Geologia Croatica	58/2	163–184	29 Figs.			ZAGREB 2005

The Benkovac Stone Member of the Promina Formation: A Late Eocene Succession of Storm-Dominated Shelf Deposits

Ervin **MRINJEK**[1], Vili **PENCINGER**[2], Jasenka **SREMAC**[1] and Boris **LUKŠIĆ**[2]

Key words: Shelf, Shoreface, Offshore transition zone, Tempestites, Hummocky cross-lamination, Wave ripples, Oscillatory waves, Combined-flow currents, Trace fossils, Braidplain delta, Sequence stratigraphy, Northern Dalmatia, Croatia.

Abstract

The Upper Eocene Benkovac Stone Member of the Promina Formation of northern Dalmatia, Croatia, is a thinly bedded succession of alternating carbonate sandstones and calcareous mudstones, ca. 40 m thick, exposed as a narrow, SE-trending outcrop belt near the town of Benkovac. This unit occurs in the middle part of the Promina Formation, which is a spectacular calciclastic succession of deposits of late Middle Eocene to Early Oligocene age, about 2000 m thick, showing an upward trasition from deep-marine turbidites to shallow-marine and alluvial deposits.

The sheet-like sandstone beds of the Benkovac Stone Member are mainly 1–25 cm thick and have been classified into 6 facies and 3 subfacies, differing in stratification or showing various internal sequences of stratification types. The thicker and most common beds show plane-parallel stratification passing upward into hummocky cross-lamination and undulatory to flat parallel lamination (Facies S1), or consist of only the latter two divisions (Facies S2). Subordinate beds show convolute stratification (Facies S3), are amalgamated (Facies S4), or are homogenized and merely graded (Facies S6). The thinner beds have more uneven boundaries and show translatory ripple cross-lamination (Subfacies S5a), climbing ripple cross-lamination (Subfacies S5b) or pinch-and-swell lamination attributed to starved and rolling-grain ripples (Subfacies S5c). The intervening mudstone beds (Facies M) are silt-streaked and bioturbated. Trace fossils indicate a combination of *Zoophycos* and *Cruziana* ichnofacies.

The sedimentary succession was deposited in a microtidal offshore transition zone characterized by muddy "background" sedimentation punctuated by discrete storm events. The observed spectrum of tempestite sandstone beds represents a wide range of storm events, varying in magnitude and in the mode of sand dispersal – from the pure action of oscillatory waves to pure geostrophic currents. The majority of tempestites are attributed to a combination of these two end-member factors, with the geostrophic currents often enhanced by a high load of sediment suspension (density-modified currents).

The Benkovac Stone Member is underlain by muddy offshore deposits (Debelo Brdo Member) and covered by sandy to gravelly shoreface deposits (Otavac Member), which in turn pass upwards into braidplain deltaic and alluvial deposits. This regressive succession is considered to be a parasequence deposited as a highstand systems tract during a gradual, stepwise rise of relative sea level. The thick parasequence consists of progradational and retrogradational sets of much smaller parasequences, the record of which differs markedly in the shoreface and offshore transitional part. The difference is attributed to the underlying contrast in the physical factors controlling the supply of sand to these shallow shelf zones.

1. INTRODUCTION

This paper is concerned with a middle member of the Promina Formation (known also as the Promina Beds) of northern Dalmatia. The Upper Eocene Benkovac Stone Member consists of thinly bedded, shallow-marine calciclastic deposits that crop out as a narrow, SE-trending belt near the town of Benkovac (Fig. 1). The component sedimentary facies of the Benkovac Stone Member are described in detail and their genesis is discussed, which leads to an environmental model of a storm-dominated offshore transition zone. The palaeogeography, stratigraphic context and regional significance of this tempestitic succession are also discussed. The paper sheds new light on the origin of a little-studied part of the Promina Formation, and thus contributes to a better understanding of the latter.

2. STRATIGRAPHIC SETTING AND PREVIOUS STUDIES

The Promina Formation is a succession of calciclastic deposits of late Middle Eocene to Early Oligocene age, approximately 2000 m thick, with a prominant shallowing-upward trend from deep- to shallow-marine and alluvial facies. The Benkovac Stone Member belongs to the transitional middle part of the Promina Formation, overlying its turbiditic lower part.

The Promina Formation is the upper part of the extensive Palaeogene clastic succession of northern Dalmatia, overlying Mesozoic to Middle Eocene platform carbonates. The Promina Formation overlies conform-

[1] Department of Geology and Palaeontology, Faculty of Science, University of Zagreb, Horvatovac 102a, HR-10000 Zagreb, Croatia; e-mail: ervin.mrinjek@zg.htnet.hr.

[2] Croatian Geological Survey, Sachsova 2, HR-10000 Zagreb, Croatia.

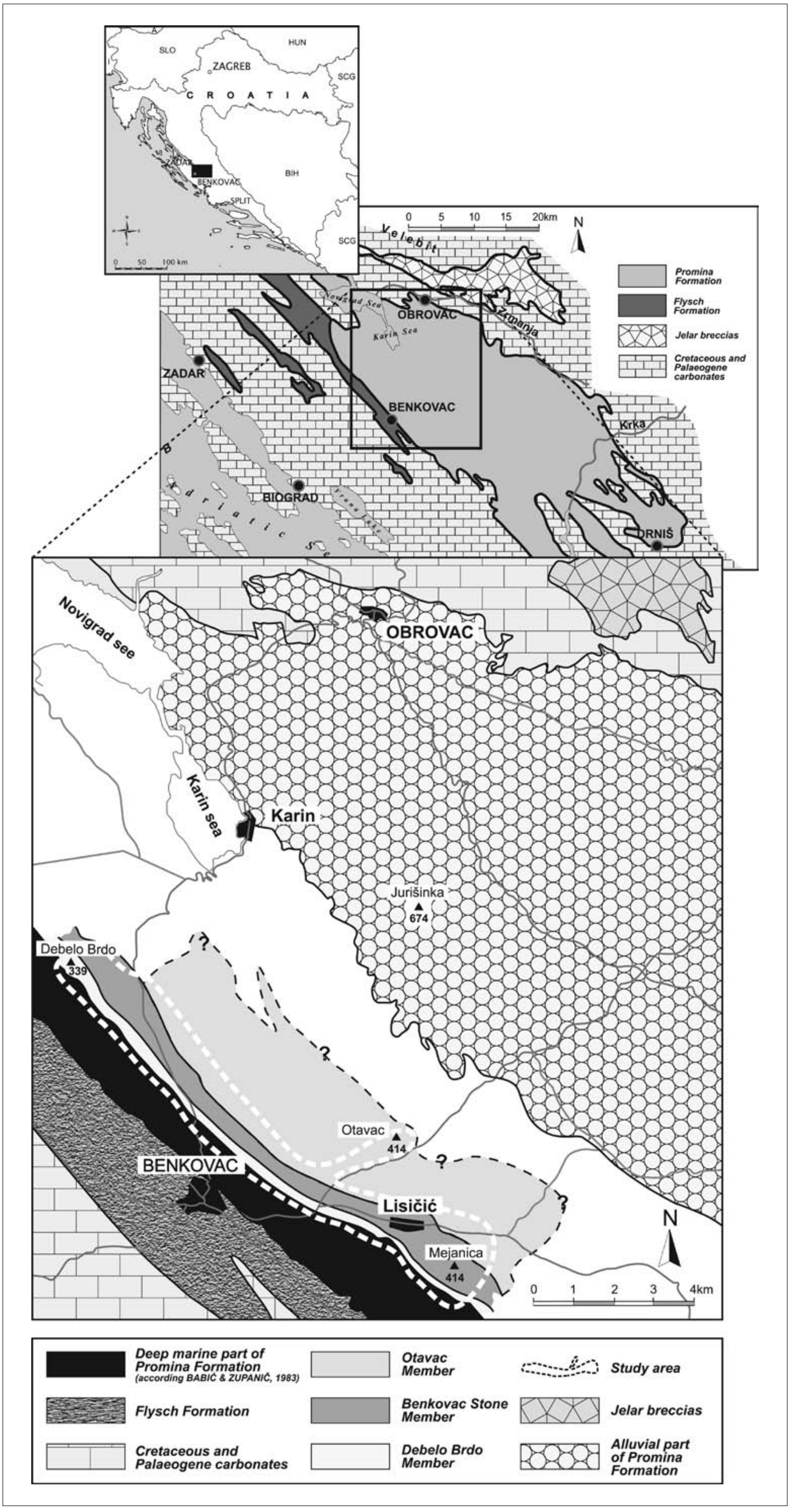

Fig. 1 Regional location (inset) and geological map of the study area, showing the main lithostratigraphic units (modified from IVANOVIĆ et al., 1973).

Fig. 2 A broad view from Mejanica hill, looking towards the northwest. The occurrence of the Benkovac Stone Member is marked by numerous small quarries and other local excavation pits.

ably the so-called Flysch Formation and covers unconformably the Cretaceous and Palaeogene carbonates in the central part of the region. The Flysch Formation is of Late Lutetian age and about 900 m thick, and constitutes the lower part of the Palaeogene clastic succession (SCHUBERT, 1905; MULDINI MAMUŽIĆ, 1972; IVANOVIĆ et al., 1976).

The Palaeogene clastic succession, together with the carbonate Jelar Breccia Formation (Fig. 1), were deposited in a common basinal setting and recorded regional phases of Eocene and younger tectonic deformation. The Jelar Breccia occurs in the basin's marginal zone, where it overlies deformed Mesozoic deposits and is considered to have been the source of carbonate detritus for the Promina Formation and the underlying Flysch Formation (IVANOVIĆ et al., 1976; MRINJEK, 1993a, b; SAKAČ et al., 1993).

On the basis of seismic lines, deep wells and surface mapping, TARI-KOVAČIĆ & MRINJEK (1994) interpreted the Palaeogene clastic succession of northern Dalmatia as "tectogenic" deposits, formed concurrently with regional tectonic deformation. In their complicated, polyphase tectonic interpretation of the northern Dalmatia basin, the authors consider the Jelar Breccia as "proximal" deposits linked to an early (Lutetian–Bartonian) compressional deformation of the carbonate platform, and the Flysch Formation to be their "distal" equivalent. The next phase of tectonic compression (Bartonian to possibly Oligocene) is thought to have caused folding and thrusting of the underlying platform carbonates, together with the tectonic transport and cannibalization of the flysch and breccia units, which led to the development of a new elongate foreland basin, trending NW–SE and filled by the shallowing-upward Promina Formation. In their seismic interpretation, TARI-KOVAČIĆ & MRINJEK (1994) consider the final tectonic structure of northern Dalmatia to be a result of the duplexing of internal thrusts and basin-edge thrusting, which caused uplift and considerable erosion of the Promina Formation.

Several papers addressed the sedimentology of the Promina Formation. In the alluvial upper part of this formation (Fig. 1), BABIĆ & ZUPANIČ (1988) and MRINJEK (1993a, b) recognized a predominance of sheet-like and channel-fill, commonly cross-stratified conglomerates. The great lateral extent and internal characteristics of these deposits indicate a braidplain environment with a consistent palaeoflow direction towards the southwest (MRINJEK, 1993a). MRINJEK (1993b, 1994) described the braided-river facies and architectural elements, and suggested a model of subsidence-driven (i.e., accommodation-controlled) sedimentation on the basis of the spatial distribution of allocyclic facies associations, with the deposition of gravel reflecting syntectonic and post-tectonic phases. MRINJEK (1993a, b) pointed out that the subaerial alluvial succession is intimately associated with shallow-marine and shoreline deposits, and represents an extensive, progradational braid-delta system (i.e., a delta formed by braidplain advance).

In the vicinity of Karin (Fig. 1), BABIĆ & ZUPANIČ (1990) described cyclically-organized deposits representing a progradational, shallowing-upward transition from alternating shelf mudstones and sandstones to shoreface sandstones, and from Gilbert-type delta conglomerates to braided-river conglomeratic alluvium. The cyclic stacking of parasequences was attributed to the phases of shoreline progradation alternating with marine transgressions (relative sea-level rises).

ZUPANIČ & BABIĆ (1981) and BABIĆ & ZUPANIČ (1983) interpreted the lower part of the Promina Formation, underlying the shallow-marine Debelo Brdo and Benkovac Stone members, as deep-marine deposits, comprising calciclastic turbidites intercalated with several thick beds containing huge olistolithic blocks of shallow-marine limestones. The Debelo Brdo Member consists chiefly of calcareous mudstones, whereas the Otavac Member (Fig. 1; unit named after the area of its best exposure at Otavac hill) is a succession of alternating calcareous sandstones and conglomerates. All these members are readily distinguishable by their characteristic lithological suites and are also mappable outside of the present study area (Fig. 1).

3. STUDY AREA

The study area is in a narrow, SE-trending belt (Fig. 1) that extends between the Debelo Brdo hill, about 10 km northwest of Benkovac and the Mejanica hill, about 1 km southeast of the village of Lisičić. The area has a low topographic relief covered with short vegetation (Fig. 2), and the general rock bedding here is gently inclined towards the northeast.

The Benkovac Stone Member, with its tabular bedding and platy splitting pattern, has long been an impor-

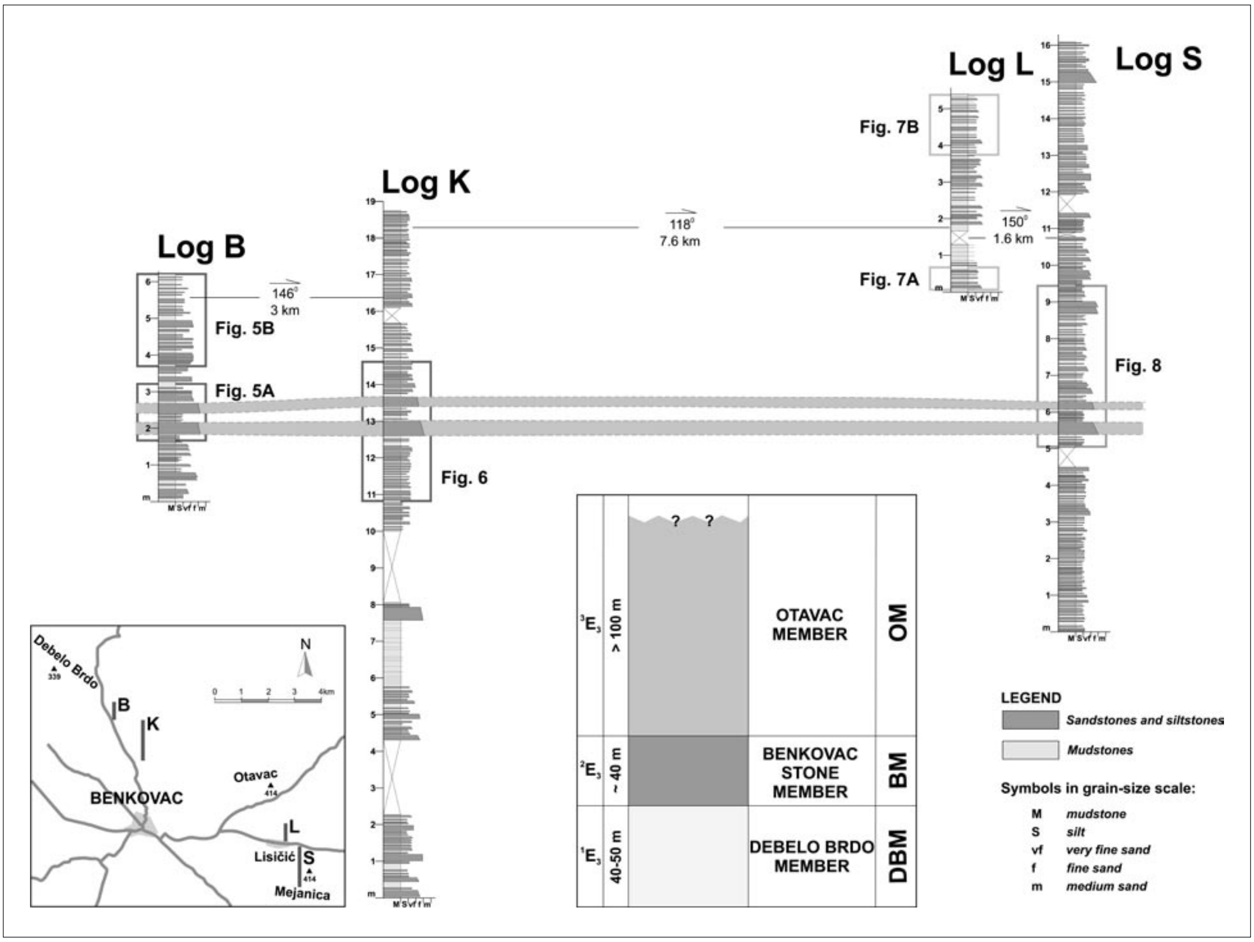

Fig. 3 Simplified logs of the Benkovac Stone Member and their location map (inset). The logs have been correlated on the basis of marker storm beds. The figure includes portions of the overlying and underlying lithostratigraphic units (inset).

tant local source of building stone (hence the member's name), and the numerous small quarries allow detailed study of this calciclastic succession. The sandstone beds are up to 35 cm thick, but mainly thinner, and the sandstone-rich heterolithic succession is readily distinguishable from the underlying and overlying members (see previous section).

