-weather wavebase environments which are characterized by greater stability and lower-energy conditions with abundant organic detritus. The depositional environments of the *Ophiomorpha* ichnocoenosis are strongly influenced by hydraulic forces associated with wave action that induces agitation of bottom water along basin margins during the Eocene (Fig. 13a). Wave effects in general are significantly reduced at depths of about 20 m or more during fair weather. Furthermore, abundant biogenic structures almost completely replace sedimentary structures below a fair-weather wavebase. Therefore the muddy sandstone of the *Teichichnus* ichnocoenosis, thoroughly bioturbated with the deposit-feeder, is interpreted to reflect accumulation below fair-weather wavebase. In this

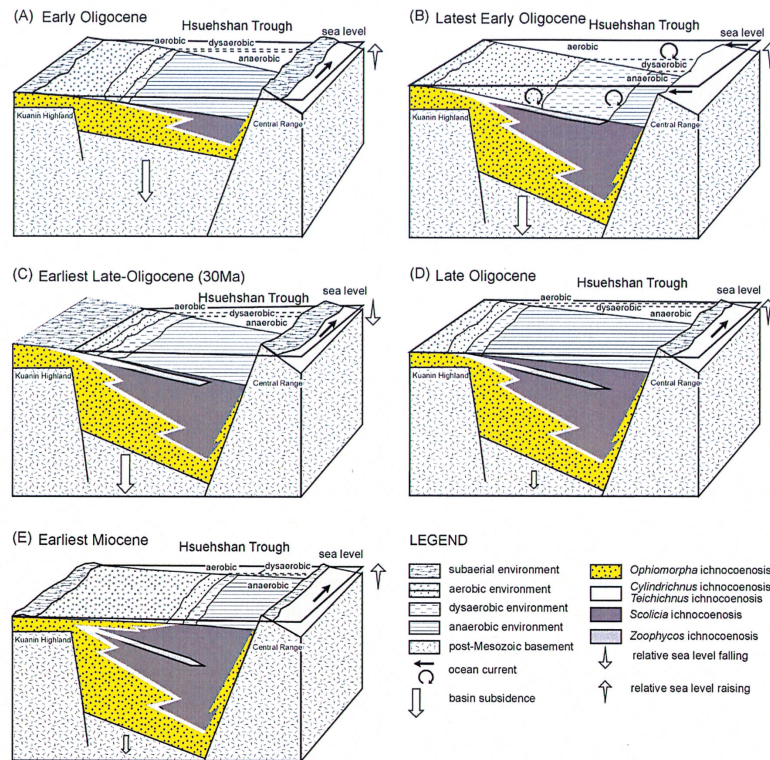


Fig. 13. Depositional model for Oligocene Formation in the Hsuehshan Range. (a) Rifting in the Eurasian continental margin created the Hsuehshan Trough enclosed by the surrounding horsts (the Kuanin Highland and paleo-Central Range). The Szeleng Sandstone was deposited by currents and waves transporting gravel and sand that flowed west out of the continent and into the Hsuehshan Trough. Rapid subsidence along the Hsuehshan Range resulted in a transgressive deepening-upward sequence of the Kankou Formation. The trough was protected from open sea by horsts; (b) The trough becomes an open-sea environment resulting in the sea-level rising over the horsts during the latest Early Oligocene. Ocean-current circulation induces the bottom water agitation, taking place with a broad change from anaerobic to dysaerobic environment on the substrate; (c) The depositional environment occurs as slightly shallowing during the earliest Late Oligocene. Tectonics is a possible cause with relative change in sea level possibly being affected more by episodes of subsidence than by eustatic change; (d) The Upper Oligocene deposits represented a coarsening- and shallowing-upward sequence that was gradually deposited by terrigenous sediments in this basin; (e) The Hsuehshan Trough was filled by sediments during the earliest Miocene.

study, it was commonly observed that the *Ophiomorpha* ichnocoenosis occurs above fair-weather wavebase and the *Cylindrichnus* ichnocoenosis near this depth and the *Teichichnus* ichnocoenosis below this depth.

