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Storm sands with swaley cross-stratification in the Lower Miocene Taliao Formation, Taiwan

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With 12 figures in the text

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Abstract: A sedimentological investigation of a sandstone interval in the Early Miocene Taliao Formation of northern Taiwan shows that these sediments were deposited in a nearshore to offshore setting. The presence of hummocky cross-stratification, swaley cross-stratification, deep erosional scours, and intraformational conglomerates indicates that storms were an important depositional agent during the accumulation of these sediments. Combining information from trace fossils and primary sedimentary structures allows a threefold subdivision of the sequence into deposits of the upper shoreface, lower shoreface, and inner shelf. Swaley cross-stratification is a relatively recently recognized feature of storm influenced shoreface deposits, and has so far only been reported from a few localities. In the Taliao Formation it is restricted to upper shoreface deposits and was initially, in smaller outcrops, mistaken for low-angle beach cross-stratification. This experience indicates that reexamination of shoreline deposits from the geologic record may well lead to the recognition of many more occurrences of swaley cross-stratification.

Zusammenfassung: Die sedimentologische Untersuchung eines Sandsteinintervalls der Taliao Formation (Unteres Miozän) zeigt, daß diese Sedimente zwischen dem flach sublitoralen Bereich und der inneren Schelfzone abgelagert wurden. Sedimentstrukturen wie zum Beispiel »swaley cross-stratification«, »hummocky cross-stratification«, tiefe Erosionsrillen und Intraklastenkonglomerate sind Anzeichen, daß Stürme ein wichtiger Faktor während der Ablagerung dieser Sedimente waren. Wenn man Sedimentstrukturen und Spurenfossilien im Zusammenhang sieht, kann man drei verschiedene Ablagerungsräume unterscheiden: flaches Sublitoral (upper shoreface), mittleres Sublitoral (lower shoreface) und innerer Schelf. »Swaley cross-stratification« ist eine sturmerzeugte Sedimentstruktur, die erst kürzlich beschrieben wurde und die bis jetzt nur von wenigen Lokalitäten bekannt ist. In der Taliao Formation kommt »swaley cross-stratification« nur im flachen Sublitoral vor und wurde ursprünglich (in kleineren Aufschlüssen) als eine Strandablagerung interpretiert. Es ist deshalb durchaus möglich, daß »swaley cross-stratification« wesentlich häufiger ist und in vielen anderen Küstenablagerungen ebenfalls vorkommt.

Introduction

Wind- and wave-induced currents, particularly those due to storms, have a major impact on shelf hydraulic regime and sediment dispersal in many modern shelf seas (JOHNSON & BALDWIN 1986). Since the initial study by HAYES (1967), storm deposits have been documented from a variety of shelf settings worldwide (e. g. Reineck et al. 1967, GADOW & REINECK 1969, REINECK & SINGH 1971,

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Kumar & Sanders 1976, Howard & Reineck 1981, Aigner & Reineck 1982, Nelson 1982, Allen 1982, Figueiredo et al. 1982, Swift et al. 1983). Because the energy level of fair weather periods is considerably lower than that of storm periods, storm deposits have high preservation potential and can form a significant proportion of a given shelf sequence. Awareness of the importance of storm processes in recent shelf sedimentation has been paralleled by increasing recognition of storm deposits in ancient shelf deposits (for compilation see Marsaglia & Klein 1983 and Duke 1985). Of all the sedimentary features that are used to recognize storm deposits in ancient siliciclastic shelf sequences, a particular low-angle, undulatory lamination, now commonly known as hummocky cross-stratification or HCS (Harms et al. 1975, Dott & Bourgeois 1982, Duke 1985), has become almost synonymous with siliciclastic storm deposits. A list of a wide range of ancient deposits with hummocky cross-stratification has been compiled by Duke (1985), and the number of known ancient examples is still growing. Swaley cross-stratification (Leckie & Walker 1982) is a variant of hummocky cross-stratification in which predominantly the swales between hummocks are preserved. Only a few examples of swaley cross-lamination have been reported so far (Leckie & Walker 1982, McCrory & Walker 1986, Plint & Walker 1987). In the present study a new locality of swaley cross-stratified sandstones from Taiwan is described and interpreted in its overall stratigraphic context.

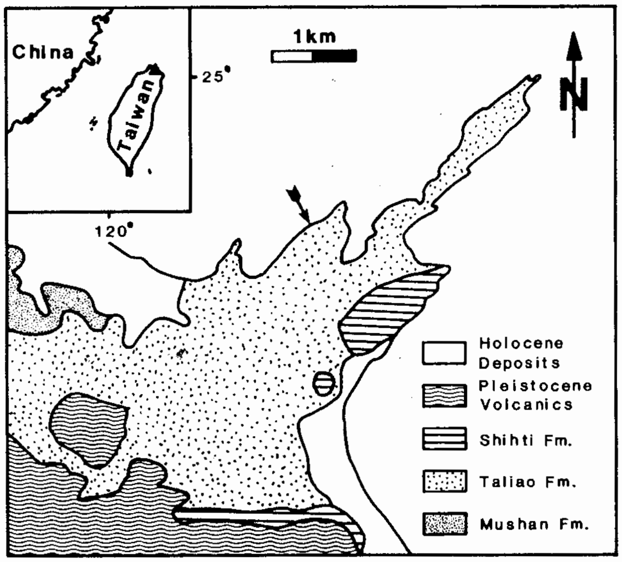


Fig. 1. Location of the study area in northern Taiwan (inset map) is indicated by black triangle. The geologic map (generalized from Huang 1981) shows the outcrop area of the Taliao Formation in the vicinity of the Yehliu promotory, as well as associated geologic units. The location of the measured section shown in Fig. 3 is pointed out with an arrow.

