Geologie en Mijnbouw **69**: 375–390, 1990.

Origins of event beds in the Jurassic 'Calcari Grigi' Formation, Venetian Alps, Italy

Gianni Galli
Dipartimento di Scienze Geologiche, Via Zamboni 67, 40127 Bologna, Italy

Received 25 July 1989; accepted in revised form 28 May 1990

Key words: shallow-water carbonates, Jurassic, tsunamis

Abstract

Three undulating, large-scale bedforms occur within a 20 km wide lagoon which was probably generated by synsedimentary tectonic processes in a Jurassic shallow water rimmed platform (Trento Platform, Italy). Bedform 1 resembles hummocky cross stratification and consists of domes and troughs which display a downcurrent increase in wavelength and decrease in amplitude. Bedform 2 is composed of low-angle undulating foresets whose downcurrent structural variations over 300 m of stratigraphic exposure mimic smaller-scale climbing-wave ripple lamination. Bedform 3 consists of three large-scale stacked 'giant ripples'. Internal characteristics (shell fabrics) of bedforms reflect a complex storm action that was ineffective as sediment transport mechanism but produced an 'in situ' reorientation of shells through strong shear stress and local pressure pulses on and below the lagoonal floor. These bedforms were generated by tsunamis as evidenced by: 1) the action of surface waves; 2) a great lateral extent of exposures; 3) the restriction of bedforms to the same stratigraphic horizon (correlated by means of 'event correlation').

Bedform 1 was produced by first-order impulse-generated waves progressing discontinuously along the deepest area of the lagoon; bedforms 2 and 3 reflect bottom return flows. The trajectory system has been tentatively explained by the hydrodynamic configuration of impulse waves propagating at supercritical conditions around a lateral obstacle.

Introduction

The possibility that tsunamis generate sedimentary structures is being mentioned in a growing body of literature (Bernstein, 1954; Bascom, 1964; Coleman, 1968; Fairbridge & Bourgeois, 1978; Kastens & Cita, 1981; Marsaglia & Klein, 1983; Duringer, 1984; Bourrouilh-LeJan & Talandier, 1985; Klein & Marsaglia, 1987; Bourgeois et al., 1988; Szulc, 1988). The sedimentary record of tsunamis within ancient shallow water settings is still obscure, owing to a lack of specific vertical sequences compared to those produced by other types of storm processes (Kreisa, 1981).

The object of this research was to investigate unusual, large-scale bedforms occurring within the Jurassic Trento Platform (Italy), an ancient shallow water carbonate platform. Bedforms described here are complex and could not be explained by traditional hydrodynamic mechanisms. Their interpretation as tsunami-generated features resulted from their identification as storm deposits and from a rejection of hurricanes and fair-weather processes as causative agents. The study was facilitated by laterally continuous outcrops and correlations of bedforms along a stratigraphic horizon by means of 'event' correlation (Ager, 1981).

Tsunami properties

Tsunamis are trains of impulse-generated, long translatory surface waves produced by catastrophic events (e.g., meteorite impacts, submarine tectonic movements; see Fairbridge & Bourgeois, 1978). Wave trains in the open sea are characterized by low, 1 to 2 m amplitudes, wavelengths of about 10 km, velocities up to 800 km/h (Ager, 1981) and periods of 30 to 60 minutes. Tsunami waves act as shallow-water waves at any depth. When they approach the shoreline, friction against the sea-floor causes a decrease in velocity and wavelength and an increase in amplitude. The build-up of water against the shore is compensated during the peak phase by a strong bottom return current which is followed by an oscillatory motion. It is thus possible that the return current develops a bottom traction carpet by current drag and local channeling. Hence, tsunamis are capable of transporting enormous volumes of shallow water sediments out to sea. Bourgeois et al. (1988) hypothesized deposition by tsunamis under initial high shear velocities (15–100 cm s^{-1}) followed by a rapid drop and eventually by an oscillatory flow. The storm flow field produced by tsunamis appears to be complicated and Klein & Marsaglia (1987) suggested that tsunamis can generate a trajectory current pattern similar to the storm current pattern on the Atlantic Shelf described by Swift et al. (1983).

Geologic and environmental setting

The 'Calcari Grigi' Formation occurs in the Venetian Alps, Italy. The Formation represents the top of the Trento Platform, 80 × 100 km^2 in extent, which is a part of a passive margin (Bernoulli & Jenkyns, 1974). The 20 × 20 km^2 study area is situated in the centre of the Trento Platform (Fig. 1). Previous studies on the 'Calcari Grigi' Formation were carried out by, among others, Bosellini (1972; 1973), Göhner (1980; 1981) and Clari (1975).

Deposition took place in a lagoonal environment which was punctuated by patches of oolite and shoal-complex facies. The depth ranges from 15 m to 2 m below sea level (Galli, 1988). *Lithiotis* wackestones are widespread; they are typified by 1 to 9 m thick beds of tightly packed accumulations of big shells of *Lithiotis problematica* Gümbel bivalves, up to 40 cm long, embedded in a micrite matrix. The growth of thick *Lithiotis* banks took place in deeper parts of the lagoon, as suggested by their thickness, absence of abrupt interruptions or disturbance by influx of intraclast detritus owing to a proximity to a shoreline. Storm action is evidenced by tempestites, similar to the swell lags described by Powers & Kinsman (1953), by hummocky cross bedding, hummocky sequences (Dott & Bourgeois, 1982), by fining-upward sequences within the shoal complex facies and by isolated scour-and-fills. The existence of an elongated lagoonal depression oriented NE–SW is revealed by an examination of isopach maps of maximum thicknesses of *Lithiotis* banks (Fig. 2A) and of isocoquinites (tentative contour map of a series of locations characterized by the same numbers of coquinite lenses: Fig. 2B; the values were obtained by dividing the number of coquinite lenses within skeletal wackestones by the thickness of skeletal wackestones that occur in single stratigraphic sections). A comparison between isocoquinite data and relative facies frequency distribution (not shown here) indicates that tempestite trends were independent of facies and would reflect 1) changing water depth and/or 2) a southwestward source of propagation of storm waves. The uneveness of the lagoonal floor resulted from the development of an array of shoals within the lagoonal depression; the paleotopographic profile mimics a miniature ramp with deeper lagoonal areas located in the west and south (Fig. 3). Directional data were collected from orientations of symmetrical ripple crests (Fig. 2A), gutter casts and scours (Fig. 2B), axes of coquinite lenses (Fig. 2C) and from the strikes of dipping *Lithiotis* shells (Fig. 2D). Measurements from shell imbrications and parting lineations suggest that currents moved from SW to NE. The maps indicate a dominant rotary storm path oriented SW–NE which was driven by the lagoonal corridor configuration and a minor mode, oriented SE–NW which indicates currents flowing oblique to the lagoonal 'bucket'. A refracted wave pattern, which displays a counterclockwise sense of rotation (Fig. 2) prob-