Occurrence of the *Scolicia* ichnocoenosis with thin-bedded tempestites is related to periodic storm deposits. A low-diversity and low-abundance association of trace fossils, formed by deposit-feeders in sandstone beds, reflects an opportunistic bottom fauna. The absence of macrobenthos and plankton within shales suggests that the substrate and water masses were generally in anaerobic conditions (Pfluger 1999). Thus, the depositional environment seems to represent an epeiric basin with restricted oceanic circulation. The basin may have been barred from ocean circulation by a series of horsts and ridges. Storm events may have temporarily oxygenated the previously anaerobic environments (Wignall and Myers 1988). The environment, as a whole, represented an environment alternating from episodically aerobic to anaerobic below fair-weather wavebase but above a storm wave-base in a middle offshore setting (Fig. 8). The *Zoophycos* ichnocoenosis is characterized by very high abundance and low diversity, including *Phycosiphon incertum*, *Zoophycos* isp., and *Chondrites* isp., which are indicative of an oxygen-limited environment with dysaerobic substrate conditions. The ichnocoenosis occurs with deep-water benthic foraminifera, relatively high concentration of planktonic foraminifers, and rarely macrobenthos. The benthic foraminifera assemblage in the *Zoophycos* ichnocoenosis contains significant amounts of calcareous foraminifers of agglutinated species, suggesting deposition of the host rocks within a dysaerobic environment (Tyszkla 1994). The abundance of planktonic foraminifers of the Tsuku Formation is attributed to the presence of aerobic conditions in water masses due to open marine circulation. Simultaneously, ocean-current circulation may have induced bottom water agitation that resulted in a change from anaerobic (*Scolicia* ichnocoenosis) to dysaerobic environments (*Zoophycos* ichnocoenosis) on the substrate (Figs. 13a, b). In addition, the host deposits of the *Zoophycos* ichnocoenosis contain abundant glauconite, also indicating slightly reducing environment and low depositional rates. Therefore it is interpreted as being deposited during sea-level highstand (Fig. 13b), when sea level lay over the horst causing extensive ocean-current circulation. The depositional environments for the Early Oligocene deposits, from the Szeleng Sandstone to the Tsuku Formation, can be thus interpreted to represent a transgressive event from wave-dominated nearshore to a storm-dominated offshore environment. Within this depositional transition, these ichnofacies variations, from the *Ophiomorpha* to *Zoophycos* ichnocoenoses, are also interpreted as a natural response to a transgressive system during the Early Oligocene.

Subsequently, the well-documented middle Oligocene sea-level fall event occurred worldwide (Haq et al. 1987). The record of the lowstand event was inconspicuously recognized in the studied succession (Fig. 13c). The Late Oligocene deposits, however, represent a regressive system from middle offshore to intertidal-subtidal. These deposits display a characteristic ichnofacies distribution that can be divided into *Scolicia*, *Teichichnus* and *Ophiomorpha* ichnocoenoses. Characteristic lithofacies changes in the Late Oligocene formations provide evidence for a regressive shallowing-upward succession. The ichnoassemblages represent a transition from the *Cruziana* ichnofacies to *Skolithos* ichnofacies, which is indicative of a shallowing-upward sequence. The sequential transition from the *Zoophycos* to *Scolicia* ichnocoenoses represents a decreasing oxygenation in bottom water (Fig. 13d). These types of

depositional systems gradually filled the Hsuehshan Trough during the Early Miocene (Fig. 13e). Depositional environments varied from a storm-dominated middle offshore to a tide-dominated nearshore. The sequential variation of ichnoassemblages is represented by the transition from the *Scolicia*, *Teichichnus* to *Ophiomorpha* ichnocoenoses, which represents a shallowing-upward and regressive coarsening-upward succession.

The Oligocene succession of the Hsuehshan Trough is interpreted as recording tide-, wave- and storm-dominated depositional systems based on the sedimentary structures. The Oligocene formations consist of two successions, a lower deepening-upward and an upper shallowing-upward succession. Coarse-grained sediments of the Late Eocene to earliest Oligocene were deposited throughout the Hsuehshan Trough. Early Oligocene fine-grained facies deposited in upper offshore to lower offshore environments during a sea-level highstand overlie the obviously coarse-grained deposits (Fig. 14). The succession exhibits a general fining-upward trend together with an increasing upwards of deposit-feeding structures and a decreasing upwards of suspension-feeding structures. Upsection increases in deposit-feeding structures are often used to recognize transgressive sequences in the stratigraphic record (e.g., Howard and Reineck 1981; Rigsby 1994). The muddy early Oligocene deposits are probably related to sediment starvation during sea-level rise. The transgressive deepening upwards succession reported here suggests that the trend is coincident with Early Oligocene global sea-level fluctuations.

The Upper Oligocene deposits exhibit a varied succession from storm-dominated offshore to tide-dominated nearshore environments. They display coarsening- and shallowing-upward successions that suggest a gradual filling of accommodation space with the Hsuehshan Trough. The environmental variation of the Upper Oligocene succession is not well correlated with the worldwide eustatic fluctuations (Fig. 14). It is suggested that the depositional rate was greater than the subsidence rate during the Late Oligocene. Basin subsidence became retarded so that sediments prograded into the basin and gradually filled it up (Teng et al. 1991). In the back-stripping model, Chou (1992) showed that rapid sediment supply rate and tectonic subsidence characterize the Upper Oligocene succession. Therefore, the influence of tectonics and sedimentation are undoubtedly related to the relative sea-level changes and environmental variation in the Hsuehshan Trough.