The succession has been logged at four representative localities (Fig. 3). Log B is from an excavation pit in the vicinity of Benkovac (Fig. 4A); log K is from a Kimont company quarry (Fig. 4B); log L is from an excavation pit near the village of Lisičić (Fig. 4C); and log S is from a quarry near a former military shooting-range in the vicinity of Strelište (Fig. 4D).

4. METHOD AND TERMINOLOGY

The sedimentological data for this study have been acquired by detailed lithostratigraphic logging of the outcrop sections, aided by thin-section analyses. The descriptive sedimentological terminology used is after HARMS et al. (1975, 1982) and COLLINSON & THOMPSON (1982). By convention, the term "lamination" is used with reference to small-scale (ripple) cross-stratification, and to planar or undulatory parallel stratification in deposits that are finer-grained than sand.

The conventional term "(sedimentary) facies" refers to the basic varieties of sedimentary deposits, distinguished descriptively on the basis of their bulk macroscopic characteristics (mineral composition, texture, colour, primary and secondary sedimentary structures, biogenic features, bedding geometry). Facies are thus considered to be the basic "building blocks" of a sedimentary succession (HARMS et al., 1975; WALKER, 1984).

The terms carbonate sandstone, siltstone and mudstone are used for deposits containing a considerable amount of calcareous grains and composed of predominantly sand, silt and mud fractions, respectively, regardless of the actual proportion of calciclastic and siliciclastic components.

5. DESCRIPTION OF THE BENKOVAC STONE MEMBER

The Benkovac Stone Member is about 40 m thick and consists of carbonate sandstones interbedded with finer-

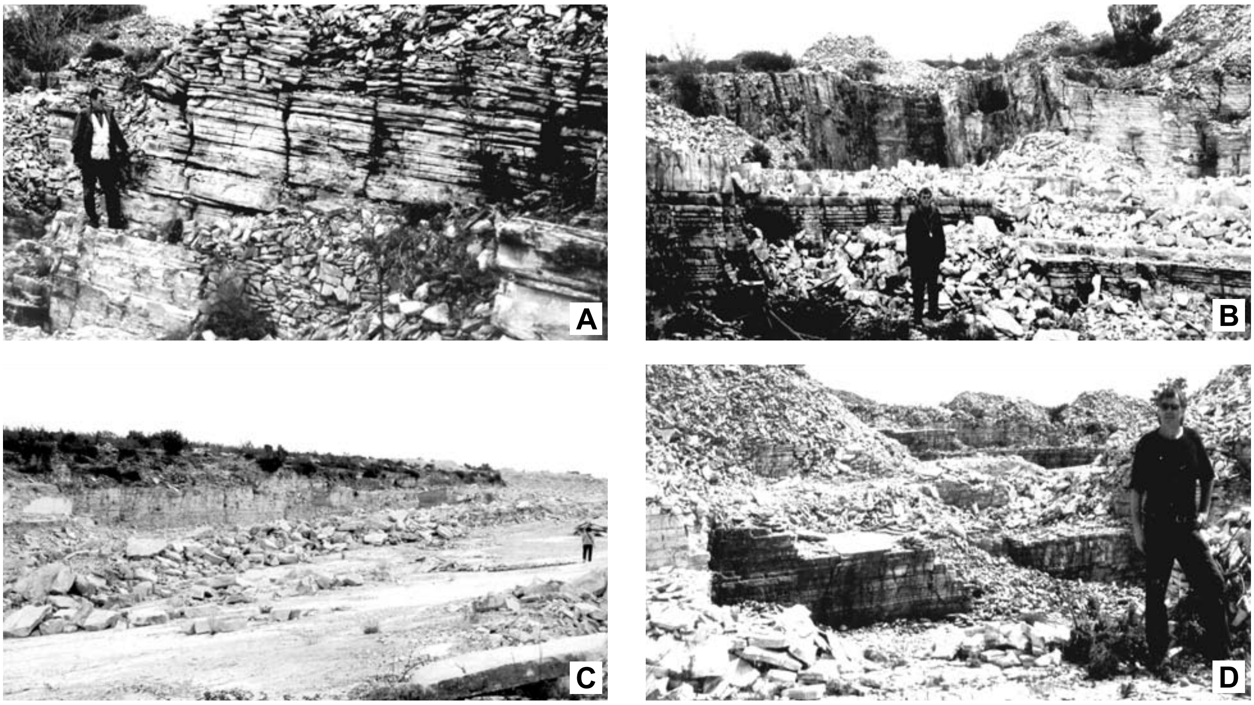

Fig. 4 Photographs of the quarries from which the logs in Fig. 3 have been derived: (A) Log B site near Benkovac; (B) Log K site in Kimont quarry; (C) Log L site near Lisičić; (D) Log S site near Strelište.

grained calcareous deposits. Its Late Eocene age was established on the basis of large benthic foraminifera (nummulitids, discocyclinids) and small pelagic globigerinids.

The sandstones are very fine- to fine-grained calcarenites, sporadically medium-grained, and consist mainly of various sparitic and micritic grains. Quartz grains are subordinate (less than 10 vol. %). The sand grains are subrounded to rounded and generally well to very well sorted, forming a grain-supported framework with mostly point or planar grain contacts. Interstitial spaces are filled with a microcrystalline carbonate cement and/or fine-grained calcareous sediment.

The finer-grained interbeds are carbonate siltstones and mudstones, moderately to strongly burrowed. Recognizable trace fossils represent a mixture of *Zoophycos* and *Cruziana* ichnofacies. The siltstones are calcisiltites composed mainly of medium to coarse silt-sized carbonate grains and up to 10 vol. % of quartz grains. The calcareous mudstones are slightly clayey micrites with scattered silt-sized carbonate and quartz grains.

5.1. Carbonate sandstone facies

The carbonate sandstone beds are predominantly tabular and separated by mudstone layers, with relatively few beds amalgamated, stacked directly upon one another. The light-brown to grey sandstones are readily distinguishable from the pale yellowish–grey mudstones, even though their weathering patterns are not necessarily dissimilar. The sandstone beds vary considerably in thickness (Figs. 5–8) and have been classified into six facies and three subfacies, which are described in the present section.

5.1.1. Facies S1: tripartite sandstone beds with planar parallel stratification, hummocky cross-lamination and flat parallel lamination

These are the thickest sandstone beds, with average thicknesses in the range of 5 to 25 cm (see logs in Figs. 5–8 and outcrop details in Figs. 9–15). Their basal surfaces are sharp and erosional, with an irregular relief of 1 to 7 cm, whereas their tops are slightly uneven or undulatory, with a relief of 2 to 6 cm. The beds are normally graded, with the particle size ranging from medium to fine or very fine sand. Even the thicker beds most often consist of fine to very fine sand and commonly coarse silt at the top. The basal surfaces locally show load casts, which are bulbous or irregularly-shaped features lacking preferred orientation. Basal mudstone injections in the form of load-flame structures occur in places (Fig. 10).

Gutter casts (LECKIE & KRYSTINICK,1989; EINSELE & SEILACHER, 1982) are sporadically found at the bases of the thickest beds. These isolated grooves are 1–2 cm deep and 4–5 cm wide, filled with sand and occasionally bearing mudstone intraclasts (Fig. 13). The groove orientation shows a NE–SW to N–S trend.

Internally, these sandstone beds characteristically consist of three divisions. The lower division (*P*) is 3 to 20 cm thick and shows planar parallel stratification (Figs. 9–13), although it is locally poorly recognizable in some beds. The strata are 0.2–0.4 cm thick, almost perfectly flat in the lower part and slightly undulatory

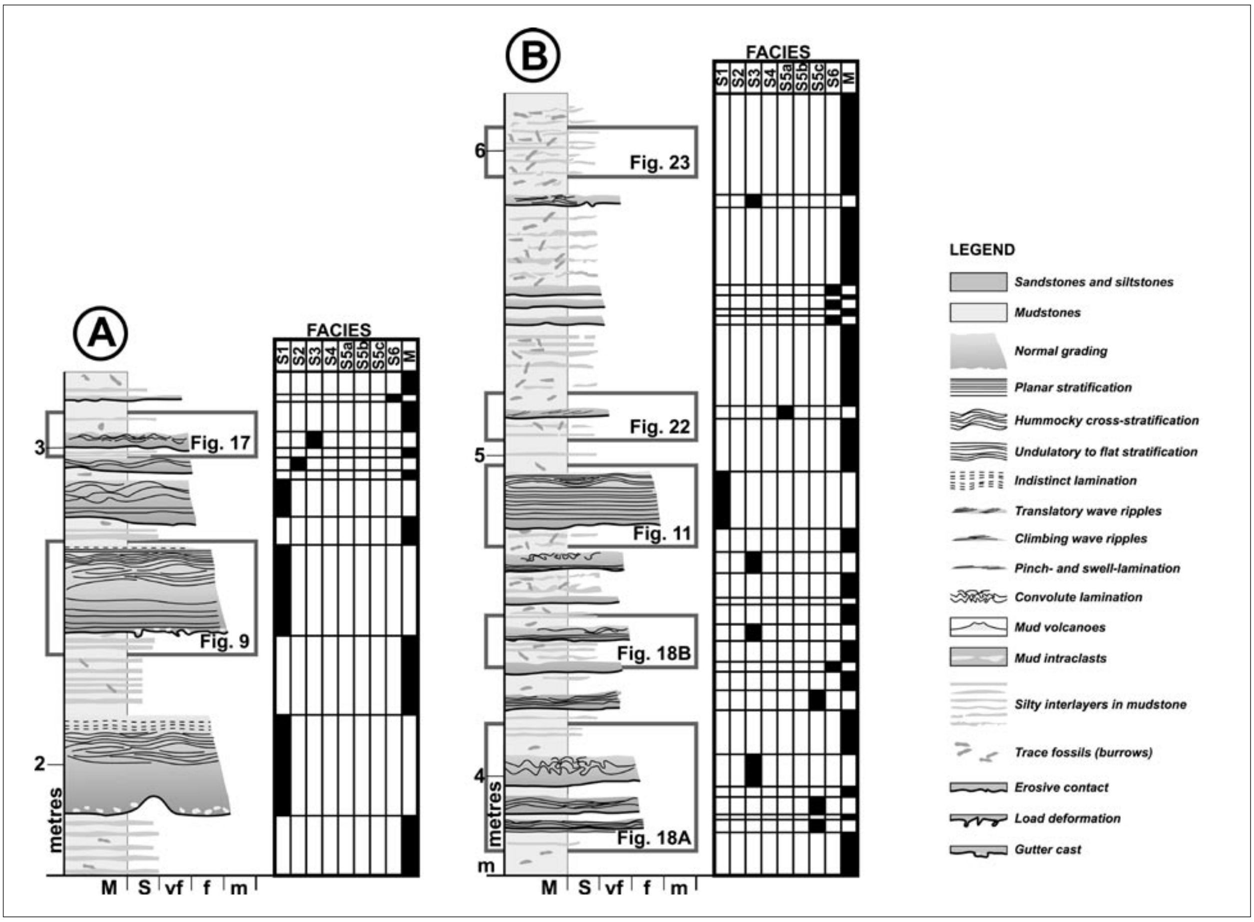

Fig. 5 Detailed portions of log B (see indicated in Fig. 3), with a general legend pertaining to Figs. 5–8.

in the upper part. Grain size varies from fine or medium to very fine sand. In the thickest beds of this facies, the parallel-stratified division is often underlain by a medium-grained sand horizon, 1 to 3 cm thick, which is rich in mudstone intraclasts. The mudclasts are angular, 0.5 to 6 cm long and flat-lying, parallel to the basal surface and sandstone strata (see Figs. 5A, 6, 8, and 13).

The overlying, middle division (*H*) is 4 to 15 cm thick and shows medium- to small-scale hummocky cross-stratification (HARMS et al., 1975); the latter is here referred to as hummocky cross-lamination. Grain size varies between fine and very fine sand on a bed to bed basis, but the division itself shows little internal grading. The strata are gently undulating, typically <10°, varying between convex- (hummocky) and concave-upward (swaley) in shape. The lateral spacing (wavelength) of the hummocks is mainly from 15 to 20 cm, and their relief (amplitude) is 1 to 2 cm. The strata are only 0.1 to 0.3 cm in thickness, which also varies laterally with their inclination (Fig. 10). These small-scale structures are similar to the "micro-hummocky" cross-lamination of KREISA (1981), attributed to 3D vortex ripples (HARMS et al., 1982, their figs. 2–14 and 3–16). Some beds show larger-scale hummocky structures at the transition of division *P* to *H* (Figs. 9, 10, 12 and 13), which have a wavelength in excess of 50–60 cm and can be regarded as "true" hummocky cross-stratification, representing combined-flow conditions (HARMS et al., 1975; DOTT & BOURGEOIS, 1982; MYROW & SOUTHARD, 1996). In most cases, at least two or three superimposed sets of hummocky strata are recognizable in division *H*. The strata within the sets (first-order bounding surface *sensu* DOTT & BOURGEOIS, 1982) are concordant with the set's lower bounding surface (second-order bounding surface), which itself is slightly erosional (Fig. 10). The transition from division *P* to *H* is either gradual or sharp and slightly erosional (Figs. 9–13).

The upper division (*F*) is 1 to 3 cm thick, consists of very fine sand or coarse silt and shows planar parallel lamination. In contrast to the lower division, the strata here are only 0.1–0.2 cm in thickness and commonly show an upward change from slightly undulatory to flat, which renders their lower boundary transitional. In some cases, thin isolated intrasets of asymmetrical wave-ripple cross-lamination occur in this division (see Figs. 9–13).