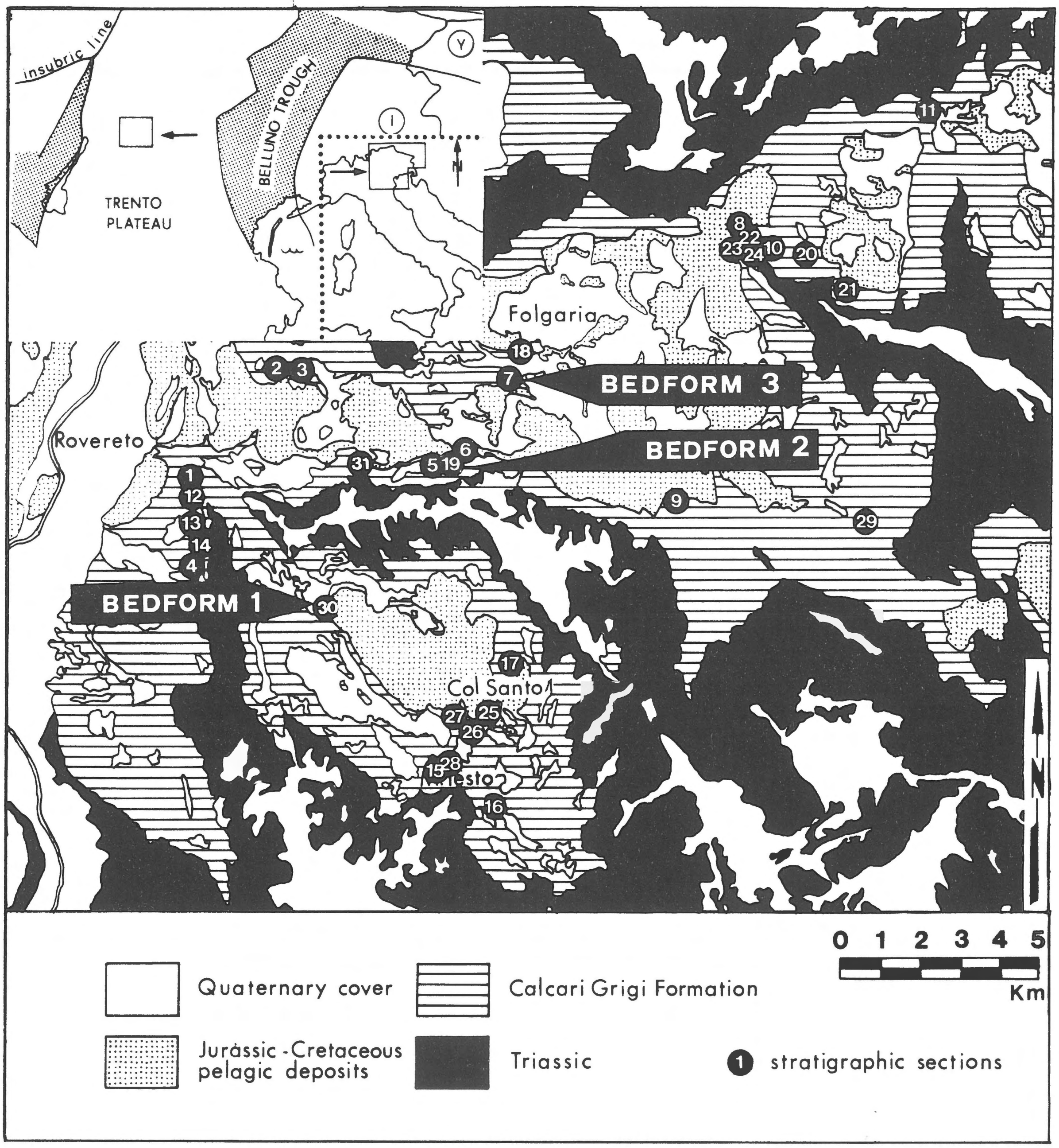


Fig. 1. Map of study area with locations of stratigraphic sections, bedforms and distribution of the shallow water 'Calcari Grigi' Formation. Upper left: relationships between study area and width of the Trento Platform (from Bosellini et al., 1981).

ably resulted from the impingement of the SW–NE oriented storm current upon the shoals which were located in the east. In cross section, the studied upper part of the 'Calcari Grigi' Formation is wedge-shaped (Fig. 3). The northeastern side, 20 m thick, is mainly composed of mudstones interpreted as marsh facies and shallow lagoon and shoal complex facies. The Formation developed at a shallower depth than at the southern side where the sedimentary prism, 60 m thick, was the site of accumulation of the thickest *Lithiotis* banks (Fig. 3). An areal zonation of sedimentary structures agrees well with the contour maps and areal facies distribution; hummocky cross bedding occurs within the deeper areas of the lagoonal depression, whereas scour structures formed around its margins. The formation of this wedge-shaped structure stems from a southward, asymmetrical, syndepositional tectonic tilting and rotation around a hinge line (Galli, 1988). Synsedimentary tectonic structures, such as syndepositional faults and deformations, are ubiquitous in the studied area. They suggest frequent offshore tectonic activity, that could have triggered tsunamis.