5. CONCLUSIONS

Trace fossil distribution incompletely corresponds with the bathymetry in the marine environments. Water depth alone is not a major ecological factor, but it does influence controlling parameters such as hydraulic regime and dissolved oxygen content, among others. In this paper, integration of trace fossil, benthic molluscan, planktonic foraminifera, glauconite, and sedimentary structures can provide useful insight into water masses and bottom-water conditions. Based upon the discussion above, aeration of the bottom water may be the most important factor in trace fossil distribution. Decimeter-scale ichnocoenosis variation may reflect episodic short-term changes by several primary paleoceanographic conditions, controlled by climatic cycles (Savrda 1995). The many hundreds of meter-scale sedimentary units of each ichnocoenosis in this succession were deposited over 1 - 2 million years. This time range

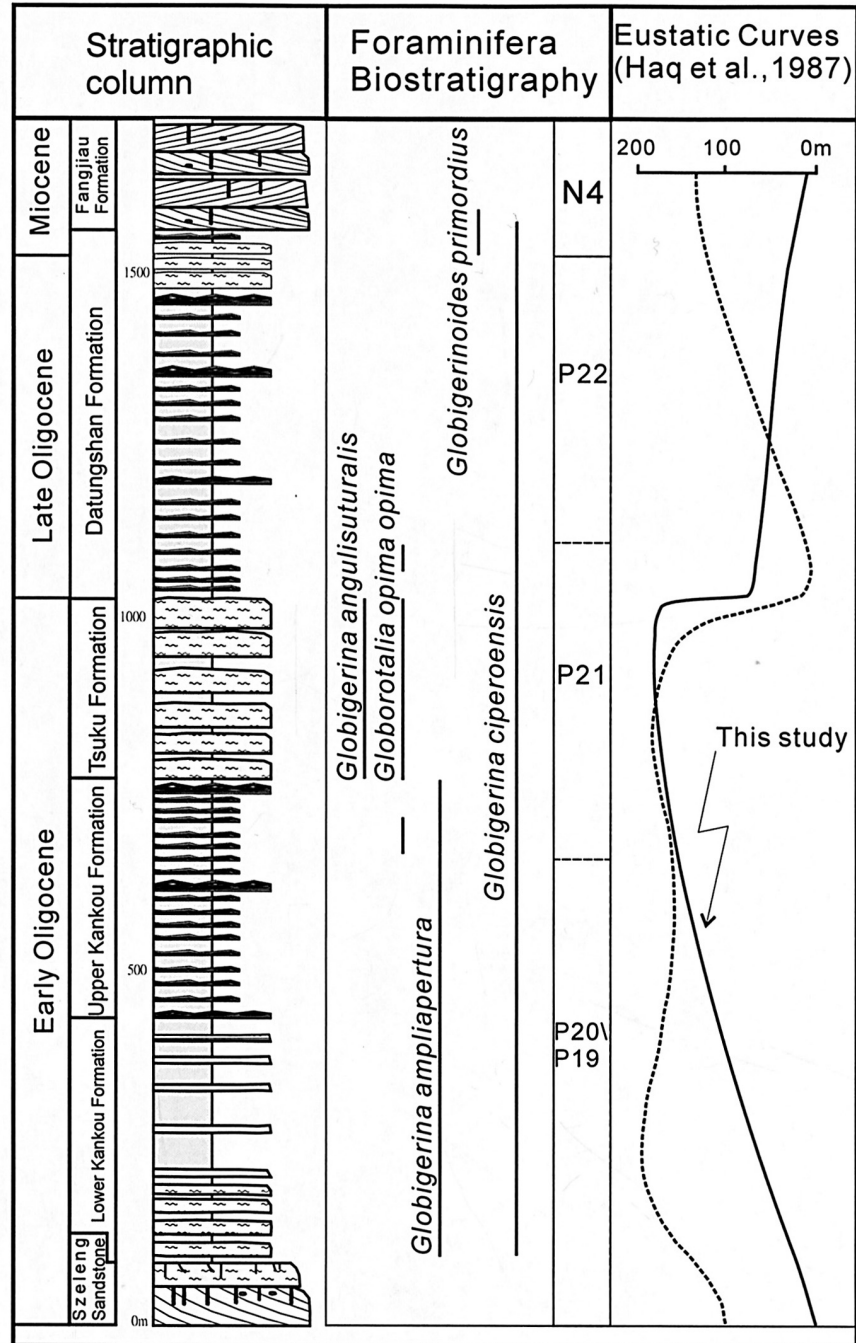


Fig. 14. Biostratigraphic and sequence-stratigraphic framework of the studied interval. Foraminifera biostratigraphy after Huang and Cheng (1983).

indicates that these trends of the Oligocene succession may be controlled by paleoceanographic conditions that are closely linked to local tectonics and the longer-term of first-order sea-level fluctuations.

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