5.1.2. Facies S2: bipartite sandstone beds with hummocky cross-lamination and flat parallel lamination

The beds of this sandstone facies are similar to those of the previous one, but are generally thinner (average thicknesses of 4–10 cm) and show only two component

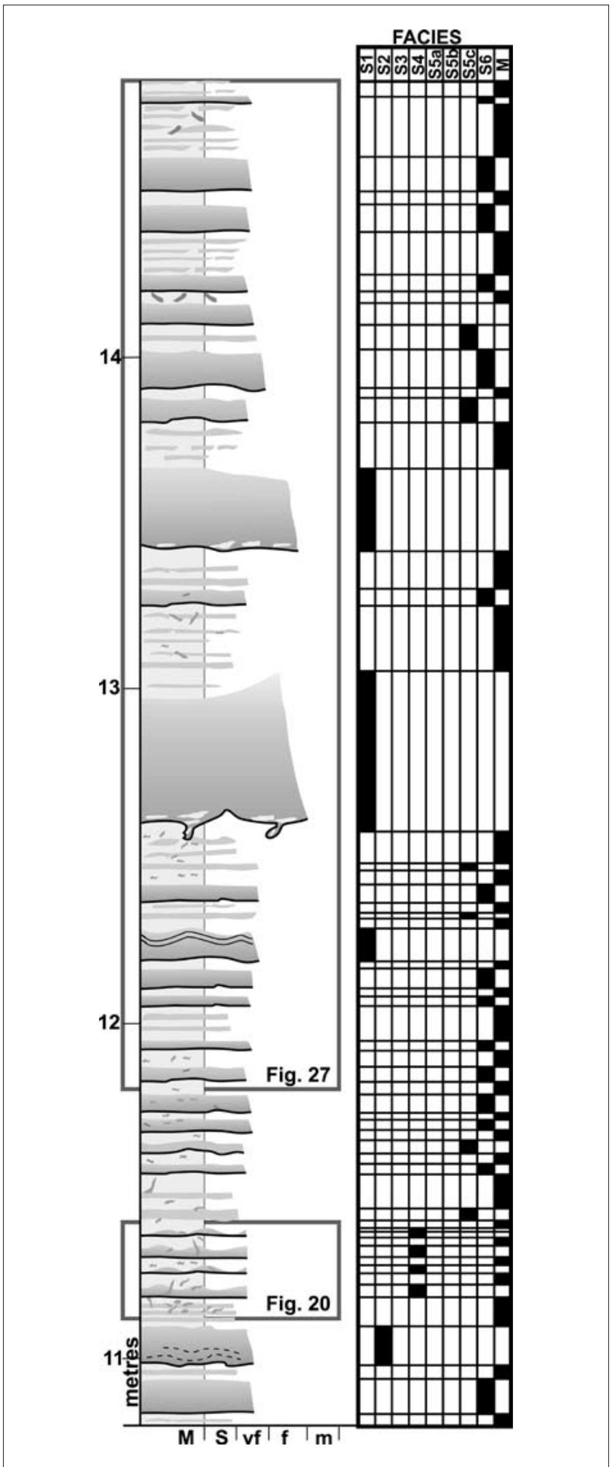

Fig. 6 Detailed portion of log K (see indicated in Fig. 3); for legend, see Fig. 5.

divisions. The basal surfaces are sharp and erosional, with a relief of 2 to 3 cm and local load casts (see Figs. 14, 16 and 19), and the bed tops are slightly uneven or gently undulatory. The beds show normal grading, with the grain size ranging from fine or very fine sand to very fine sand or coarse silt, respectively.

The lower bed division (*H*) consists of hummocky cross-lamination, similar to the previous facies, but this division here is thinner (2–5 cm), composed of slightly thinner strata, and the wavelength of hummocks is also somewhat smaller (10–15 cm). The overlying upper division (*F*) is a thin (1–2 cm) set of slightly undulatory to planar parallel laminae composed of very fine sand to coarse silt. Division *F* is often indistinct, either poorly developed or virtually absent (see Figs. 14, 16 and 19).

5.1.3. Facies S3: sandstone beds with convolute stratification

These are sandstone beds that show internal hydroplastic deformation in the form of convolute stratification, although could originally be similar to any of the previous sandstone facies. Average bed thicknesses are mainly in the range of 5 to 25 cm, and the deformation is often stronger in the bed's upper part or is locally limited to only this part. The convolutions typically occur as steep antiforms composed of deformed and locally disrupted or homogenized strata (Figs. 17–19). The antiforms are commonly asymmetrical, but generally lack preferential orientation or a recognizable spatial pattern.

5.1.4. Facies S4: amalgamated sandstone beds

This facies is relatively rare and consists of amalgamated sandstone beds, which themselves represent one or more of the previous facies. The component beds are stacked erosionally upon one another with no intervening mudstone layers. These composite, amalgamated beds are recognizable by their greater thicknesses (up to 35 cm), multiple normal grading and a more complex vertical sequence of structural divisions (see Figs. 8 and 19).

5.1.5. Facies S5: cross-laminated sandstone beds

These are thin sandstone beds (2–5 cm), composed of very fine sand or coarse to medium silt and generally lacking any obvious grain-size grading. Their bases are slightly erosional and uneven or undulatory, whereas the tops are slightly undulatory ("wavy") and occasionally transitional to the overlying silty mudstone (see Figs. 13, 15, 16, 20 and 22). Many of these sandstone beds, much like the overlying and underlying mudstone layers, are strongly burrowed (Fig. 20). Internally, the sandstone beds show a wide range of wave-ripple cross-lamination types, which form the basis for the distinction of three subfacies (see below). The wave-ripple cross-lamination is recognizable by the presence of uneven or undulatory basal surfaces and lower laminae sets, draped or offshooting geometry of foreset laminae, and chevron-like or form-discordant internal laminae sets (see DE RAAF et al., 1977; COLLINSON & THOMPSON, 1982).

Subfacies S5a: sandstone beds with translatory ripples – These beds have undulatory boundaries with well-preserved asymmetrical ripple forms, 1–3.5 cm in amplitude and 6–20 cm in wavelength (Figs. 20 and 22). Some cross-sets are underlain by a set of 2 or 3 planar laminae covering the erosional basal surface.

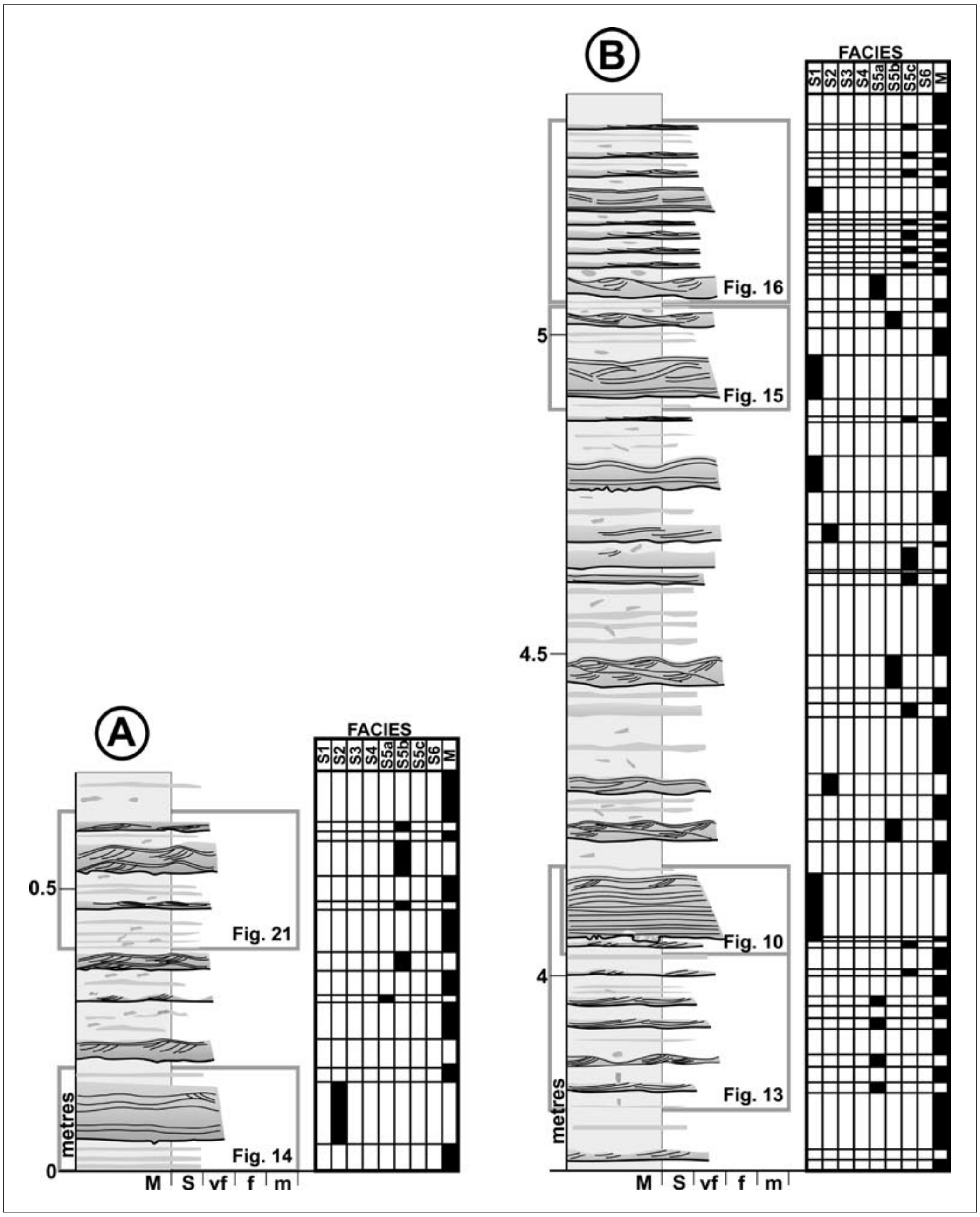

Fig. 7 Detailed portions of log L (see indicated in Fig. 3); for legend, see Fig. 5.

The well-developed foreset laminae, with discordant silty laminae on the stoss side and a "sweeping" drape of undulatory laminae (Figs. 16, bottom) are typical of migrating, translatory wave ripples (ALLEN, 1982). The dip directions of foreset laminae (ripple migration azimuths) are towards the west or northwest.

Subfacies S5b: sandstone beds with climbing ripples – These beds are slightly thicker, have undulatory and slightly erosional bases, and consist of two or three superimposed sets of asymmetrical, climbing-ripple cross-lamination with preserved stoss-side laminae. The angle of climb varies from 8 to 12° (Figs. 15 and 21). Ripple dimensions are similar to those of the previous subfacies, and the dip directions of foreset laminae are also similarly towards the west or northwest. As in the previous subfacies, a basal set of 2–3 flat or slightly undulatory laminae can often be seen covering the underlying erosional surface. A similar set of "sweeping" undulatory laminae occur often at the bed top.

Subfacies S5c: sandstone beds with pinch-and-swell lamination – These sandy to silty beds (see Figs. 10, 13, 16, 18A and 21) are the thinnest (0.5–3 cm), characterized by gently undulatory erosional bases and an undulatory, pinch-and-swell internal lamination (similar to the "rolling-grain" ripples of HARMS et al., 1982 – fig. 3–16), occasionally associated with thin, solitary lenticular cross-sets (small, sediment-starved translatory ripples – ALLEN, 1982).

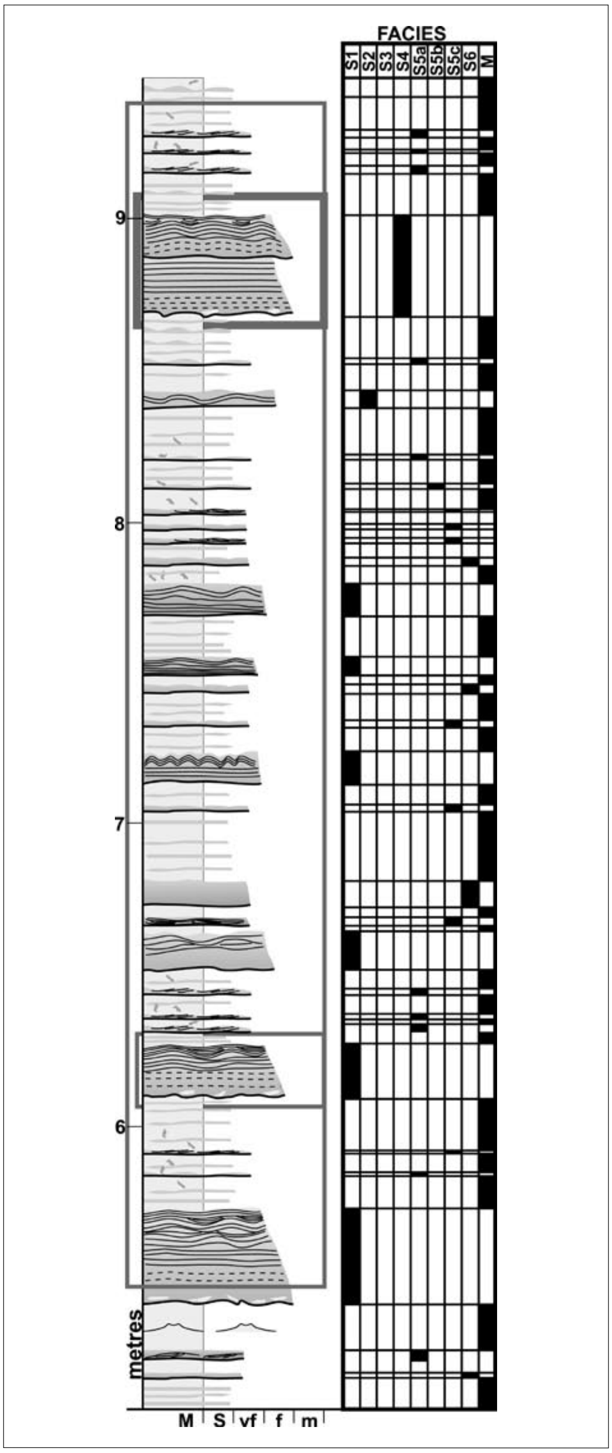

Fig. 8 Detailed portion of log S (see indicated in Fig. 3); for legend, see Fig. 5.

5.1.6. Facies S6: massive sandstone beds with normal grading

These are very common, but very thin (1–5 cm), fine-grained sandstone beds that lack recognizable internal lamination (see logs in Figs. 5B, 6 and 8, and outcrop details in Fig. 22). Their basal surfaces are sharp and slightly erosional, with a local-scale relief of 0.5 to 1 cm, whereas the tops are flat or only slightly undulatory. The beds are normally graded, ranging in grain size from very fine sand to coarse silt. The thicker beds locally show traces of primary lamination, which suggests a secondary process of sediment homogenization. The "structureless" (massive) appearance of these deposits is thus probably a result of their bioturbation and/or subsequent pervasive weathering at outcrop.