Geologic setting

The storm sands that are described in this contribution occur in the Early Miocene Taliao Formation (Ichikawa 1930) of northern Taiwan (Fig. 1). The Taliao Formation is part of Taiwan's Western Foothills province (Ho 1975). During the Miocene approximately 5500 m of predominantly clastic sediments were de-

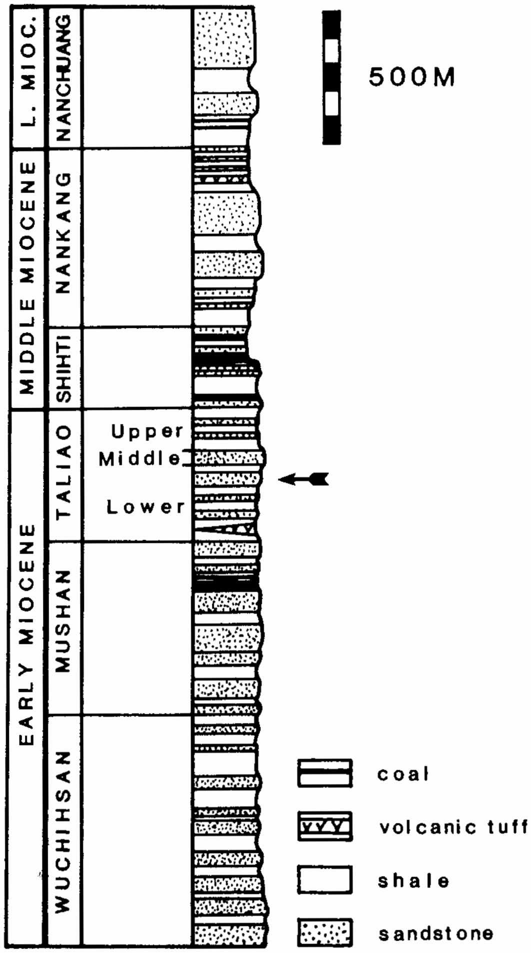
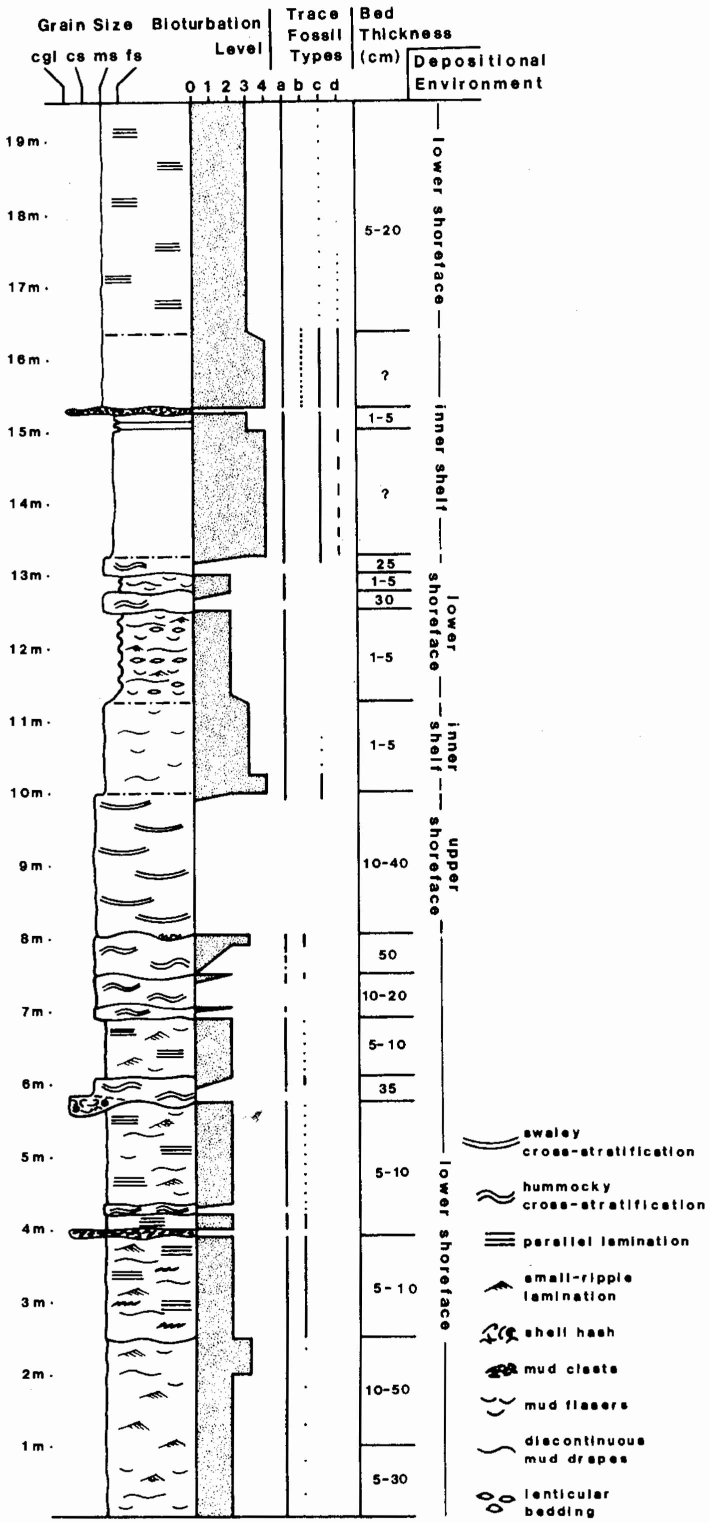