Description of bedforms

Large-scale bedforms occur along two stratigraphic horizons. The three bedforms which are described in this paper occur within the same *Lithiotis* bank. They are denoted by diamond symbols in Fig. 3 and are numbered progressively from south to north in Fig. 1. They do not form vertical sequences but consist of a body-set bounded by first-order erosional boundaries. Internal, second-order contacts are given by traces of layer surfaces which delimit coset boundaries; third-order contacts within layers (lamina-sets) separate distinct shell fabrics.

Bedform 1 (Fig. 4)

Description. This bedform consists of large-scale asymmetrical, undulating layers whose irregular thicknesses average 0.3 m. Thicknesses decrease upwards. Layers display wide domes and shorter troughs. The erosional bases of the lowermost layers are discordances between shell inclinations below and above coset boundaries, or are sudden changes in shell orientations. Erosional contacts are more accentuated in the troughs than in the domes. Upper cosets display non-erosional bases. Lateral tracings of beds over 100 m show a northward increase in wavelengths (from 4 to 10 m) and a decrease in the amplitude (0.4 m) of domes in the same direction. Towards the north, domes gradually flatten and eventually merge into slightly undulated beds. Shell inclinations follow the offshooting traces of coset boundaries. Shells are stacked and densely packed in domes and disoriented or densely packed in the troughs. An east west, lateral profile of the same bedform shows large-scale swales and layers draping over slightly scoured topography and expanding laterally in thickness within swales.

Interpretation. A storm origin for this bedform is inferred from the predominating fining-upward and thinning-upward trends, from sharp bases associated with a complex organization and from sharp contacts between different fabric types. Convex-up and concave-down sets, cross stratification dipping at low angles, rarity of high-angle dipping beds, erosional and non-erosional set boundaries fit characteristics of hummocky cross bedding listed by Harms et al. (1975). Wavelengths, up to 10 m in extent, are less common. The lengths attained by shells (as much as 30 cm), unusual in hummocky cross stratification, are in direct evidence, together with erosional contacts between coset and lamina-sets, of high current velocities. In fact, currents with speeds in excess of 2 m s^{-1} are required to transport pebbles attaining 5 to 10 cm in diameter (Komar & Miller, 1975). The current drag was so strong that shells 10 to 30 cm in length which were deeply driven into mud were reoriented and dragged up the crests. The pressure gradient produced a migration of mud through shells with a resulting sorting and concentration of shells. The mechanism of shell sorting would be analogous to that described by Powers & Kinsman (1953). Accordingly, this bedform could represent a residual shell concentration resulting from repeated swell events.

Bedform 2 (Fig. 5)

Description. This bed configuration is composed of low-angle, undulating foresets which average 0.4 m in thickness. Topsets and bottomsets are represented by swollen to erosional surfaces (Fig. 5). The topset consists of symmetrical, 3 m-wide un-