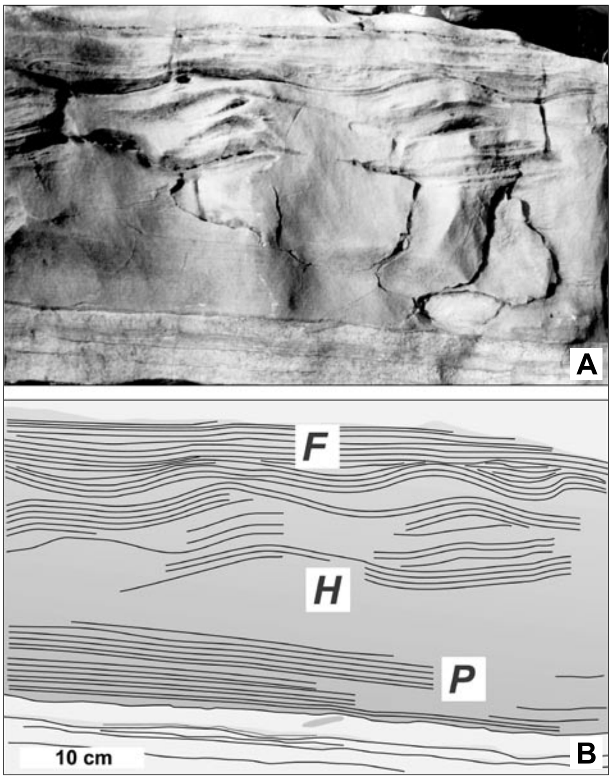

Fig. 9 Close-up view of a carbonate sandstone bed of Facies S1 (A); a corresponding sketch (B) from the site of log B (see Fig. 5A). Note that the sandstone bed has a sharp, erosional base and consists of a planar parallel-stratified division *P* (6 cm thick) overlain by a hummocky cross-stratified division *H* (15 cm) and capped with an undulatory to flat laminated division *F* (3–4 cm). The underlying and overlying deposits are silt-streaked calcareous mudstones of Facies M.

5.2. Calcareous mudstone facies

The mudstone interbeds (Facies M) are common and laterally continuous on an outcrop scale, ranging in thickness between a few mm and 30 cm (see logs in Figs. 5–8, and outcrop details in Figs. 9, 12–17, 18B and 20–25). Most beds contain thin (0.2–1 cm) silty interlayers in the form of flat streaks and distinct lenses with signs of pinch-and-swell lamination, apparently representing sediment-starved small ripples of wave or tidal origin (see REINECK & SINGH, 1975; and the "rolling-grain" ripples of HARMS et al., 1982). The interlayers usually show normal grading from coarse to fine silt, and many have slightly erosional bases. The vertical spacing of these interlayers varies from a few centimetres to 20 cm or more, and they are commonly disrupted and deformed by animal burrows (see Figs. 20 and 22–24).

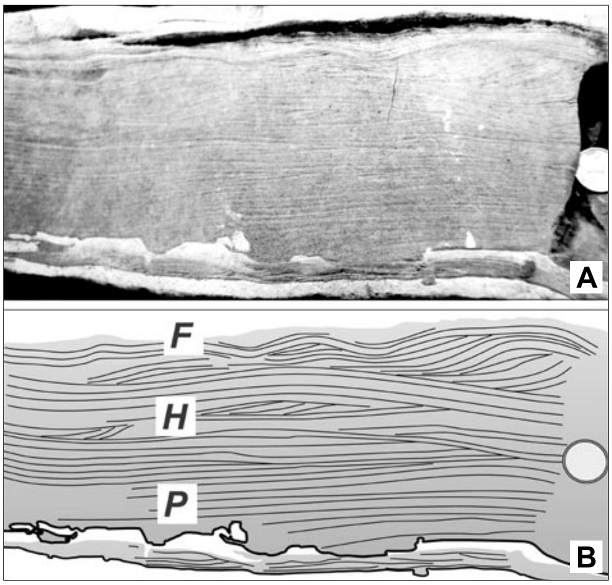

Fig. 10 Close-up view of a carbonate sandstone bed of Facies S1 (A), and a corresponding sketch (B) from the site of log L (see Fig. 7B). Note that the sandstone bed has a sharp, loaded base and consists of a planar parallel-stratified division *P* (5 cm thick) overlain by hummocky cross-laminated division *H* (4–5 cm) and capped with an undulatory to flat laminated division *F* (2–3 cm). The wavelength of hummock forms is about 20 cm, but is considerably greater at the transition of divisions *P* to *H*, where medium-scale hummocky cross-stratification (HCS) is recognizable. The underlying deposits are mudstones of Facies M with a thin interbed of Facies S5c sandstone. The coin (scale) is 2.2 cm in diameter.

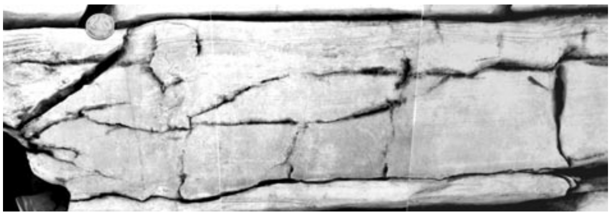

Fig. 11 Close-up view of a carbonate sandstone bed of Facies S1 from the site of log B (see Fig. 5B). Note that the sandstone bed has a sharp, erosional base and consists of a planar parallel-stratified division *P* (6–8 cm thick) overlain by a hummocky cross-laminated division *H* (6–7 cm) and capped with an undulatory to flat laminated division *F* (1 cm). The wavelength of hummock forms is about 15 cm. The coin (scale) is 2.2 cm in diameter.

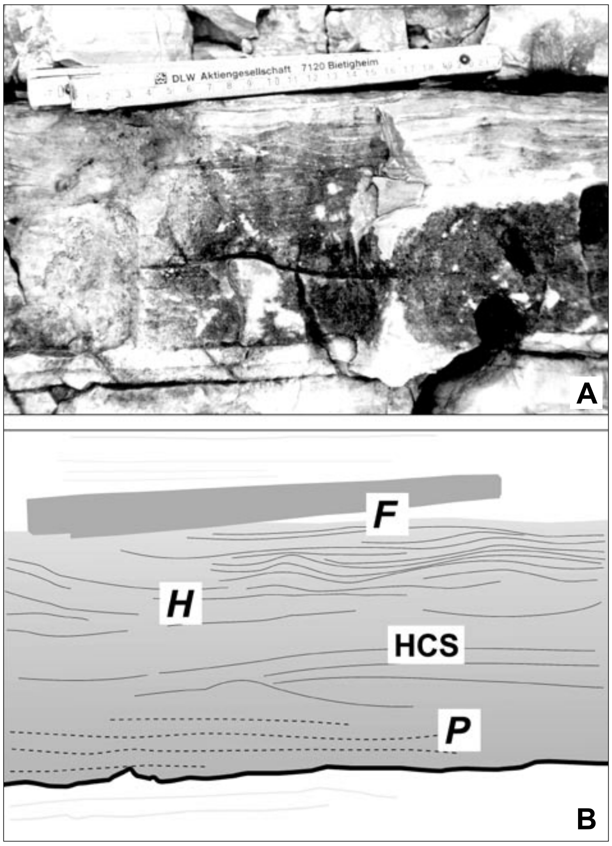

Fig. 12 Close-up view of a carbonate sandstone bed of Facies S1 (A) and a corresponding sketch (B) from the site of log S (see Fig. 8). Note that the sandstone bed has a sharp, erosional base and consists of a planar parallel-stratified division *P* (7 cm thick) overlain by a hummocky cross-laminated division *H* (4–5 cm), which passes gradually into an undulatory to flat laminated division *F* (1–2 cm). Note the occurrence of medium-scale hummocky cross-stratification (HCS) at the transition of divisions *P* to *H*. The underlying and overlying deposits are silt-streaked mudstones of Facies M.

5.3. Other significant features

5.3.1 Mud volcanoes

Small mud volcanoes (REINECK & SINGH, 1975), circular or elliptical in shape, occur locally on isolated bedding surfaces in the mudstone Facies M (Fig. 25). These conical features are typically 15–32 cm in diameter and 3–6 cm in relief, and apparently represent seafloor mud extrusions buried by younger mud. A few such features have been found at the site of log K, and as many as 12 volcanoes have been counted on a mudstone surface with an area of ca. 50 m^2 at the site of log S (see Fig. 8, bottom).

5.3.2. Trace fossils

The sedimentary succession shows a wide range of trace fossils, which abound in the mudstone facies, (Figs. 5–8, 20 and 22–24), but are also common in the sandstone beds (Fig. 26). The thicker sandstone beds most often lack burrows, except for the top parts. The degree of bioturbation of the thinner bedded and muddy facies generally varies from moderate to high (grades 3–4 *sensu* REINECK, 1963).

The majority of identifiable traces belong to *Zoophycos* and *Cruziana* ichnofacies (Fig. 26B, D). The grazing *Helminthoida* traces, produced by deposit-feeding animals, are particularly common (Fig. 26A) and often show well-developed patterns. The grazing *Palaeodictyon* traces (Fig. 26C) have only been found at two localities.

According to conventional interpretations (PEMBERTON et al., 1992; BROMLEY, 1996), the *Cruziana* ichnofacies is typical of a sublittoral, neritic shelf zone, whereas the *Zoophycos* ichnofacies is typical for an upper bathyal zone, such as a continental slope environment. However, *Zoophycos* ichnofacies may occur

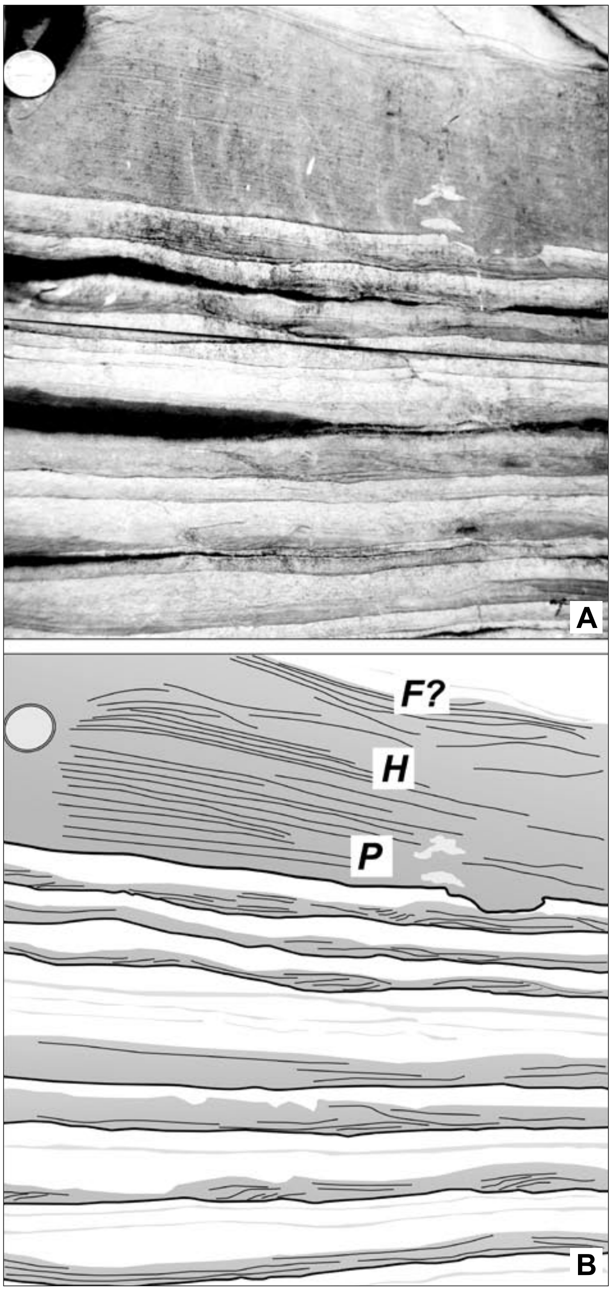

Fig. 13 (A) A portion of the deposits depicted in log L (see Fig. 7B); (B) a corresponding sketch, showing a package of the alternating beds of Facies M and sandstone Facies S5a (lower part) and S5c (middle part), overlain by a thicker sandstone bed of Facies S1. The wavelength of hummock forms in the latter bed's division *H* is about 20 cm, but is considerably greater at the transition of divisions *P* to *H*, where medium-scale hummocky cross-stratification (HCS) is recognizable; note also the localized basal scour and mudstone intraclasts in the lower division *P*. The coin (scale) is 2.2 cm in diameter.

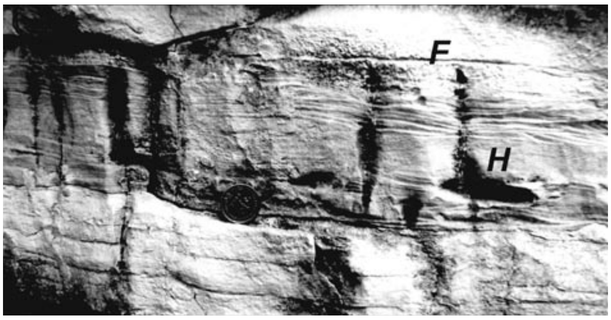

Fig. 14 Close-up view of a carbonate sandstone bed of Facies S2 from the site of log L (see Fig. 7A). Note that the sandstone bed has a sharp, slightly uneven base and consists of a hummocky cross-laminated division *H* (5–6 cm) that passes gradually into an undulatory to flat laminated division *F* (3–4 cm). The underlying and overlying deposits are silt-streaked calcareous mudstones of Facies M. The coin (scale) is 2.2 cm in diameter.

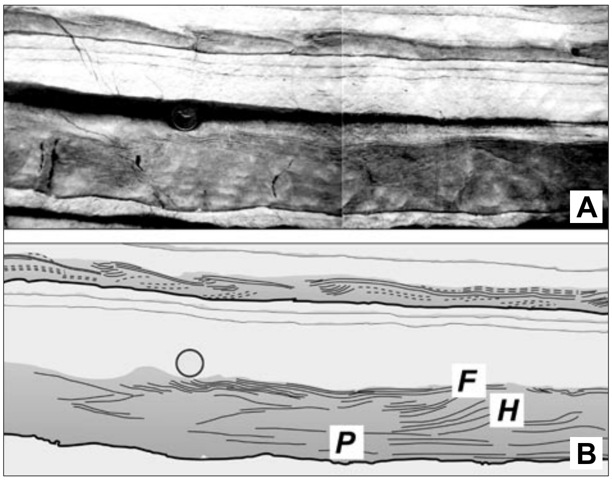

Fig. 15 (A) Some of the deposits depicted in log L (see Fig. 7B); (B) a corresponding sketch, showing a package of alternating beds of silt-streaked mudstone Facies M and sandstone Facies S1 (lower bed) and S5b (upper bed). In the latter bed, the translatory ripples have an amplitude of 2–3 cm and wavelength of 8–12 cm, with an angle of climb in the range of 8–10°; note the preserved thin intrasets of stoss-side laminae. The coin (scale) is 2.2 cm in diameter.

also in low-energy shallow-marine and lagoonal environments (BROMLEY, 1996). For example, UCHMAN et al. (2004) reported on the occurrence of *Zoophycos* and *Helminthopsis* traces in tempestitic offshore-transition deposits, whereas PEMBERTON et al. (2001) and PERVESLER & UCHMAN (2004) found *Zoophycos* traces in shoreface deposits. It has been suggested that water energy and nutrient supply, rather than bathymetry, may often be the dominant factor controlling the distribution of ichnotaxa (ORR, 2003; PERVESLER & UCHMAN, 2004). This is apparently the case in the Benkovac Stone Member, where some "deep-water" ichnotaxa occur in an undoubtedly shallow-marine, wave-influenced sedimentary succession.