Fig. 2. Generalized stratigraphic column of Miocene strata along the northern coast of Taiwan. Arrow points out the position of the detailed section shown in Fig. 3.

Fig. 3. Detailed stratigraphic section measured at location pointed out by arrow in Fig. 1. Grain size abbreviations: cgl = conglomerate, cs = coarse sand, ms = medium sand, fs = fine sand. Bioturbation levels are displayed in five stages, from 0 (meaning no bioturbation) to 4 (meaning intense bioturbation with no primary sedimentary structures preserved). Trace fossil types: a = vertical tubes of the *Skolithos* type, b = horizontal branching burrow systems of the *Thalassionides* type, c = spreite burrows of the *Rhizocorallium* type, d = *Ophiomorpha* type burrows.


Grain Size
cgl cs ms fs
Bioturbation Level
0 1 2 3 4
Trace Fossil Types
a b c d
Bed Thickness (cm)
Depositional Environment
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17m
16m
15m
14m
13m
12m
11m
10m
9m
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6m
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lower shoreface
inner shelf
lower shoreface
inner shelf
upper shoreface
lower shoreface
swaley cross-stratification
hummocky cross-stratification
parallel lamination
small-ripple lamination
shell hash
mud clasts
mud flasers
discontinuous mud drapes
lenticular bedding

posited in this area with only minor depositional breaks. Three successive regressive-transgressive cycles are recognized within the Miocene sequence of northern Taiwan. Each cycle begins with a coalbearing facies, indicating a general regression of the sea. The coal-bearing facies is overlain by transgressive shallow marine strata. The sediment packages that constitute these three successive cycles are referred to as the Yehliu Group (Early Miocene; HO 1975), the Juifang Group (Middle Miocene; HO 1975), and the Sanshia Group (Late Miocene; ICHIKAWA 1929) respectively. Fig. 2 shows a generalized stratigraphic column of the lower two of these cycles and the base of the third cycle. Volcanic activity throughout most of Miocene time is indicated by scattered, irregular, and discontinuous lenses of basaltic pyroclastic rocks, lava flows, and tuffaceous sediments within these strata. The Taliao Formation is the uppermost formation of the Yehliu Group, which accumulated during the first depositional cycle in Early Miocene times (Fig. 2). The lower two formations of the Yehliu Group, the Wuchishan Formation and the Mushan Formation (YEN & CHEN 1953), reach a cumulative thickness of approximately 1600 m, are dominated by massive bedded medium to coarse grained sandstone, and contain interbedded shale rich units. Thin coal seams (in most places uneconomic) occur in the shaley units. Interbeds of glauconitic sandstone and shale indicate a mixed fluvial-deltaic to shallow marine origin of these sediments. The Taliao Formation itself consists in most places of thickbedded to massive sandstones that alternate with intervals of shale and silty shale (sandstone to shale ratio between 1 and 1.5). A rich fauna of foraminifers, mollusks, and echinoids indicates marine deposition (ICHIKAWA 1930, HO et al 1964). In northernmost Taiwan and also in the study area near Yehliu (Fig. 1), a calcareous sandstone unit (50–60 m thick) occurs in the middle of the Taliao Formation and allows subdivision into three members (HO et al 1964). A summary stratigraphic column of the Taliao Formation near Yehliu is shown in Fig. 2. In this study well exposed shoreline cliffs of the lower member of the Taliao Formation (Fig. 1) were examined in detail for sedimentary features, and a detailed stratigraphic section was measured (Fig. 3). Because the Taliao Formation has so far not been investigated sedimentologically, description of swaley cross-stratification will be integrated with a sedimentological interpretation of the measured sequence.