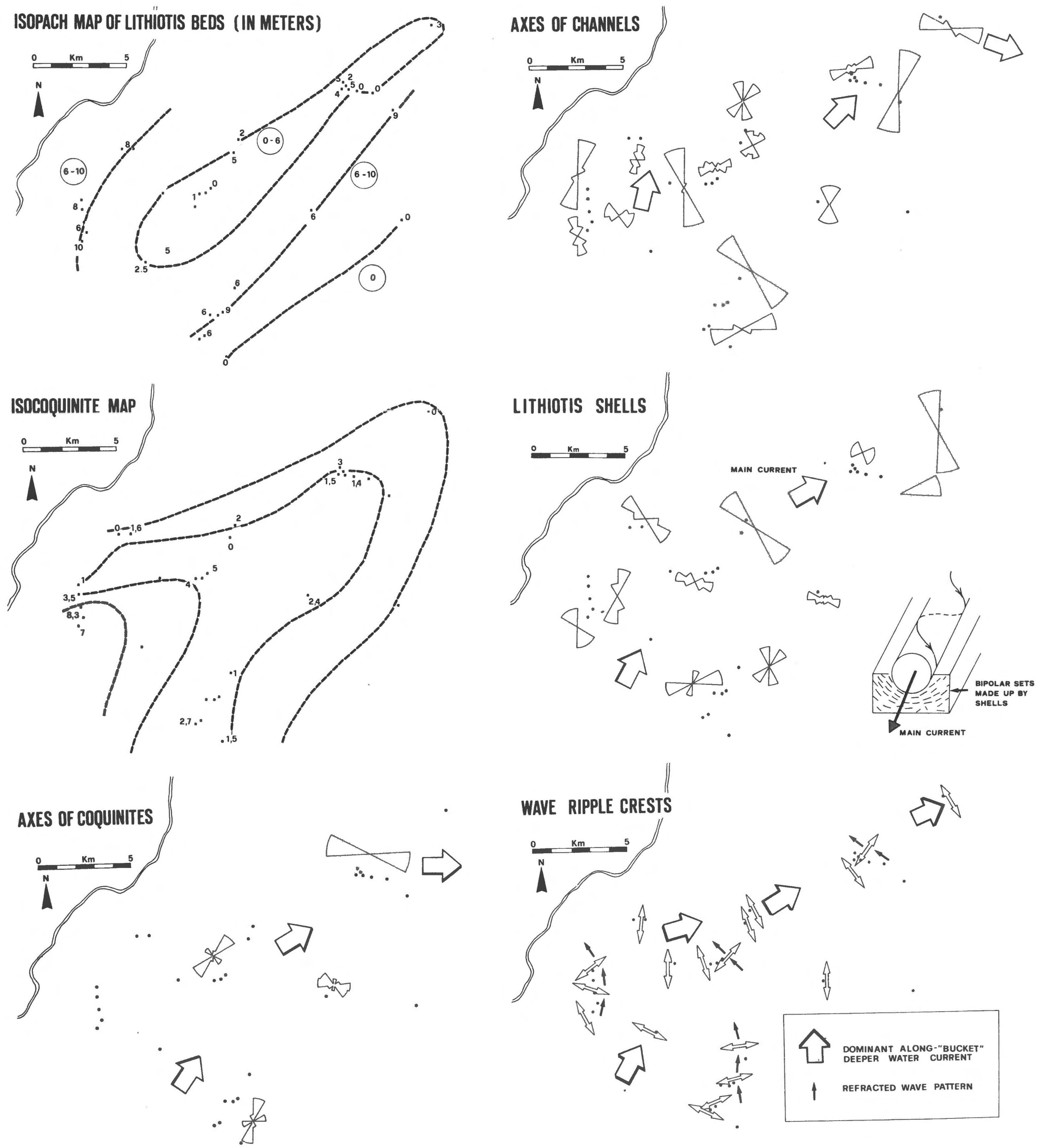
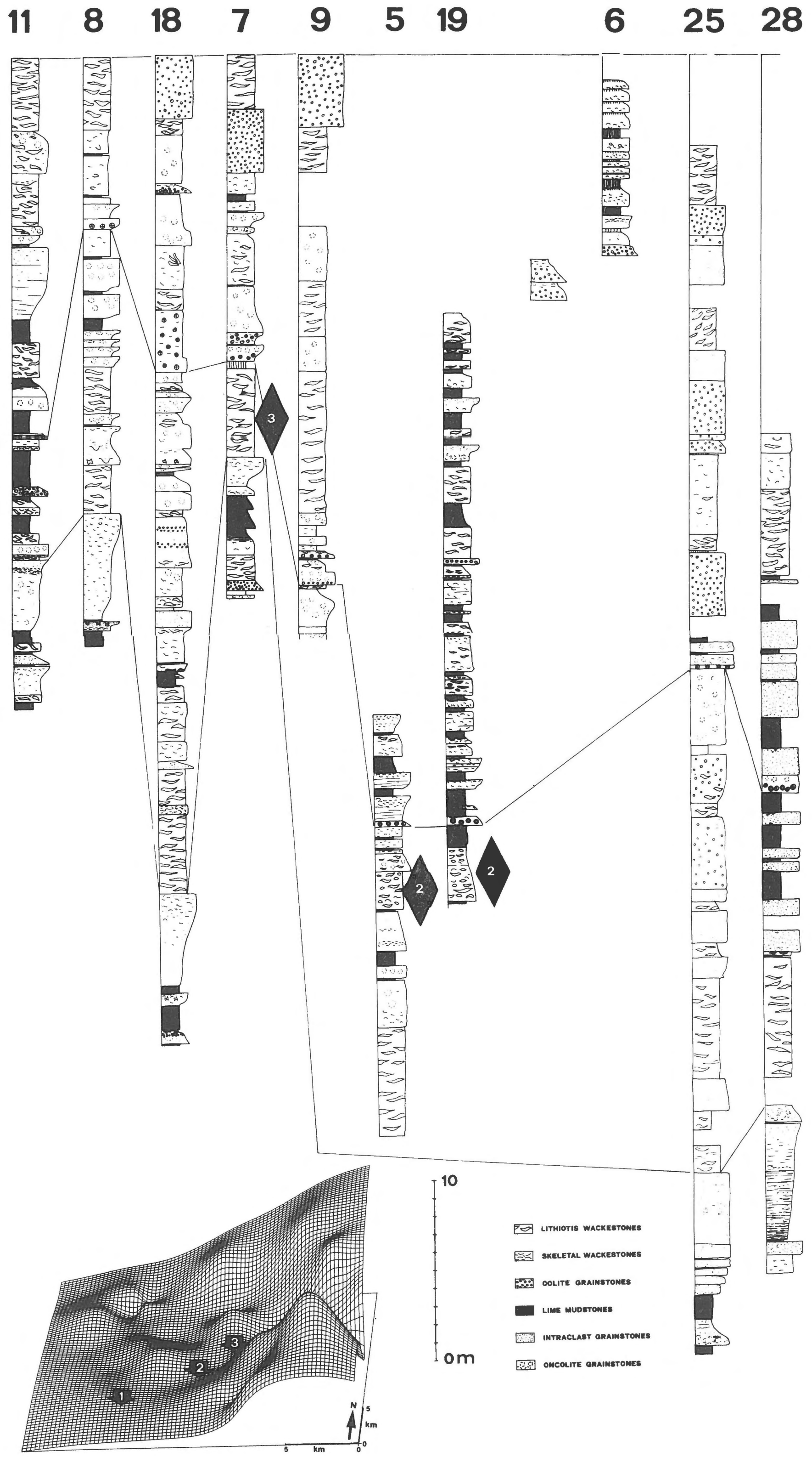


Fig. 2. Contour maps and paleocurrent data. The isopach map of *Lithiotis* beds, based on maximum measured thicknesses of *Lithiotis* beds, is interpreted to reflect changing water depths. Paleocurrent data from the lagoonal and shoal complexes were obtained from less than 10 measurements at each locality. Strikes of dipping *Lithiotis* shells obtained from approximately 1000 measurements. Dots in all maps represent locations of stratigraphic sections shown in Fig. 1.



11
8
18
7
9
5
19
6
25
28
3
2
2
10
0m
LITHIOTIS WACKESTONES
SKELETAL WACKESTONES
OOLITE GRAINSTONES
LIME MUDSTONES
INTRACLAST GRAINSTONES
ONCOLITE GRAINSTONES
1
2
3
N
5
km
5
km
0

dulations which truncate underlying inclined cosets. Shells, organized into a fining-upward trend, are densely packed and randomly oriented close to the tops of cosets, inclined in a direction opposite to foreset inclinations in the lower part of cosets (Fig. 5). An alignment of shells parallel to the lower erosional concave-up surface is present above the troughs of the undulating surfaces (Fig. 5), where local shell imbrications in the swales result in a denser packing; close to topsets shells become gradually horizontally aligned.