6. INTERPRETATION OF THE BENKOVAC STONE MEMBER

The internal characteristics of the sandstone Facies S1–S6, together with their sheet-like bedding geometry (Figs. 27 and 28), indicate sand deposition by waves in combination with unidirectional currents (see DE RAAF et al., 1977; HAMBLlN & WALKER, 1979; DOTT & BOURGEOIS, 1982; LECKIE & WALKER, 1982; WALKER et al., 1983). The intervening, silt-streaked mudstone layers of Facies M indicate quiet-water con-

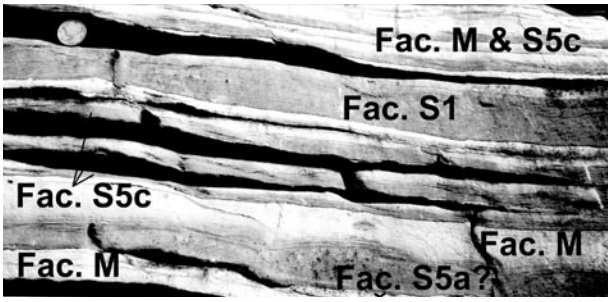

Fig. 16 A section of the deposits depicted in log L (see Fig. 7B), showing the alternating beds of silt-streaked, slightly burrowed mudstone Facies M and sandstone Facies S1, S2 and S5c. The coin (scale) is 2.2 cm in diameter.

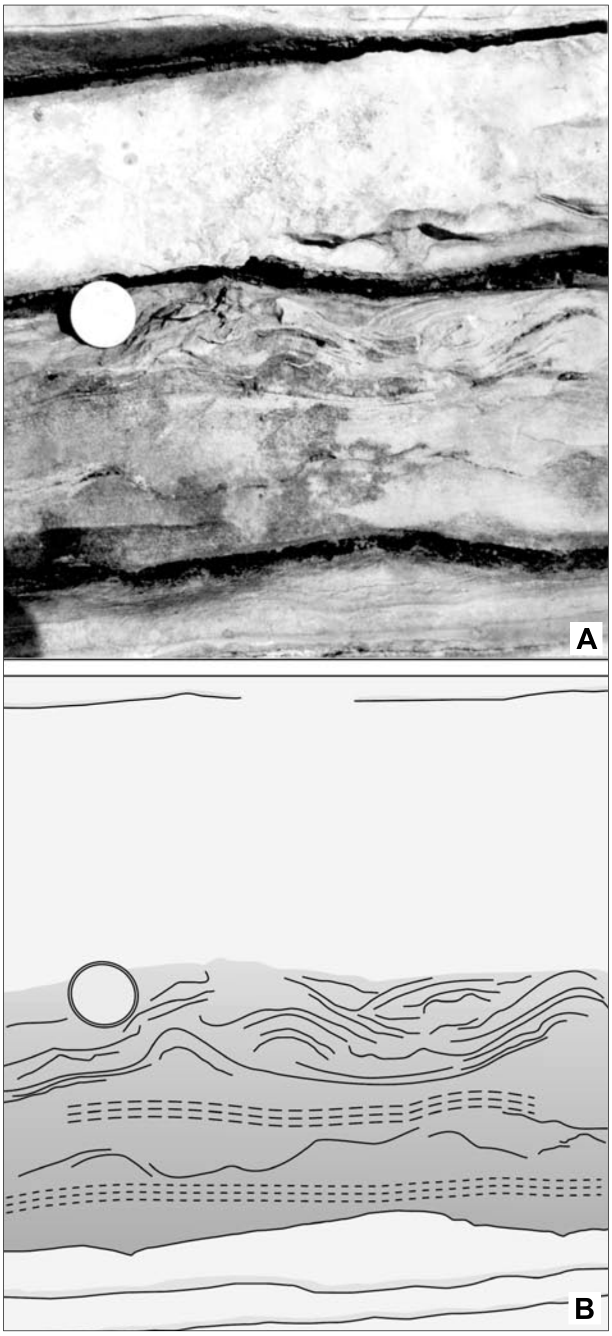

Fig. 17 (A) Convoluted sandstone bed of Facies S3; (B) a corresponding sketch from the site of log B (see Fig. 5A). The underlying and overlying deposits are silt-streaked mudstones of Facies M. The coin (scale) is 2.2 cm in diameter.

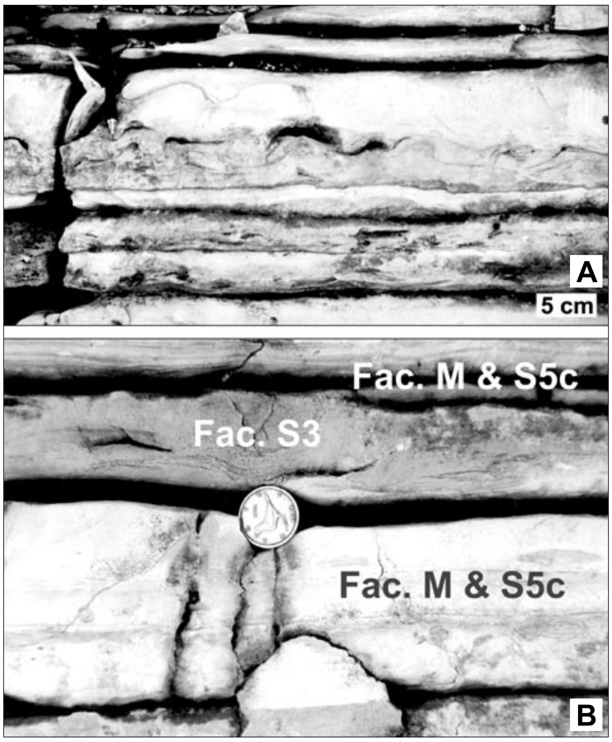

Fig. 18 (A) Sandstone bed of Facies S3 (middle), covered by the silt-streaked mudstone Facies M and underlain by the alternating thin beds of Facies M and S5c. (B) Sandstone bed of Facies S3, underlain and covered by the silt-streaked mudstone Facies M alternating with thin sandstone beds of Facies S5c. Note that the convoluted beds show some preserved primary stratification and most likely represent hydroplastic deformation of deposits analogous to Facies S2. Details from log B (see Fig. 5B). The coin (scale) is 2.2 cm in diameter.

ditions dominated by hemipelagic suspension fallout and biogenic activity, with the sand-starved seafloor episodically affected by very weak wave action and/or tidal currents. The intimate association of the discrete, erosional sandstone sheets rhythmically alternating with mudstone layers indicates episodic deposition from storm events in an offshore transition zone (SWIFT et al., 1987; SNEDDEN et al., 1988; LECKIE & KRYSTINIK, 1989; WALKER & PLINT, 1992), which means a shelf bathymetric area extending between the average fair-weather wave base and the average storm wave base (READING & COLLINSON, 1996, their fig. 6.6). The offshore transition zone thus occurs outside the shoreface zone (perennially affected by waves) and is subject to episodic incursions of sand during storm events ("event" sedimentation *sensu* EINSELE & SEILACHER, 1982). The actual width, or seaward distance, of these zones depends on the local seafloor inclination and may vary from a few hundred metres to several kilometres (READING & COLLINSON, 1996).

Accordingly, the sandstone facies are considered to be tempestites (storm deposits), embedded in a "background" mudstone facies (fair-weather deposits). In the following part of this section, the hydrodynamic regime of the offshore transition zone is briefly reviewed as a conceptual basis for the subsequent detailed interpretation of the individual sandstone facies.

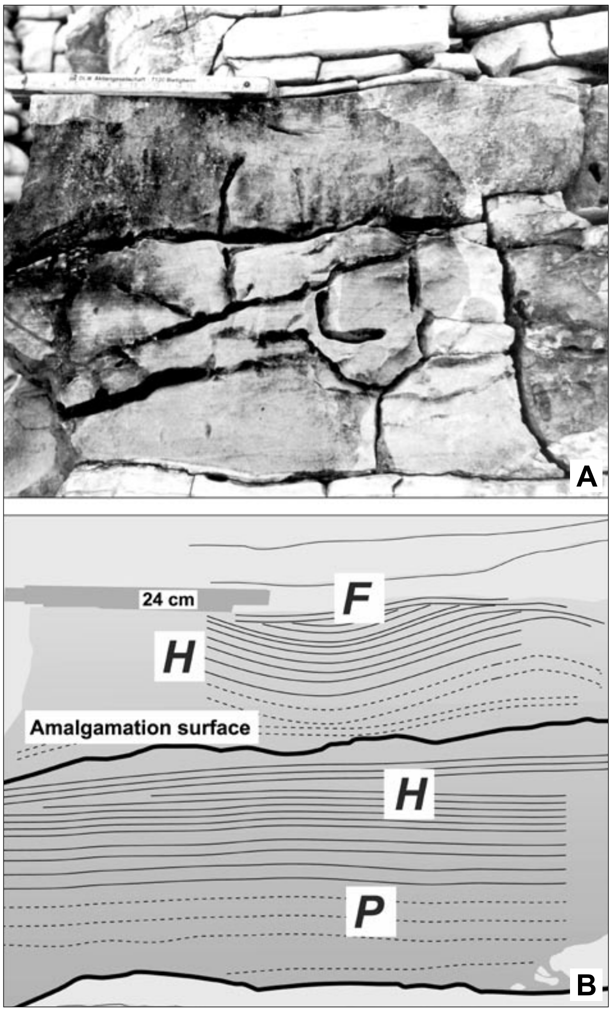

Fig. 19 (A) Compound, amalgamated sandstone bed of Facies S4 and (B) a corresponding sketch; detail from log S (see Fig. 8, top). Note the sequence of component bed divisions, including planar parallel stratification (*P*), hummocky cross-stratification (*H*) and undulatory to flat parallel lamination (*F*). The lower division *H* shows broader, medium-scale hummocky cross-stratification (HCS), whereas the upper division *H* shows hummocky cross-lamination (ripple-scale hummocks). The underlying and overlying deposits are silt-streaked mudstones of Facies M.

6.1. Processes in the offshore transition zone

As the storm winds push seawater against the coast as a surface current, the resulting coastal setup generates strong bottom currents of seaward-returning ("ebbing") water, such as the rip currents, ebb surges and the wide and longer-running geostrophic currents (WALKER & PLINT, 1992; READING & COLLINSON, 1996). As a result, the nearshore water column divides into three internal layers: a highly turbulent surficial layer, an inviscid inner (core) flow layer and a bottom boundary layer (see MYROW & SOUTHARD, 1996 – fig. 1). This latter layer combines the boundary layers produced by waves and currents, such that its lower part is effectively a "combined-flow" boundary layer, where waves and currents interact nonlinearly to produce bottom shear stresses considerably stronger than a simple sum of the two energy components. Importantly, the

Fig. 20 Silt-streaked mudstone Facies M, alternating with thin sandstone beds of Facies S5a in the upper part; detail from log K (see Fig. 6, bottom). Ripple forms have an amplitude of 3–5 cm and wavelength of 15–20 cm. The measuring stick is 24 cm.

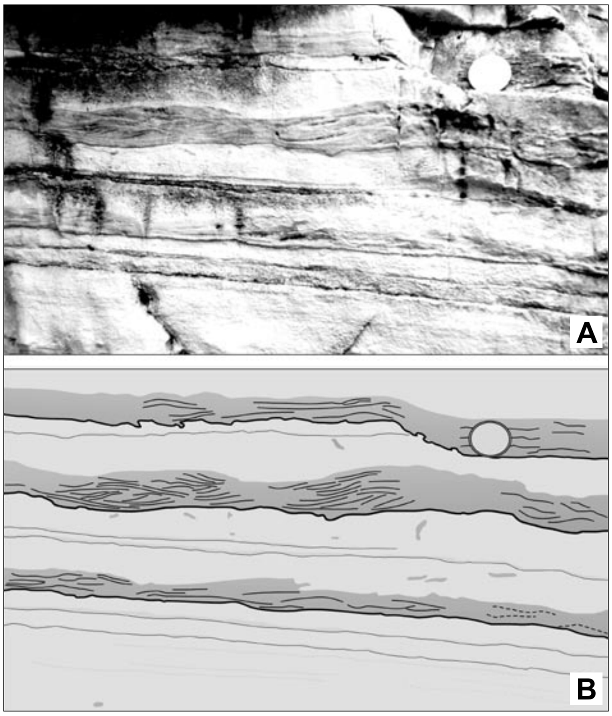

Fig. 21 (A) Some of the deposits depicted in log L (see Fig. 7A); (B) a corresponding sketch, showing the alternating beds of silt-streak, burrowed mudstone Facies M and sandstone Facies S5b. The small ripple forms in the sandstone beds have an amplitude of 1–1.5 cm, a wavelength of 7–8 cm and a low angle of climb (>10°). The coin (scale) is 2.2 cm in diameter.

storm-generated current tends to be non-uniform and unsteady, which means that the relative role of waves and unidirectional flow in the boundary layer may vary in both space and time.

Four basic forces affect the geostrophic current (see MYROW & SOUTHARD, 1996 – fig. 2): (1) the seaward pressure gradient created by the coastal setup; (2) the Coriolis force that rotates the current to the right in the Earth's northern hemisphere; (3) the flow-retarding force of bottom friction, and (4) the downslope component of gravity force due to excess weight of sediment-laden water. Depending on the temporal history of these

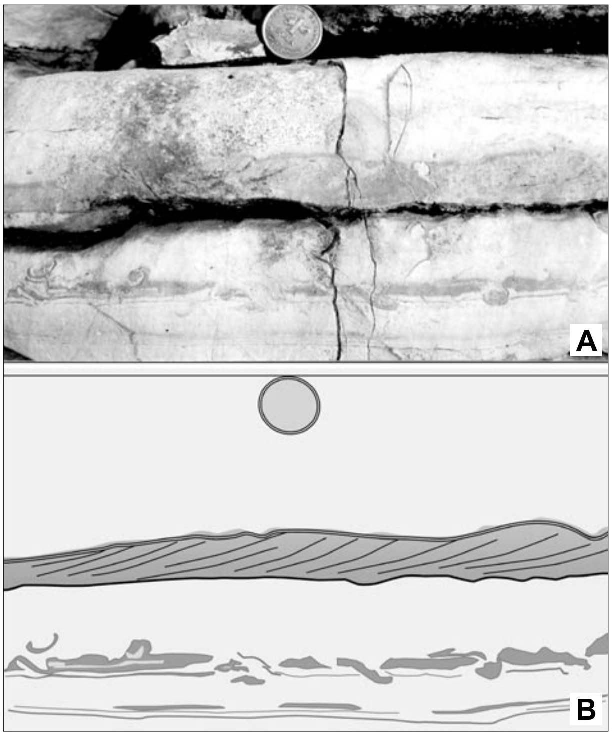

Fig. 22 (A) Deposits depicted in log B (see Fig. 5B); (B) a corresponding sketch, showing the silt-streaked mudstones of Facies M with thicker (<0.5 cm) siltstone interlayers and a sandstone interbed of Facies S5a (2 cm thick) in the middle. Note that some of the interlayers are strongly disrupted by animal burrows. The coin (scale) is 2.2 cm in diameter.