Description of measured sequence

Petrographic features

The measured sequence (Fig. 3) consists predominantly of very thin to thick bedded medium grained feldspathic sandstones. In addition to quartz and feldspars (K-spar and plagioclase), these sandstones contain variable amounts of metamorphic rock fragments (schists and polycrystalline quartz), volcanic rock fragments (basaltic to andesitic), chert and mudstone fragments, glauconite,

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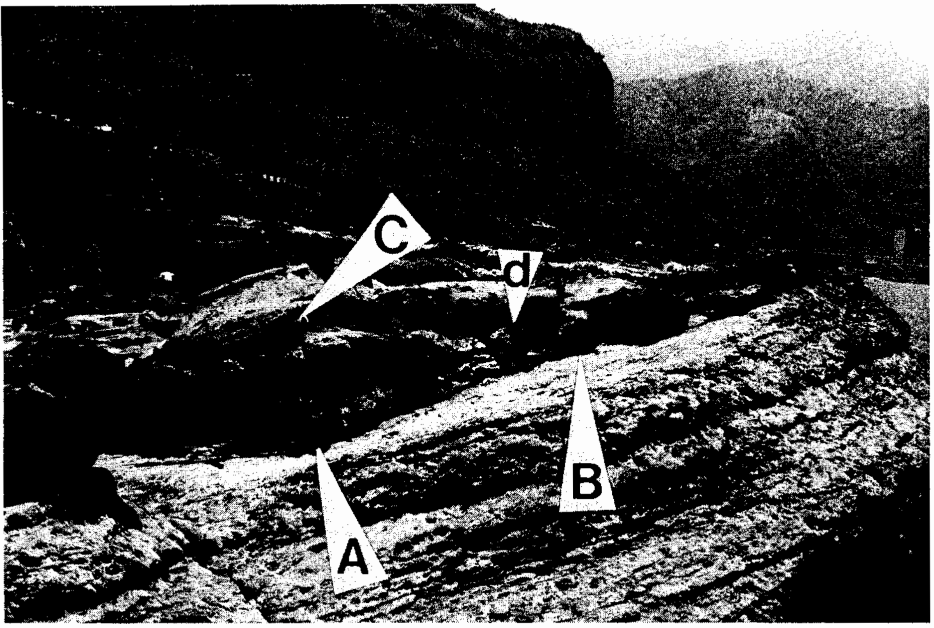


Fig. 4. Storm sand bed (at 6 m) with strong erosional base overlies bioturbated sands with remnants of parallel lamination. The deeper eroded scours at the base of this bed (arrow A) contain accumulations of gastropod and pelecypod shells. Top of bed pointed out by arrow C, erosional base pointed out by arrow B. Hammer (arrow D) is 32 cm long.

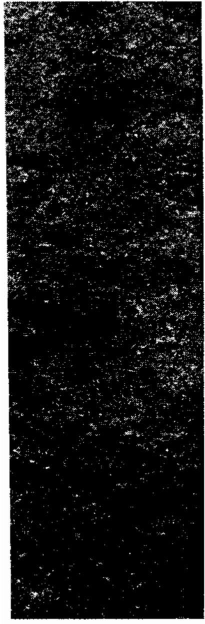
grains, micas, and traces of zircon and tourmaline. Grains are typically angular to subangular and of intermediate to low sphericity. Pore spaces may be filled with calcite cement or with a pseudomatrix of deformed mudstone fragments. At two stratigraphic levels (4 m and 15.25 m) thin wavy conglomerate beds, consisting of mudstone clasts (5–30 mm in size) in a sandy matrix, occur. Small lenses of mudstone clasts are found at the base of sandstone beds. Invertebrate shells and fragments thereof are present in calcareous concretions but essentially absent elsewhere in the sequence. This observation indicates that most calcareous shell material was dissolved during diagenesis. Large accumulations of pelecypod and gastropod shells are only found in erosive scours at the base of a sandstone bed at 6 m (Fig. 4).

Trace fossils

Bioturbation and trace fossils occur throughout most of the section measured at Yehliu, but intensity of bioturbation and relative abundances of trace fossil types vary considerably (Fig. 3). The dominant trace fossil type is *Skolithos*, followed by *Rhizocorallium*, *Diplocraterion*, *Thalassionides*, and *Ophiomorpha* (Figs. 5, 6, 7, 8). A variety of curved and horizontal burrows was observed in addition to the very distinct *Skolithos* tubes. Though common throughout the sequence, these burrows did not lend themselves to clear classification in outcrop. They

Fig. 5. Vertical burrow tube of the *Skolithos* type (14 m). Hammer handle is 45 mm wide at top.

Fig. 6. *Thalassionides* type branching horizontal burrow system. Hammer is 32 cm long.



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probably belong to trace fossil types such as *Arenicolites* and *Planolites*. Of the rhizocorallid spreite burrows (SEILACHER 1967), vertical forms (*Diplocraterion*) generally occur associated with variably inclined forms (*Rhizocorallium*), and the *Rhizocorallium* type burrows are predominant. For this reason these two trace fossil forms are not separately recorded in Fig. 3.

Sedimentary structures

The distribution and association of sedimentary structures is indicated in Fig. 3. Bedding planes throughout the sequence are of wavy character. Bioturbation has in places completely destroyed primary sedimentary structures (Fig. 7), and in other places primary sedimentary structures are only partially preserved (Fig. 4). In places where bioturbation intensity was between levels 0–2, identification of primary sedimentary structures is not problematic. At more intense levels of bioturbation, identification of primary sedimentary structures becomes increasingly tentative.