Going westward, over approximately 300 m, the body-set of Fig. 5 (right) acquires a 'vertical accretion' morphology: individual beds are thinner, less inclined and undulose; swales and hummocks (wavelengths: 10 to 4 m; amplitudes: 0.6 to 3 m) are clearly distinguishable (Fig. 5). Undulations are regular and nearly symmetrical; domes are composed of vertically accreted sets which thicken in the crests with the formation of undulations displaying an opposed, divergent symmetry with respect to trough axes (Fig. 5). Tops of domes are not sharp or straight-crested (as occurs westward) but are gently sinuous. Lower and upper boundaries of the body-set show partial erosional truncations (Fig. 5). Boundaries between individual layers are also non-erosional. A general fining-upward trend consists of a decrease at the very top in size, packing and abundance of shells. Dip angles of vertically accreted sets become progressively more horizontal as they approach the bottomset (Fig. 5).

Interpretation. The body-set at west (Fig. 5) is similar, apart from obvious differences in scale and size, to the climbing-wave ripple lamination described by Kreisa (1981), which is interpreted as the result of rapid, wave-generated, oscillatory currents. Westward lateral transitions from inclined beds to upbuilded beds are analogous to variations from inclined lamination to climbing-wave ripple lamination which were found within a hummocky sequence within the 'shoal complex facies'. Transitions between body-sets are explained by a storm-generated waning flow which changed properties in evidence of a west-directed, unidirectional current (as suggested by directions of shell inclinations) to those of a predominating oscillatory water motion in deeper zones in the West, consequent to a superimposition of wave orbital components to the unidirectional current. In the East these orbital components only modelled inclined beds into symmetrical undulations. Such wave orbital components flattened and deformed sharp-crested beds in the West with the formation of a mound-like topography.

Bedform 3 (Fig. 6)

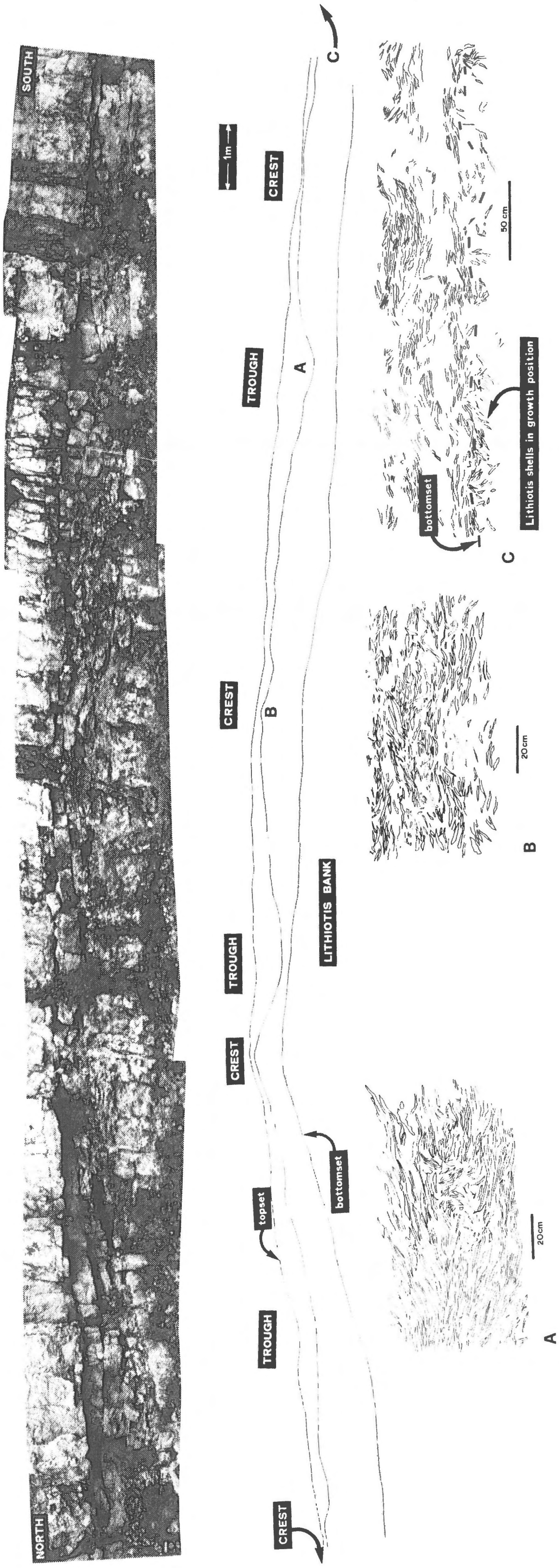
Description. This bedform consists of three stacked 'giant ripples'. The lowermost one occurs within *Lithiotis* wackestones whereas the uppermost 'giant ripples', which are somewhat smaller in size, occur within micrite lithologies. The relief of these 'giant ripples' is approximately 2 m. Each ripple consists of a more or less planar bottomset surface and an undulated unit which is overlain by fine grained layers (mud drapes) which thicken towards the west and display normal grading. 'Giant ripples' are asymmetric with the east side steeper than the west side. The eastern swale (Fig. 6) is filled with homogeneous mud containing dispersed bioclasts (Fig. 6B). The uppermost undulated surface of the lowermost 'giant ripple' is represented by well-sorted sub-mm thick, faint micrite laminations composed of fine grained, angular lithoclasts and peloids (Fig. 6D). Shells are disoriented within the lowermost bedform; they become aligned parallel

←

Fig. 3. North-south cross section showing the wedge-shaped geometry of the examined uppermost part of the 'Calcari Grigi' Formation. A southward and westward tilting, contemporaneous with sedimentation, was probably responsible for the formation of the 'miniature ramp' and lagoonal corridor shown in the block-diagram at the lower left which results from computer manipulation of bathymetric interpretations of facies (arrows indicate the locations of bedforms 1, 2 and 3 described in this paper). Marker horizons utilized in the 'event' correlation of stratigraphic sections were: 1) the top of the 'Calcari Grigi' Formation (flooding surface according to Barbujani et al. 1986); 2) a 10 cm-thick horizon containing radial oolites; and 3) a 'triple disconformity' (Riding & Wright 1981) (Galli 1988). The location of bedforms 2 and 3 is shown by black diamonds.

to the undulated topset close to the top. Microstructures visible within the upper 'giant ripples' are subspherical micro-mud balls composed of disoriented larger allochem fragments (Fig. 6C) and faint micrite laminations (Fig. 6D).