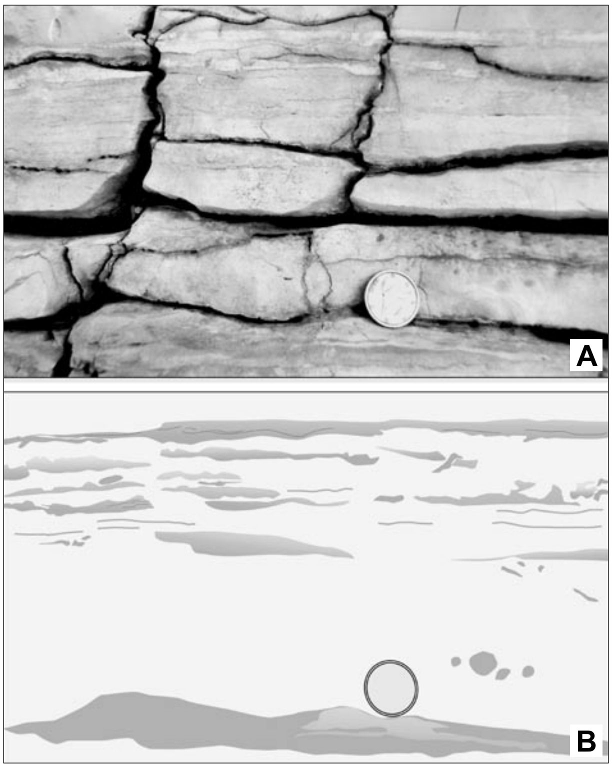

Fig. 23 (A) A portion of the deposits depicted in log B (see Fig. 5B, top); (B) a corresponding sketch, showing the mudstones of Facies M with siltstone streaks and thicker (< 2 cm) ripple-form lenses. Note that many of the silty interlayers are deformed and disrupted by animal burrows. The coin (scale) is 2.2 cm in diameter.

four controlling forces, the hydrodynamic regime of a storm event may theoretically represent any of the following cases (MYROW & SOUTHARD, 1996 – fig. 8 and table 1): (1) a temporal increase and then decrease in the magnitude of all four forces; (2) a greater change in bottom friction than in the other forces; (3) a seaward and then landward rotation of the flow direction relative to shoreline, and (4) weak flow conditions at all times, with a predominant oscillatory waves. Another consequence of the combined forces is that weaker currents tend to be nearly shore-parallel, whereas the stronger and denser currents are directed offshore at a higher angle. Furthermore, the local hydrodynamic behaviour of the storm-agitated bottom water can vary through a whole spectrum of cases defined by the following three end-members (MYROW & SOUTHARD, 1996 – fig. 7): (1) an "ideal" combined-flow geostrophic current, (2) pure oscillatory wave action, and (3) a density-driven flow somewhat analogous to a turbidity current. The various intermediate, "modified" cases are thought to be commonplace in shelf environments.

MYROW & SOUTHARD (1996 – fig. 9) also explained as to how the relative role of waves, geostrophic flow and density-driven flow may change during the predepositional and depositional phase of a storm event, with reference to a nearshore (shoreface) site and seafloor sites above and below the storm wave base (i.e., in the offshore transition and offshore zone, respectively). Three hypothetical storm events are considered as an illustration. In an event involving relatively weak waves and a decelerating geostrophic current, the wave action increases in the shoreface zone; the relative role of a density-modified current increases and then decreases in the offshore transition zone; and only the density-driven current will be recorded in the offshore zone. In an event involving a relatively weak geostrophic current and strong waves with decreasing orbital velocities, the process record in all three zones will be nearly identical, except that the geostrophic flow may gradually prevail in the shoreface zone. In a disequilibrium event with high nearshore suspension concentration, the action of a density-driven current will predominate in all three zones.

6.2. Interpretation of sedimentary facies

The sandstone beds of Facies S1 show planar parallel stratification (division *P*) overlain by medium- to small-scale hummocky cross-stratification (division *H*) and capped with undulatory to flat parallel lamination (division *F*). If the sporadic medium-scale hummocky cross-stratification is ignored, the sequence of stratification types can be attributed to the action of oscillatory waves (see the bedform stability diagrams in ALLEN, 1982 – figs. 11–18; HARMS et al., 1982 – figs. 2–14), with the temporal trajectory of seafloor hydraulic regime

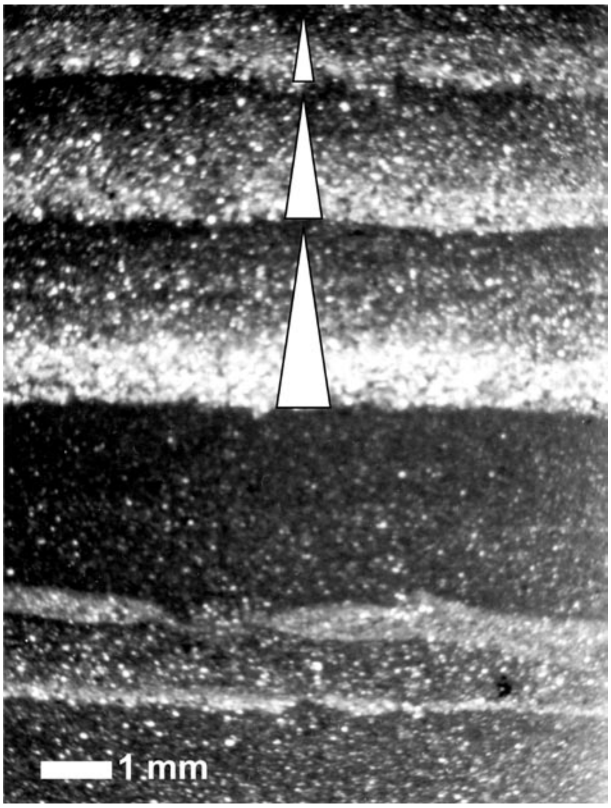

Fig. 24 Microscopic detail of a silt-streaked calcareous mudstone of Facies M. Note that the silt interlayers vary from thin (1–2 mm) lenses and pinch-and-swell features (lower part), to thicker (2–3 mm), sharp-based sheets with normal grading (upper part).

beginning in the plane-bed field and re-entering this field again after crossing the field of 3D vortex ripples (see also WALKER et al., 1983; MYROW & SOUTHARD, 1996). The action of a geostrophic current in such a case would be limited to supplying sand to the offshore transition zone, and to aiding briefly the development of medium-scale hummocks. Alternatively, the basal division *P* could partly or entirely be deposited by a geostrophic current, if the latter was sufficiently powerful, laden with sediment and characterized by high suspension fallout rate, such that tractional plane-bed transport occurred (see LOWE, 1988 – fig. 3). The action of waves would then directly follow that of the density-modified current. This possibility is particularly likely for beds that show medium-scale hummocky cross-stratification in the lower part of their division *H*, because this stratification type is widely attributed to a combined-flow regime.

The sandstone beds of Facies S2 show a hummocky cross-laminated division *H* overlain by an undulatory to flat parallel-laminated division *F*, which can be attributed to oscillatory waves – with the temporal trajectory of the hydraulic regime commencing in the stability field of 3D vortex ripples and passing into the plane-bed field as the sediment supplied becomes finer-grained (see ALLEN, 1982 – figs. 11–18; HARMS et al., 1982 – figs. 2–14). In this case, the sand delivered to the offshore transition zone by a waning geostrophic current would be thoroughly worked by waves.

It is worth pointing out that the action of waves on the seafloor in the offshore transition zone will cease abruptly as soon as the wave base detaches itself from the seafloor. This means that the storm event of sand deposition can abruptly be terminated at a non-zero level of general wave energy; and that is why most tempostites have not only sharp bases, but also sharp tops, which are often also undulatory, showing well-preserved ripple forms.

The sandstone beds of Facies S1 and S2 also stand out by their greater thicknesses, implying the strongest storm events that affected the offshore transition zone in the present case. Geostrophic currents would play a greater role in the deposition of Facies S1, attributed to the strongest storm. In this context, the significance of sandstone Facies S4 would be to represent strong storms that closely followed one another, such that little or no fair-weather sedimentation took place between these events.

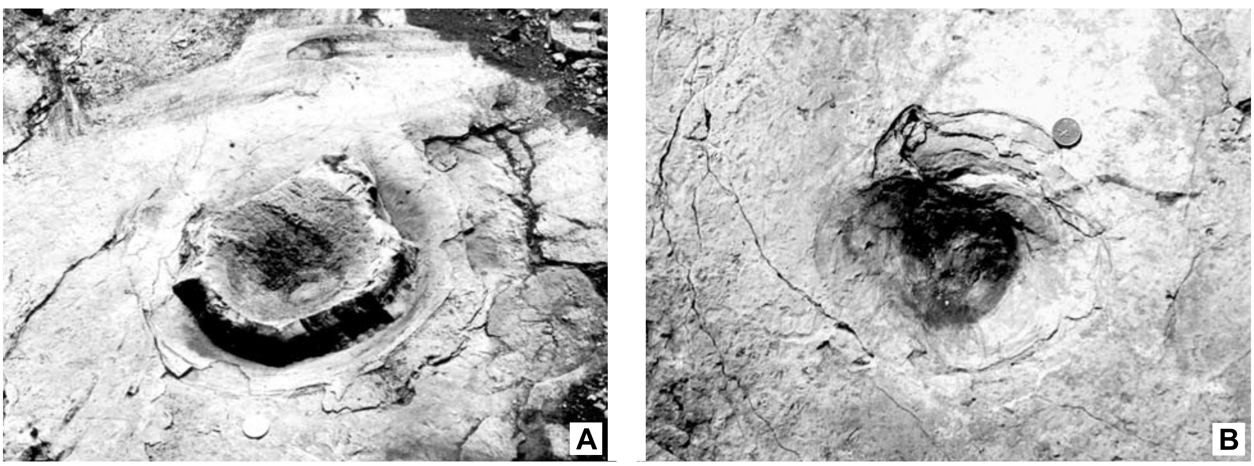

Fig. 25 Small mud volcanoes in calcareous mudstone Facies M; bedding surface details from the site of log S (see Fig. 8, bottom). (A) This volcano has a slightly elliptical plan-view shape with the longer axis of 32 cm and cone relief of 6 cm. (B) This volcano has a circular plan-view shape with a diameter of 28 cm and cone of 5 cm. The coin (scale) is 2.2 cm in diameter.

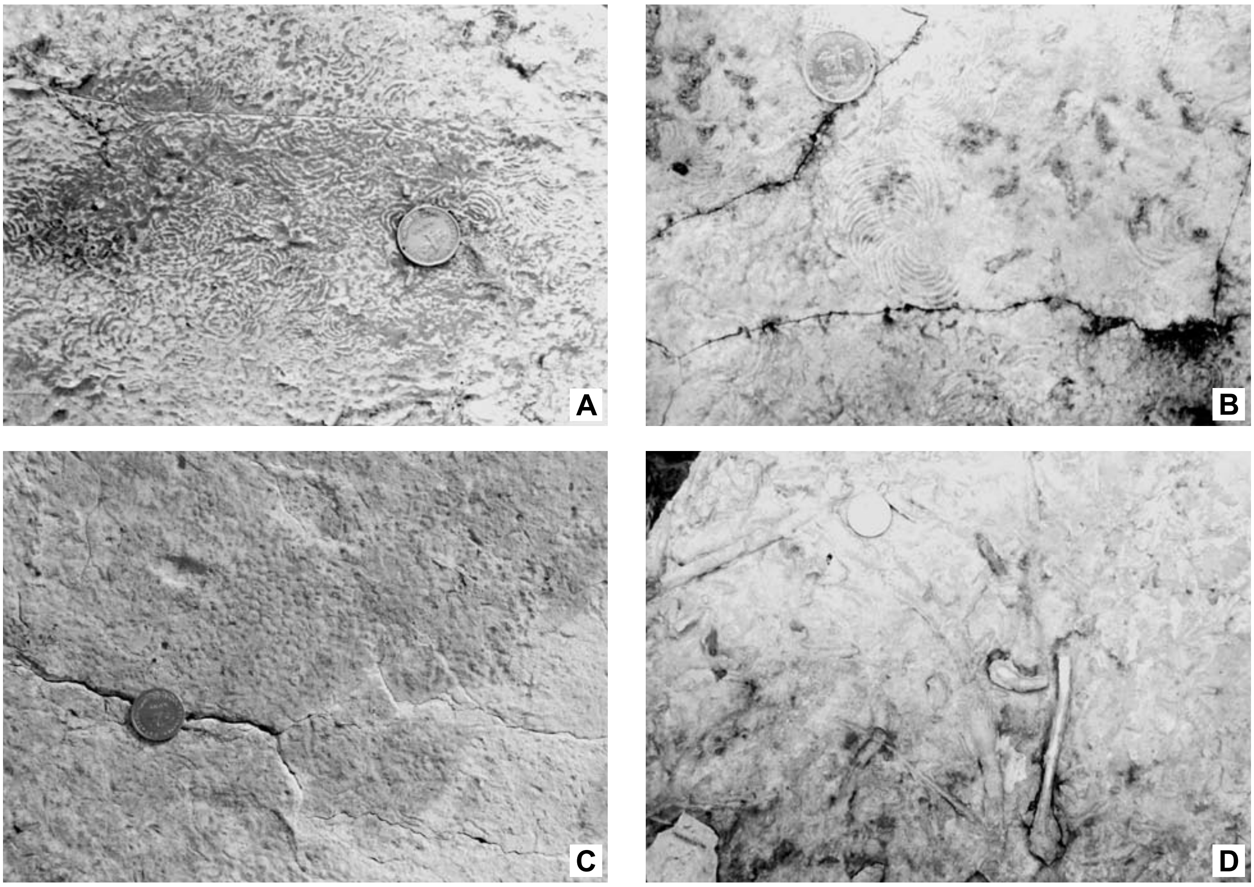

Fig. 26 Trace fossils on sandstone bedding surfaces. (A) Grazing traces *Helminthoida*, from log K. (B) Horizontal feeding burrow system of *Zoophycos*, from log K. (C) Grazing trace *Palaeodictyon*, from log S. (D) Poorly organized burrowing system of *Cruziana*, from log K. The coin (scale) is 2.2 cm in diameter.

The erosional bases and normal grading of these tempestite beds are consistent with the notion of an initial, strong ebb-surge followed by a waning geostrophic current that supplied increasingly fine-grained sediment to the offshore transition zone. The sporadic occurrence of gutter casts at the bases of Facies S1 beds may theoretically be due to either oscillatory waves or combined-flow currents (MYROW & SOUTHARD, 1996). However, some authors suggested that a unimodal orientation of gutter casts may indicate unidirectional currents, possibly density-modified (HAMBLlN & WALKER, 1979; LECKIE & WALKER, 1982; WALKER et al., 1983). The NE–SW to N–S trend of the gutter casts in the present case is roughly perpendicular or oblique with respect to the inferred palaeoshoreline (see palaeogeographic reconstruction in subsequent section), which may support the notion of strong ebb-surges or powerful geostrophic currents. This interpretation is further supported by the occurrence of mudclast-rich horizons, considered to be lag deposits of powerful, erosive currents (SEPKOSKI, 1982; WALKER et al., 1983). The fact that the mudclast lags are uncommon may reflect either their limited preservation potential or deposition from somewhat exceptional currents.