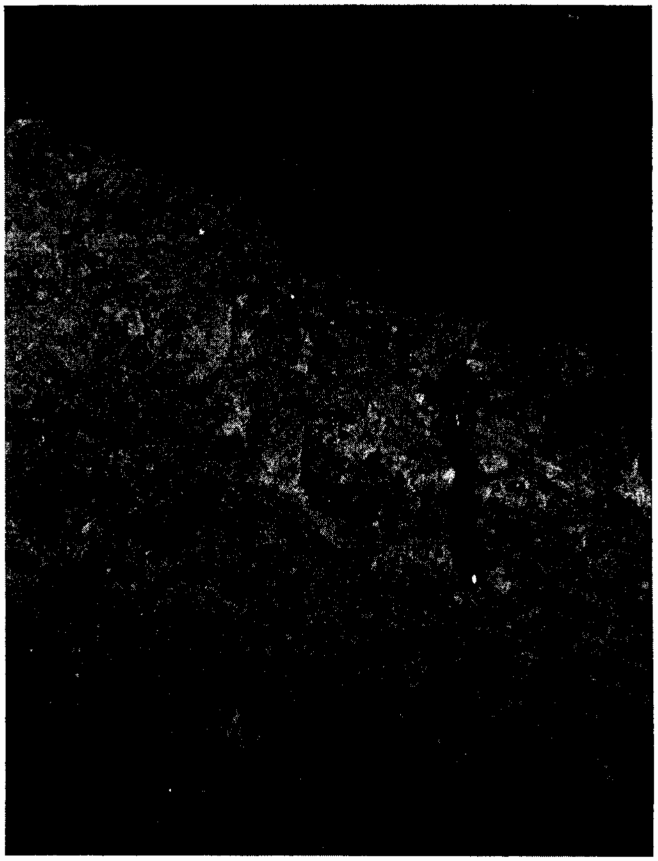


Fig. 7. *Rhizocorallium* type spreite burrows on an erosion surface subparallel to bedding (at 10.1 m). Pencil is 15 cm long.

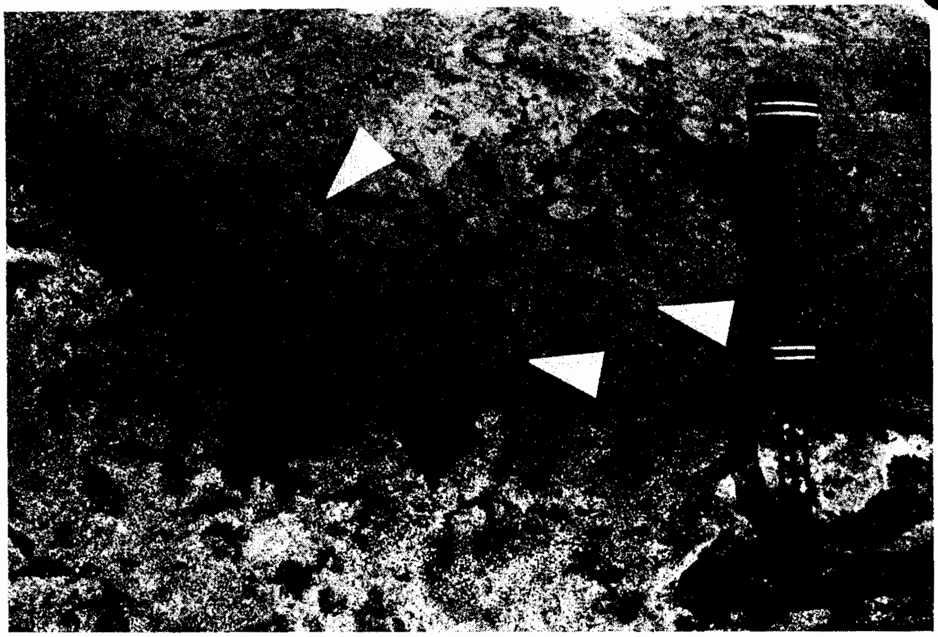


Fig. 8. *Ophiomorpha* type burrow tubes at 16 m. Note pelleted burrow linings (arrows). Hammer is 32 cm long.

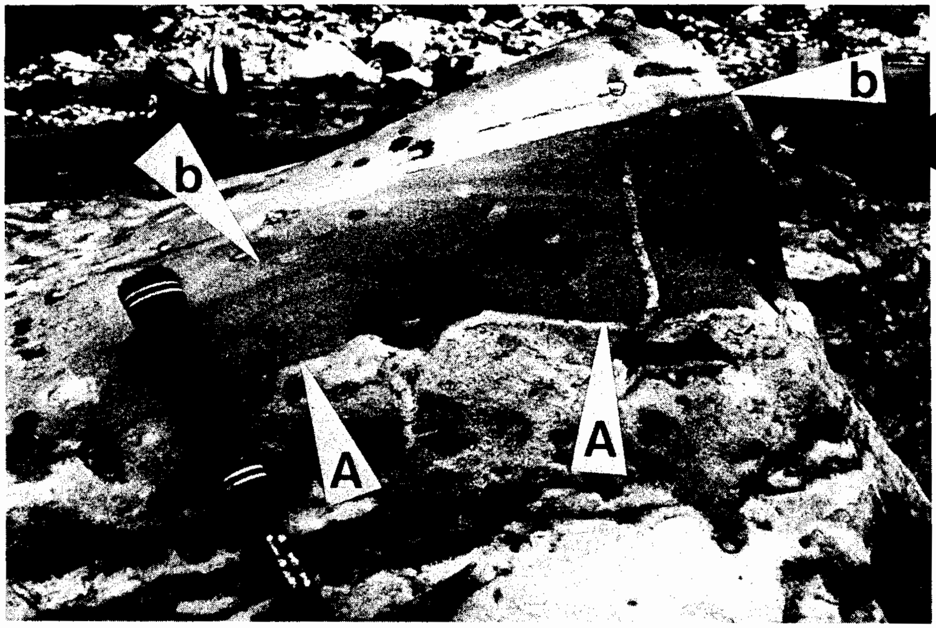
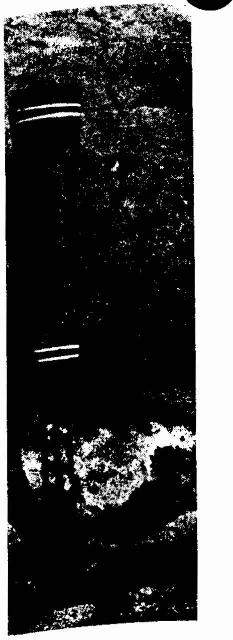