Interpretation. The westerly thickening of drape layers and the westward shift of giant ripple crests are a large scale evidence for a westward directed, unidirectional current. The massive fine-grained megaripples record periods of rapid deposition; traces of bioturbation were not observed. The alignment of shells parallel to the upper sinusoidal surface and a lack of fragmented shells resulted from high amplitude swells associated with a vertical pressure gradient. Subparallel, sub-mm thick laminations within 'giant ripples' record a remobilization of sediment and probably a lateral movement of mud. Lateral transport of muddy sediment with the formation of laminated mud under high energy conditions was reported in the study of Surinam (Rine & Ginsburg, 1985) and Florida Bay mud banks (Bosence, 1988). Within the lower giant ripple there is no sharp contact between sheared *Lithiotis* shells and undisturbed, disoriented *Lithiotis* shells: it is possible that there was no sediment-water interface during the remobilization of the *Lithiotis* bank. Micro-mud balls (Fig. 6C) testify that mud had already acquired some consistency or that it was semifluid during the formation of giant ripples. The abrupt transition from intensively sheared muddy sediments (Fig. 6A) to mud drapes (Fig. 6B) with a distribution grading indicates that the storm-stirred, high suspension load began to settle during waning energy conditions, following a rapid drop in shear stress. Bosellini (1972) proposed that this bedform originated by high amplitude swells.



→

Fig. 4. Partial view of bedform 1 showing geometry and internal characters of sets. *Lithiotis* shells are more densely packed, sorted and fragmented in the troughs (A) than on the crests (B). At the lower right (C) the lower contact with a *Lithiotis* bank is shown where vertical shells are overlain by undulations formed by *Lithiotis* shells. Inferred current direction from right to left.

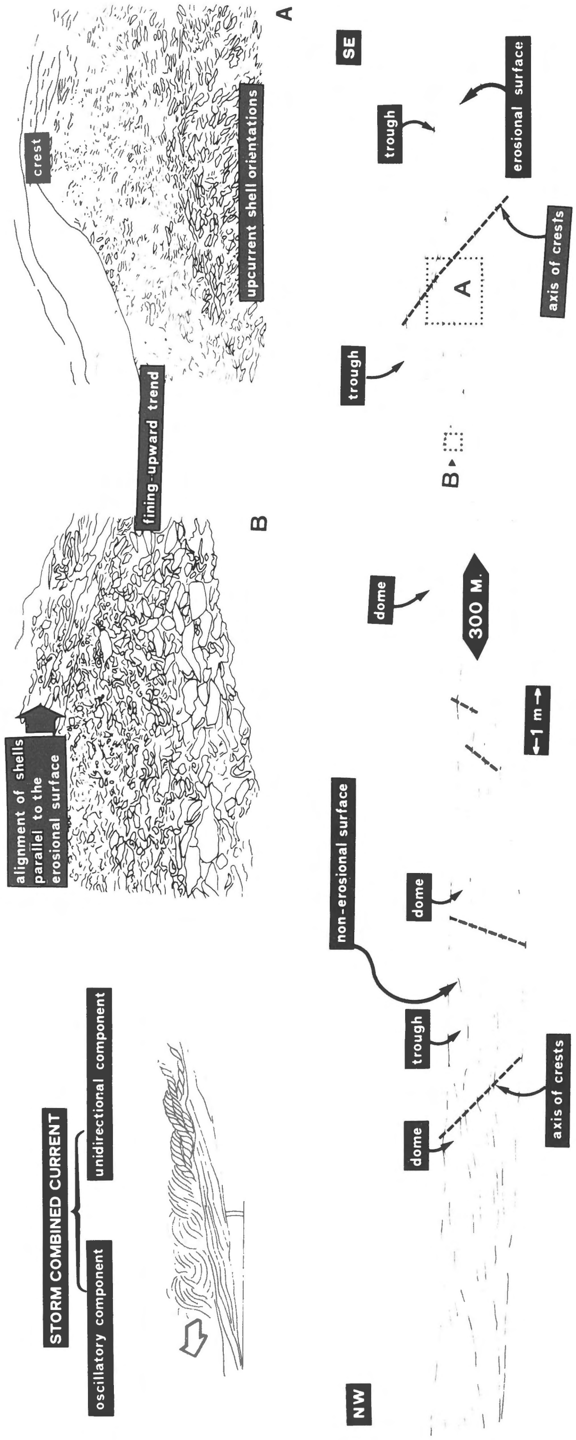


Fig. 5. Geometry and internal structure of bedform 2. The transition from inclined beds (right) to more undulated beds (left) is explained by the superimposition of oscillatory components to a unidirectional upcurrent component of a storm combined current. Inferred current direction from right to left.

Origins of bedforms

An interpretation of the three bedforms described above is problematic because inclined beds and to a lesser degree mound-like bedforms may form under many different conditions and by a large variety of processes.

Lateral accretion bedding in an ancient carbonate setting was recently interpreted to be in evidence of laterally migrating tidal channels (Cloyd et al., 1990). Inclined beds of Fig. 5 resemble tidal point bars (e.g., example Loucks & Anderson, 1980). However, inclined beds in the study area are not associated with levee deposits of tidal channels which have a very high preservation potential (Hardie & Garrett, 1977). There is no upward increase in the degree of exposure higher up the bedform, comparable to that observed in Andros tidal channels (Hardie & Garrett, 1977).