The convoluted sandstone beds of Facies S3 were apparently deposited in a similar way to those of Facies S1 and S2, but underwent a late syndepositional or early post-depositional hydroplastic deformation. These deformed beds indicate partial sediment liquefaction, but are relatively rare, and hence the cause of the deformation itself can be regarded as a rare factor. The seafloor was clearly affected by sporadic shallow liquefaction, as is also indicated by the horizons of mud volcanoes. The origin of mud volcanoes is attributed to the upwelling of pore-water springs through liquefied quickmud (REINECK & SINGH, 1975), which may occur in response to a rapid sediment deposition, cyclic seafloor loading by storm waves or shaking by seismic "ground-roll" wave (i.e., the combined S and L shock waves propagating at ground level). The same factors, or the shearing by an overpassing current (SANDERS, 1965), could occasionally liquefy the seafloor when it was covered with sand (Facies S1 or S2), rather than mud, and hence result in Facies S3 (see MIDDLETON & HAMPTON, 1973). A more intense liquefaction and/or pervasive bioturbation are thought to have similarly produced Facies 6, which seems to have resulted from a sporadic internal homogenization of freshly-deposited sand beds of Facies S5.

The sandstone Subfacies S5a and S5b indicate storm events with a prevalent role of geostrophic currents, which were sand-laden and characterized by a moderate

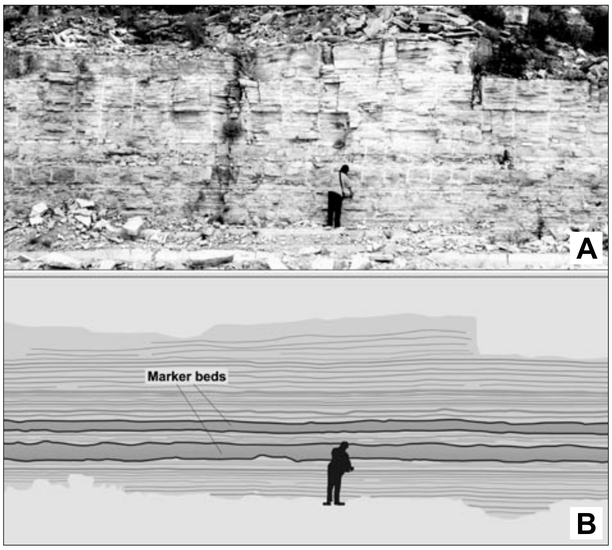

Fig. 27 (A) Some of the deposits depicted in log K (see Fig. 6) with (B) a corresponding sketch, showing the alternating, sheet-like beds of sandstone and mudstone facies. Note the two marker beds of Facies S1 that are used for log correlation (Fig. 3).

(Subfacies S5a) to high suspension fallout rate (Facies S5b) (see HARMS et al., 1982). These beds are thin and fine grained, which implies relatively weak, highly subcritical (HARMS et al., 1975) and low-density currents (*sensu* LOWE, 1982). The orientation of ripple cross-lamination indicates currents flowing towards the west (obliquely offshore) or northwest (alongshore).

At the other end of the whole spectrum of tempestites are the very thin and fine-grained beds of Facies S5c, whose geometry and internal features indicate sand-starved vortex ripple and rolling-grain ripples, implying weak action of "pure" oscillatory waves (ALLEN, 1982; HARMS et al., 1982).

The silt-streaked calcareous mudstones of Facies M represent quiet-water sedimentation during the inter-storm periods of fair-weather conditions, accompanied by widespread biogenic activity (seafloor burrowing). The fallout of hemipelagic muddy suspension was frequently interrupted by sparse incursions of silt, which can be attributed to weak tidal currents and/or minor seasonal storms.

7. SPATIAL DISTRIBUTION OF FACIES

The sedimentary succession is characterized by tabular bedding, with the sheet-like sandstone and mudstone beds showing lateral continuity on an outcrop scale of up to several hundred metres (Figs. 27 and 28). Two of the thickest sandstone beds of Facies S1 can be correlated as markers, on an outcrop to outcrop basis, over a distance of at least 15 km parallel to the inferred palaeoshoreline (Fig. 3).

The succession of alternating sandstone and mudstone beds shows considerable variation in their thicknesses, but little obvious vertical organization (cf. Fig. 3). The only recognizable trend is that the thicker beds of Facies S1 are more common, and the mudstone beds of Facies M are thinner and less bioturbated, in the middle part of the succession (Figs. 5, 6 and 8). This stratigraphic pattern may reflect a temporal change in relative sea level, sediment supply or sea-wave climate. An episode of an accelerated shoreline advance seems likely to have been the case, because it would inevitably increase the frequency and magnitude of storm events affecting the offshore transition zone, and thus increase the supply of sand to the latter. The subsequent, temporal recession of the shoreline could be due to any of the three factors mentioned above, but was most likely caused by a relative sea-level rise (as discussed further in Section 9).

8. THE ORIGIN OF CONTIGUOUS LITHOSTRATIGRAPHIC MEMBERS

The underlying Debelo Brdo Member and the overlying Otavac Member of the Promina Formation are not the main topic of the present paper and hence are characterized here in only broad terms. These contiguous lithostratigraphic units (Fig. 1) occur in areas covered with dense vegetation, where their exposure is generally poor. Field observations suggest conformable, transitional boundaries of these units with the Benkovac Stone Member (Fig. 3).

The Debelo Brdo Member – This unit is about 50 m thick and consists of calcarous mudstones with rare, thin

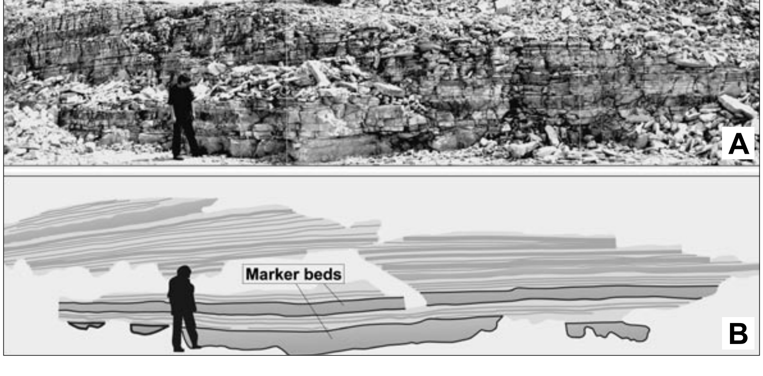

Fig. 28 (A) Photomosaic of the deposits depicted in log S (see Fig. 8) with (B) a corresponding sketch, showing the alternating, sheet-like beds of sandstone and mudstone facies. Note the same two marker beds of Facies S1 that are shown in Figs. 3 and 27.

interlayers of very fine-grained sandstone and/or siltstone. The silt-streaked mudstones are similar to those of Facies M, and also the thin sandy to silty interlayers resemble those of Facies S5c. This facies assemblage indicates deposition below the average storm wave base (offshore zone *sensu* READING & COLLINSON, 1996 – fig. 6.6). Notably, the general lack of deposits analogous to Facies S5a and S5b indicates that few, if any, density-modified (turbidity-driven) geostrophic currents have reached this distal shelf zone in the present case.

The Otavac Member – This unit is more than 100 m thick and composed of carbonate conglomerates, sandstones and subordinate mudstones. The conglomerates are clast-supported and typically have a bimodal grain-size distribution, with a pebble framework and sand- to granule-size matrix. Gravel clasts are subrounded to rounded, derived from Cretaceous limestones and subordinately also from rocks of Palaeogene, Jurassic and Triassic age (rare fragments of sandstone, marl, chert, dolomite and rudist molluscs). The conglomerates form sheet-like beds 0.3–2.5 m thick, with uneven erosional bases, crude planar or gently inclined stratification and commonly also a tractional, "rolling" clast fabric of *a*(t)*b*(i) type (notation after HARMS et al., 1975, p. 134). Their lateral extent is estimated to be at least several hundred metres. The conglomerate sheets are most often isolated, both underlain and overlain by sandstones or occasionally mudstone facies.

The calcareous sandstones are mainly coarse-grained, but include also fine- and medium-grained varieties, and are similar in their mineral composition to the sandstone facies of the Benkovac Stone Member. Granules are commonly scattered in coarse-grained sandstones. Sandstone beds are 0.5–1.5 m thick and show planar parallel, low-angle inclined and locally hummocky or swaley cross-stratification. Some beds are nearly massive ("structureless") and amalgamated into units 3–4 m thick.

The calcareous mudstones are silt-streaked and similar to those in the Benkovac Stone and Debelo Brdo members. They form isolated layers 10–40 cm thick, with moderate to abundant bioturbation.

The three component facies of the Otavac Member tend to form recognizable coarsening-upward cyclothems comprising either mudstone–sandstone–conglomerate or more rarely mudstone–conglomerate. At least 10 such cyclothems, each several metres thick, have been recognized as stacked upon one another in the stratigraphic succession.

The facies assemblage of the Otavac Member indicates an alternation of lower- to upper-shoreface environment, which was dominated by waves and supplied with gravel from a coeval beach or coarse-grained delta front (see READING & COLLINSON, 1996). The cyclothemic organization of the shoreface succession can be attributed to a series of minor relative sea-level rises followed by normal (progradational) regressions (see also BABIĆ & ZUPANIČ, 1990). The sporadic mudstone–conglomerate cyclothems may indicate minor forced regressions, but more likely represent episodes of a rapid shoreline advance due to extreme river floods combined with powerful storms.

9. DEPOSITIONAL MODEL

The Promina Formation has previously been recognized to be the record of an overall upward transition from deep-water turbiditic facies to braid-delta and fluvial braidplain deposits (BABIĆ & ZUPANIČ, 1990; MRINJEK, 1993a, b, 1994). The present study indicates that the Benkovac Stone Member consists of the offshore transition deposits of a storm-dominated, microtidal shelf variously affected by oscillatory waves and sediment-laden geostrophic currents. The underlying Debelo Brdo Member is considered to represent a corresponding muddy offshore zone, whereas the overlying Otavac Member represents a wave-dominated shoreface supplied with sediment – an advancing, wide braid-delta front. A somewhat similar braidplain delta, many tens of kilometres wide and passing into a storm-dominated offshore-transition zone, was described from the Lower Cretaceous of Svalbard (NØTTVEDT & KREISA, 1987; NEMEC et al., 1988; NEMEC, 1992).

The palaeogeographic scenario for the stratigraphic succession of these three members (Fig. 29A) takes into account the SE-trending basin margin (cf. Fig. 1) and implies a stratigraphic model of a long-term normal regression (Fig. 29B) punctuated by minor, shorter-term relative sea-level rises. Overall, a considerable rise of relative sea level must have occurred, because the thickness of the Otavac Member (shoreface deposits) exceeds 100 m, whereas the depth of the mean fair-weather wave base is unlikely to have exceeded 15 m (WALKER & PLINT, 1992). The smaller thickness of the Benkovac Stone Member (ca. 40 m) reflects a relatively low net rate of sediment accumulation in the offshore transition zone (area of episodic sand incursions), markedly different than that in the associated shoreface zone (nearshore sediment trap) and the strongly aggrading braidplain (see the thick alluvium in Fig. 1).

In sequence stratigraphic terms (EMERY & MYERS, 1996), the basinward advance of the thick alluvial upper part of the Promina Formation (Fig. 1) would most likely represent the culmination of a highstand systems tract. The large-scale regressive parasequence is thought to be composite, comprising sets of higher-order, forward-stepping (progradational) and back-stepping (retrogradational) parasequences, probably reflecting the basin's tectonic subsidence. This suggestion concurs with the earlier interpretation by BABIĆ & ZUPANIČ (1990). Three such crude sets are recognizable in the Benkovac Stone Member, represented by its coarsening- to fining-upward trend with further upward coarsening at the transition to the Otavac Member,

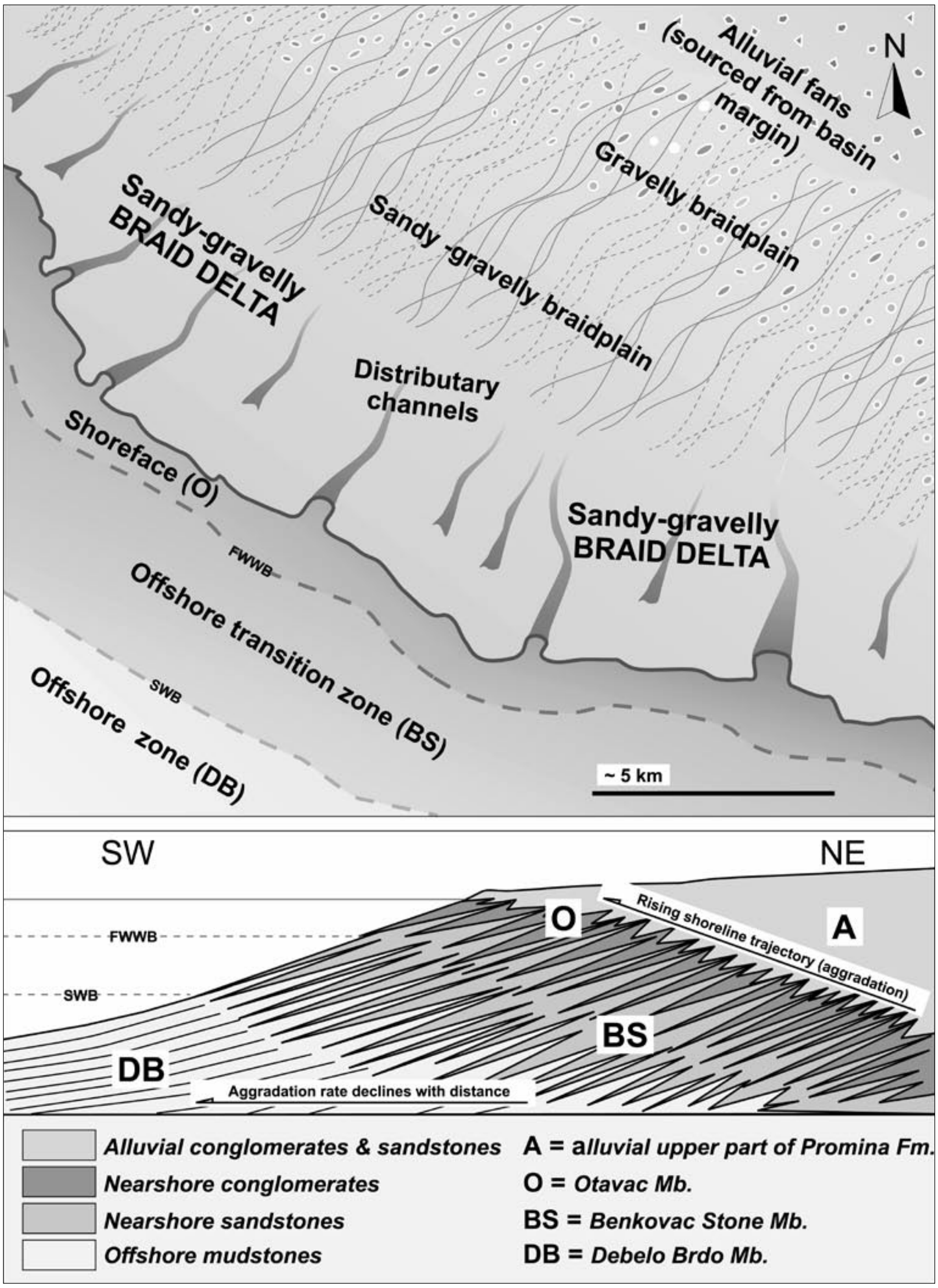

Fig. 29 A depositional model for the Benkovac Stone Member, in the form of a schematic palaeogeographic map (A) and a shore-transverse stratigraphic cross-section (B). The vertical scale and seafloor gradient in diagram B are grossly exaggerated for graphical purposes. FWWB = fair-weather wave base; SWB = storm wave base; other symbols explained in the legend. For discussion, see text.

although the higher-order parasequences themselves are difficult to recognize in this succession. The opposite situation occurs in the Otavac Member, where the higher-order parasequences are readily recognizable as coarsening-upward cyclothems, whereas their sets are more difficult to pinpoint.