Fig. 9. Hummocky cross-stratified sandstone bed with sharp erosional base (arrows A) and escape traces. Note internal lamination and low angle truncation surfaces (arrows B). Hammer is 32 cm long.



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The basal 2.5m of the sequence are dominated by thin to medium bedded sandstone with wavy bedding planes, discontinuous mud drapes (1–10mm thick), mud flasers, and small-ripple bedding. Most of the interval between 2.5 and 7m is similar to the interval between 0–2.5 m, but contains in addition parallel lamination and three beds that are essentially free of bioturbation. The lowermost of these beds (at 4m) is a conglomerate bed (see above) that can be traced across the whole outcrop area. The other two beds are sandstone beds with a sharp base, a bioturbated top, and escape traces (Fig. 9). They contain internal sets of low angle undulating laminae that are separated by low angle truncation surfaces and fit the definitions set forth for hummocky stratification (HARMS et al. 1975, HAMBLIN & WALKER 1979, DOTT & BOURGEOIS 1982). One bed (at 6m) contains at the base deep erosional scours (up to 50cm thick) that are filled with gastropod and pelecypod shells in a sandy matrix. The interval between 7–8m consits of partly bioturbated HCS beds.

The interval from 8–10m is characterized by thick sets (10–14cm thick) of low angle curved laminae (concave-upwards) with truncation surfaces at the base of each set. No upward arched sets of laminae, only trough shaped sets (troughs about 2–4m wide) were observed. These features suggest that the observed type of low angle cross-stratification is what has been described as swaley cross-stratification (LECKIE & WALKER 1982). The base of the swaley cross-stratified inter-

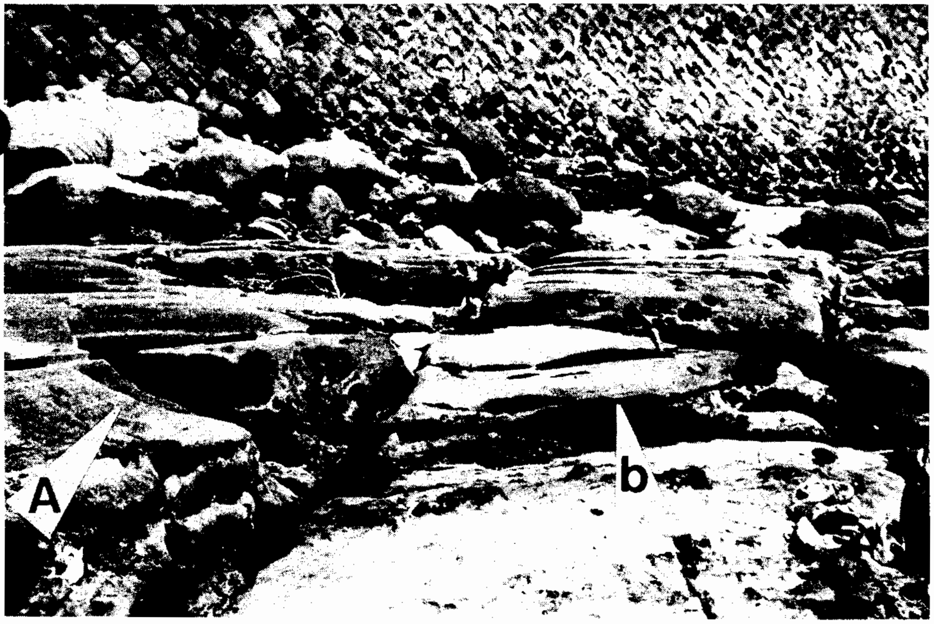

Fig. 10. Base of swaley cross-stratified interval. Basal unit of laminated sand (arrow A) that extends into a swale (arrow B) is truncated on top (dashed line) and overlayn by another unit of laminated sand. Hammer base is 18 cm long.