Tidal facies are absent in the study area and inclined beds do not display a basal channel lag, mud lumps and a heterogeneous faunal composition, all features typical of tidal channel deposits. These inclined beds do not fit characteristics of siliciclastic 'coarse grained point bars' (McGowen & Garner, 1970) because shells dip in a direction opposite to foreset inclinations. Ripple lamination overlying reactivation surfaces as well as herringbone and large scale cross stratification were not observed (cf. De Mowbray & Visser, 1984). The uniform bimodal fossil orientation of *Lithiotis* shells in the investigated area (Fig. 2) involves a unidirectional current which is incompatible with current dispersion patterns typical of meandering streams (Edwards et al., 1983: Fig. 1).

Unidirectional currents act not only in inshore channel systems, but also offshore as unidirectional (Johnson, 1977), rectilinear and partially rotary currents (Houbolt, 1968). A downcurrent decrease in inclination and thickness of sets, similar to that displayed by bedform 2 (Fig. 5) was described from tidal sandwaves (Nio & Siegenthaler, 1978). On the other hand, sandwaves and mud banks in modern shelves form dune fields and the paleocurrent mode is directed alongshelf or alongshore (Nio, 1977; Rine & Ginsburg, 1985). In the Bahama Banks fringing the border of Exuma Sound sand-

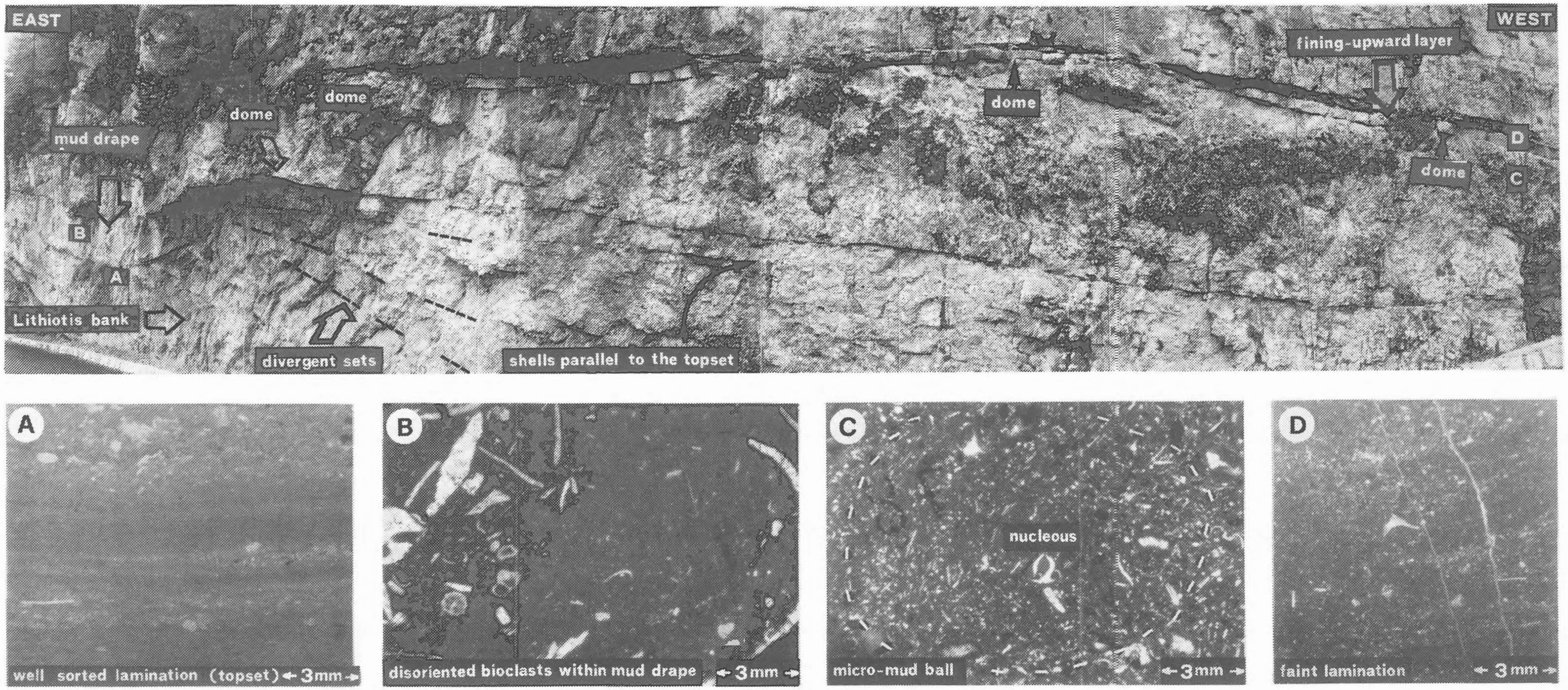


Fig. 6. Bedform 3 showing two 'giant ripples' and internal characteristics (photos A–D). Trees and road for scale. Inferred current from left to right.