This striking difference probably reflects the underlying difference in the physical factors that controlled the supply of sand to the shoreface and offshore transition zone, respectively. The short-term advances and retreats of the braid-delta shoreline were likely due to changes in fluvial sediment supply, the impact of which would be recorded chiefly in the shoreface zone and could be of local extent, rather than basin-wide. The transfer of sand to the offshore transition zone, in turn, would obviously depend on the frequency and magnitude of storm events, rather than fluvial floods and fair-weather wave action. Furthermore, the deposition of sand in the two zones would necessarily occur on an out-of-phase basis: the episodes of offshore sand transfer would correspond to shoreface erosion, whereas the longer phases of sediment dispersal and accumulation in the shoreface zone would be coeval with the phases of slow mud deposition in the offshore transition zone. These marked differences might explain why the stratigraphic records of the two zones have different thicknesses and are seemingly incompatible, difficult to correlate on a high-resolution basis.

10. CONCLUSIONS

The Benkovac Stone Member of the Promina Formation consists of alternating, sheet-like calcareous sandstone and mudstone beds deposited in a shallow-marine sublittoral environment. The sedimentary facies succession represents muddy "background" sedimentation punctuated by discrete storm events, which implies an offshore transition zone. The observed spectrum of tempestite sandstone beds indicates a wide range of storm events, varying greatly in their magnitude and the mode of sand dispersal – from the pure action of oscillatory waves to pure geostrophic currents. The majority of tempestites are attributed to a combination of these two end-member factors, with the geostrophic currents often enhanced by a high load of sediment suspension (density-modified currents).

The Benkovac Stone Member is underlain by muddy offshore deposits (Debelo Brdo Member) and covered by sandy to gravelly shoreface deposits (Otavac Member), which pass upwards into braidplain deltaic and alluvial deposits. This whole succession overlies deep-marine turbiditic deposits and is interpreted to be a regressive parasequence deposited as a highstand systems tract during a slow, stepwise rise of relative sea level. The overall shallowing of the basin was apparently controlled by sediment supply, rather than accommodation. The large-scale parasequence consists of progradational and retrogradational sets of higher-order (much smaller) parasequences, but this high-resolution record differs markedly in the shoreface and offshore transition successions. This contrast is attributed to the underlying difference in the physical factors that controlled the supply of sand to these zones. The higher-order parasequences probably reflect incremental tectonic subsidence of the foreland basin floor under the load of active thrust-sheets, and hence reflect the controlling role of basin accommodation.

Acknowledgements

The authors gratefully appreciate and acknowledge the review by Wojtek NEMEC whose comments significantly improved our paper. We would also like to thank Josip TIŠLJAR and Francesco MASSARI for their constructive comments.

11. REFERENCES

ALLEN, J.R.L. (1982): Sedimentary Structures: Their Character and Physical Basis.– Developments in Sedimentology, 30. Elsevier, Amsterdam, 1255 p.

BABIĆ, Lj. & ZUPANIČ, J. (1983): Paleogene clastic formations in northern Dalmatia.– In: BABIĆ, Lj. & JELASKA, V. (eds.): Contributions to Sedimentology of some Carbonate and Clastic Units of the Coastal Dinarides. Excursion Guidebook, International Association of Sedimentologists 4th Regional Meeting, Split, 37–61.

BABIĆ, Lj. & ZUPANIČ, J. (1988): Coarse-grained alluvium in the Paleogene of northern Dalmatia (Croatia, Yugoslavia).– Rad JAZU, 441 (23), 139–164, Zagreb.

BABIĆ, Lj. & ZUPANIČ, J. (1990): Progradacijski sljedovi u paleogenskom klastičnom bazenu Vanjskih Dinarida, od sjeverne Dalmacije do zapadne Hercegovine [*Progradational sequences in the Paleogene clastic basin of the Outer Dinarids, from northern Dalmatia to western Hercegovina* – in Croatian] – Rad JAZU, 449(24), 319–343, Zagreb.

BROMLEY, R.G. (1996): Trace Fossils: Biology, Taphonomy and Applications.– 2nd edn., Chapman & Hall, London 361 p.

COLLINSON, J.D. & THOMPSON, D.B. (1982): Sedimentary Structures.– Allen and Unwin, London, 207 p.

DE RAAF, J.F.M., BOERSMA, J.R. & VAN GELDER, A. (1977): Wave-generated structures and sequences from a shallow marine succession: Lower Carboniferous, County Cork, Ireland.– Sedimentology, 24, 451–483.

DOTT, R.H., Jr. & BOURGEOIS, J. (1982): Hummocky stratification: significance of its variable bedding sequences.– Bull. Geol. Soc. Am., 93, 663–680.

EINSELE, G. & SEILACHER, A. (eds.) (1982): Cyclic and Event Stratification.– Springer-Verlag, Berlin, 536 p.

EMERY, D. & MYERS, K.J. (1996): Sequence Stratigraphy.– Blackwell Science, Oxford, 291 p.

HAMBLIN, A.P. & WALKER, R.G. (1979): Storm-dominated shallow marine deposits: the Fernie–Kootonay (Jurassic) transition, southern Rocky Mountains.– Can. Jour. Earth Sci., 5, 1673–1690.

HARMS, J.C., SOUTHARD, J.B., SPEARING, D.R. & WALKER, R.G. (1975): Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences.– SEPM Short Course, 2, Lecture Notes. Society of Economic Paleontologists and Mineralogists, Dallas, 161 p.

HARMS, J.C., SOUTHARD, J.B. & WALKER, R.G. (1982): Structures and Sequences in Clastic Rocks.– SEPM Short Course, 9, Lecture Notes. Society of Economic Paleontologists and Mineralogists, Calgary, 249 p.

IVANOVIĆ, A., SAKAČ, K., MARKOVIĆ, S., SOKAČ, B., ŠUŠNJAR, M., NIKLER, L. & ŠUŠNJARA, A. (1973): Osnovna geološka karta SFRJ 1:100.000. List Obrovac L33–140 (Basic Geological Map of SFRY, Obrovac sheet).– Inst. geol. istraž. Zagreb (1962–1967), Savezni geol. zavod, Beograd.

IVANOVIĆ, A., SAKAČ, K., SOKAČ, B., VRSALOVIĆ-CAREVIĆ, I. & ZUPANIČ, J. (1976): Osnovna geološka karta SFRJ 1:100.000. Tumač za list Obrovac L33–140 (Basic Geological Map of SFRY, Geology of Obrovac sheet).– Inst. geol. istraž. Zagreb (1967), Savezni geol. zavod, Beograd, 61 p.

KREISA, R.D. (1981): Storm-generated sedimentary structures in subtidal marine facies with examples from the Middle to Upper Ordovician of southwestern Virginia.– J. Sedim. Petrol., 51, 823–848.

LECKIE, D.A. & KRYSTINICK, L.F. (1989): Is there evidence for geostrophic currents preserved in the sedimentary record of inner to middle-shelf deposits?– J. Sedim. Petrol., 59, 862–870.

LECKIE, D.A. & WALKER, R.G. (1982): Storm- and tide-dominated shorelines in Cretaceous Moosebar–Lower Gates interval: outcrop equivalents of Deep Basin gas trap, western Canada.– Am. Assoc. Petrol. Geol. Bulletin, 66, 138–157.

LOWE, D.R. (1982): Sediment gravity flows II. Depositional models with special reference to the deposits of high-density turbidity currents.– J. Sedim. Petrol., 52, 279–297.

LOWE, D.R. (1988): Suspended-load fallout rate as an independent variable in the analysis of current structures.– Sedimentology, 53, 765–776.

MIDDLETON, G.V. & HAMPTON, M.A. (1973): Turbidites and Deep Water Sedimentation. Sediment Gravity Flows: Mechanics of Flow and Deposition.– Short Course Lecture Notes, Soc. Econ. Paleont. and Mineralog., Pacific Section, 38 p.

MRINJEK, E. (1993a): Conglomerate fabric and paleocurrent measurment in the braided fluvial system of the Promina Beds in northern Dalmatia (Croatia).– Geol. Croat., 46/1, 125–136.

MRINJEK, E. (1993b): Sedimentology and depositional setting of alluvial Promina Beds in northern Dalmatia, Croatia.– Geol. Croat., 46/2, 243–261.

MRINJEK, E. (1994): Internal architecture of alluvial Promina Beds in northern Dalmatia, Croatia.– Acta geol., 24/1–2, 1–36, Zagreb.

MULDINI-MAMUŽIĆ, S. (1972): Biostratigrafija paleogenskih slojeva u širem području Zadra [*Biostratigraphy of Palaeogene beds in the broader Zadar area* – in Croatian].– Nafta, 22, 195–207, Zagreb.

MYROW, P.M. & SOUTHARD, J.B. (1996): Tempestite deposition.– Jour. Sed. Res., 66, 875–887.

NEMEC, W. (1992): Depositional controls on plant growth and peat accumulation in a braidplain delta environment: Helvetiafjellet Formation (Barremian–Aptian), Svalbard.– In: McCABE, P.J. & PARRISH, J.T. (eds.): Controls on the Distribution and Quality of Cretaceous Coals. Geol. Soc. Am. Spec. Pap., 267, 209–226.

NEMEC, W., STEEL, R.J., GJELBERG, J., COLLINSON, J.D., PRESTHOLM, E. & ØXNEVAD, I.E. (1988): Anatomy of collapsed and re-established delta front in Lower Cretaceous of eastern Spitsbergen: gravitational sliding and sedimentation processes.– Am. Assoc. Petrol. Geol. Bull., 72, 454–476.

NØTTVEDT, A. & KREISA, R.D. (1987): Model for the combined-flow origin of hummocky cross-stratification.– Geology, 15, 357–361.

ORR, P.J. (2003): Bathymetric indicators.– In: BRIGGS, D.E. & CROWTHER, (eds.): Palaeobiology II. 2nd ed., Blackwell Science, Oxford, 475–478.

PEMBERTON, S.G., MACEACHERN, J.A. & FREY, R.W. (1992): Trace fossil facies models: environmental and allostratigraphic significance.– In: WALKER, R.G. & JAMES, N.P. (eds.): Facies Models: Response to Sea Level Change. Geol. Assoc. of Canada, St. John's, 47–72.

PEMBERTON, S.G., SPILA, M., PULHAM, A.J., SAUNDERS, T., MACEACHERN, J.A., ROBBINS, D. & SINCLAIR, I.K. (2001): Ichnology and sedimentology of shallow to marginal marine systems: Ben Nevis and Avalon reservoirs, Jeanne D'Arc Basin.– Geol. Assoc. of Canada, Short Course Lecture Notes, 15, 1–343.

PERVESLER, P. & UCHMAN, A. (2004): Ichnofossils from the type area of the Ground Formation (Miocene, Lower Badenian) in northern Lower Austria (Molasse Basin).– Geol. Carpath., 55, 103–110.

READING, H.G. & COLLINSON, J.D. (1996): Clastic coasts.– In: READING, H.G. (ed.): Sedimentary Environments: Processes, Facies and Stratigraphy. 3rd ed., Blackwell Science, Oxford, 154–231.

REINECK, H.-E. (1963): Sedimentgefüge im Bereich der sudlichen Nordsee [*Sedimentary pattern in the area of southern North See* – in German].– Senckenberg. Naturforsch. Ges. Abh., 505, 1–135.

REINECK, H.-E. & SINGH, I.B. (1975): Depositional Sedimentary Environments.– Springer-Verlag, Berlin, 439 p.

SAKAČ, K., BENIĆ, J., BAHUN, S. & PENCINGER, V. (1993): Stratigraphic and tectonic position of Paleogene Jelar Beds in the Outer Dinarides.– Natura Croatica, 2, 55–72, Zagreb.

SANDERS, J.E. (1965): Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms.– In: MIDDLETON, G.V. (ed.): Primary Sedimentary Structures and Their Hydrodynamic Interpretation. Soc. Econ. Paleontol. Mineral. Spec. Publ., 12, 192–219.

SCHUBERT, R.J. (1905): Zur Stratigraphie des istrisch–norddalmatinischen Mitteleocäns [*Middle Eocene Stratigraphy of Istria and north Dalmatia* – in German].– Jahrbuch geol. Reichsanst., 55, 153–188, Wien.

SEPKOSKI, J.J.Jr. (1982): Plat-pebble conglomerates, storm deposits, and the Cambrian bottom fauna.– In: EINSELE, G. & SEILACHER, A. (eds.): Cyclic and Event Stratification. Springer-Verlag, Berlin, 372–385.

SNEDDEN, J.W., NUMMEDAL, D. & AMOS, A.F. (1988): Storm- and fair-weather combined flow in the central Texas continental shelf.– Jour. Sed. Petrol., 58, 580–595.

SWIFT, O.J.P., HUOELSON, P.M., BRENNER, R.L. & THOMPSON, P. (1987): Shelf construction in foreland basin: storm beds, shelf sandbodies, and shelf–slope depositional sequences in the Upper Cretaceous Mesa Verde Group, Book Cliffs, U.S.A.– Sedimentology, 34, 423–457.

TARI-KOVAČIĆ, V. & MRINJEK, E. (1994): The role of Palaeogene clastics in the tectonic interpretation of northern Dalmatia (southern Croatia).– Geol. Croat., 47/1, 127–138.

UCHMAN, A., JANBU, N.E. & NEMEC, W. (2004): Trace fossils in the Cretaceous–Eocene flysch of the Sinop–Boyabat Basin, Central Pontides, Turkey.– Ann. Soc. Geol. Polon., 74, 197–235.

WALKER, R.G. (1984): General introduction: facies, facies sequences and facies models.– In: WALKER, R.G. (ed.): Facies Models. Geoscience Canada, Geol. Assoc. of Canada, St. John's, 1–9.

WALKER, R.G, DUKE, W.L. & LECKIE, D.A. (1983): Hummocky stratification: significance of its variable bedding sequences: Discussion.– Geol. Soc. Am. Bull., 94, 1245–1251.

WALKER, R.G. & PLlNT, A.G. (1992): Wave- and storm-dominated shallow marine systems.– In: WALKER, R.G. & JAMES, N.P. (eds.): Facies Models: Response to Sea Level Change. Geol. Assoc. of Canada, St. John's, 219–238.

ZUPANIČ, J. & BABIĆ, L. (1981): Postanak starijeg dijela Promina-formacije (paleogen) sjeverozapadno od Benkovca [*The origin of the lower part of Promina Formation (Palaeogene), northwest of Benkovac, Dalmatia* – in Croatian]. Vesnik Zavoda za Geol. Istr. (A), 1980–81, Beograd, 38–39, 227–230.

Manuscript received February 15, 2005.

Revised manuscript accepted November 11, 2005.