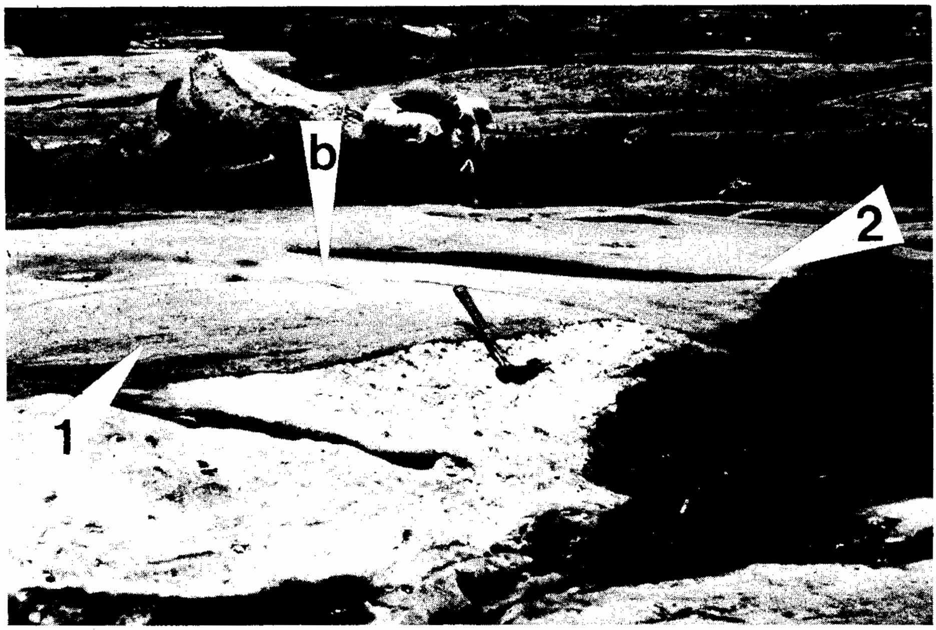

Fig. 11. Base of the Swaley cross-stratified interval (hammer handle at contact). Note sharp contrast to bioturbated sands below contact (at hammer handle). Two superimposed lamina sets (arrows 1 and 2) are separated by erosional surface (arrow B), the right lamina set is branching out into a swale to the right. Hammer is 32 cm long.

val shows a very sharp contact to the bioturbated sands below (Figs. 10, 11). This contact can be traced without difficulty through the whole extent of the cliff exposure. The top of the swaley cross-stratified interval is bioturbated and is overlain by thin bedded sandstones with discontinuous mud drapes and mud flasers.

The interval from 11.25–13.25m consists mainly of interbedded sandstone and mudstone and is characterized by mud flasers and wavy to lenticular bedding. Two thicker sandstone beds in that interval show sedimentary features of HCS beds, bioturbation at the top, and escape traces (Fig. 12). The top of the HCS bed at 13m is heavily bioturbated and grades into overlying heavily bioturbated and homogenized sandstone (from 13.25–15.25m). At 15.25m another conglomerate bed, very similar to the one at 4m and also continuous across the outcrop area, occurs. The sandstone interval above 15.25m is strongly bioturbated, but parallel low angle lamination and wavy beds are still recognizable.

Interpretation and discussion

That storms played a role during the deposition of these sediments is indicated by the presence of hummocky cross-stratified (HCS) sandstone beds, which in many other places have been interpreted as storm deposits (Duke

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Fig. 12. Storm sand bed with well developed escape trace (12.7 m). Ruler is 24 cm long.

1985). Bioturbation at the top of these beds and escape traces (Figs. 9, 10) indicate very rapid, episodic deposition of these beds. Accumulation of shells and shell fragments in deep erosional scours as well as the erosion and concentration of mudstone fragments suggests the occasional presence of exceptionally strong currents at the seafloor. Both, episodic deposition and occasional strong currents, are indications that storms were active during deposition of the sequence.

Within more strongly bioturbated portions of the section (0–7m and 15.25–19.5m), relicts of parallel low angle lamination, wavy bedding planes, discontinuous mud drapes, and truncated burrows indicate multiple erosional and depositional events. These features and the association of these intervals with HCS beds suggests that they are amalgamated hummocky sequences (Dott & Bourgeois 1982). In such sequences beds were thin enough and periods between storms were long enough so that bioturbation could destroy significant portions of the original sedimentary features.

Intervals of the sequence that contain discontinuous mud drapes, mud flasers, wavy and lenticular bedding (0–7m and 10–13m), require that conditions of current or wave action alternate with slack water periods to allow deposition of mud (REINECK & SINGH 1980). Though commonly found in tidal seas, above sedimentary features can also be produced by storms in shelf seas (REINECK & SINGH 1980). That storms were contributing to deposition of these sediments is also indicated by thin wavy sand beds that show less bioturbation than sediments below and above.

Following other authors that have published on hummocky cross-stratification (e.g. HAMBLIN & WALKER 1979, DOTT & BOURGEOIS 1982, SWIFT et al, 1983) the general depositional environment of the HCS beds in the Taliao Formation can be considered an open marine offshore area below fair weather wave base. The paucity of mudstone intervals in the sequence and the presence of bioturbated amalgamated HCS sequences suggests deposition in a proximal, relatively shallow setting (DOTT & BOURGEOIS 1982).

Swaley cross-stratification (SCS) as observed in the interval from 8–10m also indicates deposition by storms (LECKIE & WALKER 1982, DUKE 1985). In the examples that have been described from the stratigraphic record (LECKIE & WALKER 1982, MCCRORY & WALKER 1986, PLINT & WALKER 1987), sands with swaley cross-stratification are found directly above offshore sediments with HCS beds, and are capped by nonmarine sediments or erosion surfaces. This association suggests that swaley cross-stratification most likely forms on the shoreface, probably shallower than fairweather base (DUKE 1985). In the Taliao Formation swaley cross-stratified sands are under and overlain by sediments that contain HCS beds. Because swaley cross-stratification appears to form in shallower water than hummocky cross-stratification (DUKE 1985), the measured portion of the Taliao Formation (Fig. 3) may indicate upward shallowing (or shoreface advance), followed by renewed submergence (or shoreface retreat). In small outcrops of SCS in the Taliao Formation the trough-shaped swales can not be recognized, and only evenly laminated sands with low-angle discordances are observed. Because the latter cross-bedding type is typical for beach deposits, SCS sands in the Taliao Formation were initially mistaken for beach sands.

The trace fossil types identified in these rocks, particularly the presence of *Skolithos* throughout most of the sequence (Fig. 3), indicate that the sediments were deposited along a sandy shoreline (SEILACHER 1967, CRIMES 1975; FREY & SEILACHER 1980), in environments ranging from shoreface (*Skolithos* facies) to offshore (*Cruziana* facies). Beach-offshore zonations of lebensspuren from studies of recent shorelines (DÖRJES & HERTWECK 1975) show a predominance of vertical tubes (similar to *Skolithos*) in shoreface sediments. A variety of U-shaped burrows (similar to *Rhizocorallium*), in association with multibranched burrow systems (similar to *Thalassionides* and *Ophiomorpha*) and vertical tubes characterizes the offshore-transition (or inner shelf region). Thus, comparison of trace fossil distributions in the Taliao Formation with those observed in ancient and recent sediments suggest that the examined section of the Taliao Formation was deposited in a shoreface to offshore setting.

In preceding paragraphs it has been shown that the same overall depositional setting is indicated by trace fossils and primary sedimentary structures. A combination of the two approaches can tentatively be used to distinguish three depositional environments in the studied sequence, upper shoreface (above fair weather wave base), lower shoreface (below fair weather wave base), and inner shelf (below fair weather wave base).

The SCS interval between 8–10m is thought to represent the upper shoreface environment. This interpretation is supported by other studies of SCS (Leckie & Walker 1982, McCrory & Walker 1986; Plint & Walker 1987) and the complete absence of bioturbation. Paucity of bioturbation in upper shoreface deposits has for example been noted by Reineck & Singh (1971) and by Harms et al. (1982).

Those portions of the section that are dominated by *Skolithos* type trace fossils (0–8m, 11.25–13.25m, and 16.25–19.5m), discontinuous mud drapes, and relicts of amalgamated HCS beds are considered as deposits of the lower shoreface. Trace fossil content (Fig. 3) and amalgamation of HCS beds indicates a shallow nearshore setting (Dott & Bourgeois 1982, Crimes 1975), and the fact that the lowest interval (0–8 m) is overlain by nonbioturbated SCS beds of probably upper shoreface origin suggests a lower shoreface origin. Within the interval from 0–8m, an upward increase of thicker and well preserved HCS beds can be observed (Fig. 3). This circumstance suggests a shallowing trend and increasing proximity to the shoreline (Aigner & Reineck 1982).

Intensely bioturated portions of the sequence (10–11.25m, 13.25–16.25m) that contain evidence of sediment feeders (*Rhizocorallium*) are considered to indicate an inner shelf setting, because of the direct association with lower shoreface sediments, the extreme bioturbation (no primary structures preserved), and the sandy nature of the deposits. Recent beach-shelf profiles are characterized by the highest degree of bioturbation in the inner shelf region (e.g. Reineck et al. 1968, Reineck & Singh 1971, Howard & Reineck 1972) and an appreciable increase in mudstone towards the outer shelf.

Conclusions

A new example of swaley cross-stratification has been identified in the Early Miocene Taliao Formation of Taiwan. Investigation of sedimentary and biogenic structures in the sequence that contains these swaley cross-stratified beds shows, (a) that these sediments accumulated in an upper shoreface to inner shelf setting, and (b) that storms played a major role in their deposition. As in other studied examples, SCS beds of the Taliao Formation are found at the top of a progradational shoreline sequence, overlying lower shoreface sediments with HCS (hummocky cross-stratification). Inner shelf sediments on top of this progradational sequence (0–10m) indicate renewed transgression (Fig. 3). Intercalated inner shelf and lower shoreface sediments in the upper half of the section indicate repeated shoreline oscillations. The sharp contact at the base of the SCS interval (Fig. 11) is an unusual feature for progradational shoreline sequences which are commonly gradational as one goes upsection (REINECK & SINGH 1971, HARMS et al. 1982). A sudden increase in sand supply to the shoreline may have caused fast buildup of the SCS interval and could have prevented the formation of a transition interval between lower and upper shoreface. Because swaley cross-stratification resembles cross-bedding typical of beach deposits, there may be many other occurrences of SCS in the geologic record that have not yet been recognized.

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