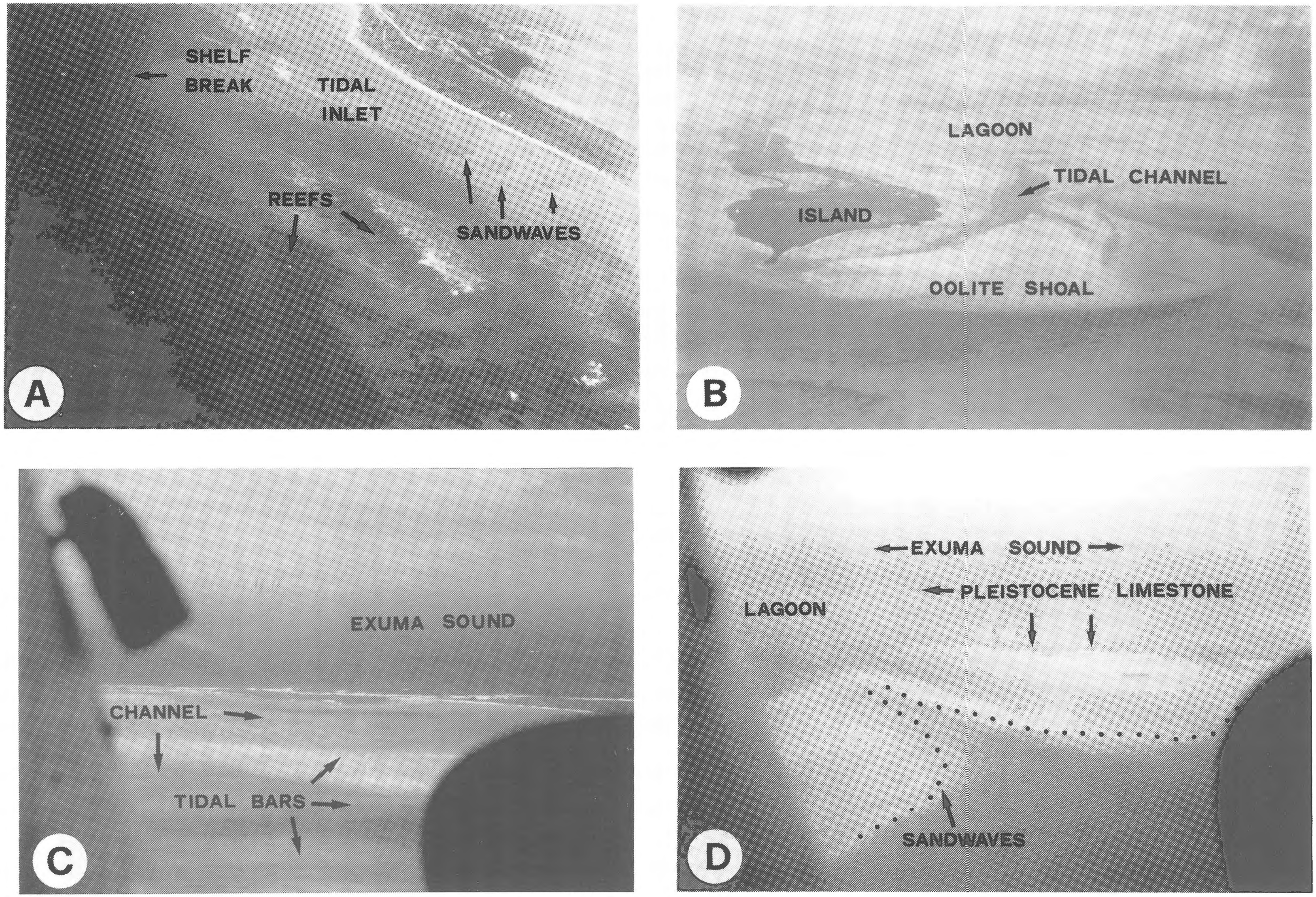


Fig. 7. Sandwave and dune fields in the Exuma Cays, Bahama Bank, in proximity to the barrier island complex, close to the border of the platform.

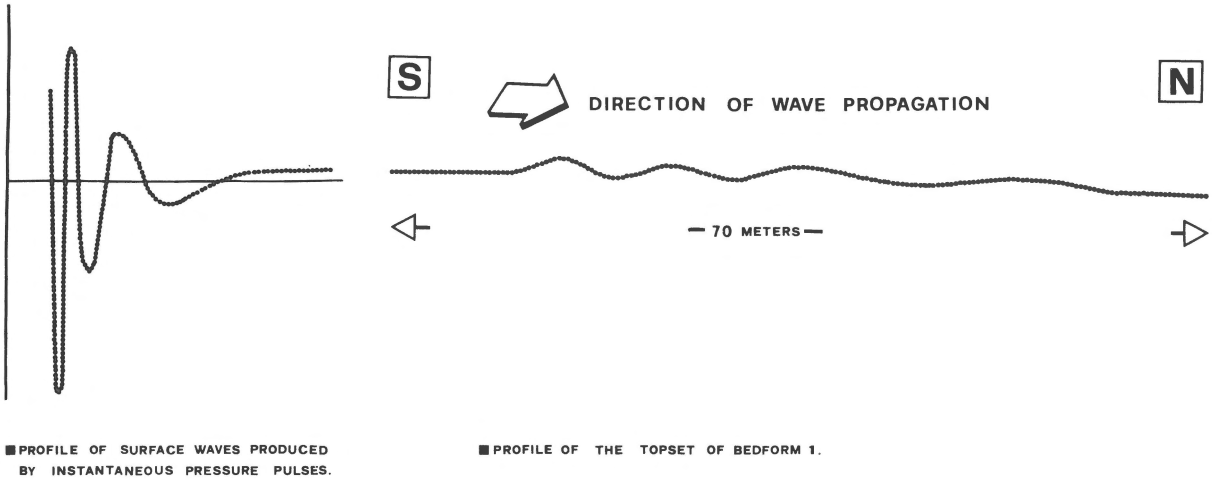


Fig. 8. The profile of the topset of hummocky cross stratification (Fig. 4) consists of a downcurrent decrease in steepness of hummocks and increase in wavelength that can be explained by the dynamic evolution in space of surface waves (left: after Lamb 1945: p. 390).

waves are located within tidal channels cutting through Pleistocene islands (Fig. 7A) and oolite sand deltas (Fig. 7B). They also occur within secondary tidal channels parallel to the strike of the barrier island complex (Fig. 7C). I have also observed wide sandwaves within wider, open lagoons (Fig. 7D) in the northern side of the Exuma Cays. Tidal channels cutting through oolite shoals at Exuma Cays are up to 500 m wide and 3 to 10 m deep. The floor is occupied by large ooid dune fields. Transverse ridges of sandwaves developed at the channel margins are 10 m long and 1 to 2 m high; sets are directed towards the platform and reflect a water movement towards the platform interior. Velocities of tidal currents are up to 150 cm/s (Kendall et al., 1989; pers. obs.). In the study area and more in general in the Trento Platform (Bosellini, 1972) inclined beds are very rare. Within migrating sandwaves individual sets may be fining-upward, when the total sequence is coarsening-upward (De Raaf et al., 1977). Westward dipping foresets are in evidence of the development of transverse bedforms rather than of rectilinear, longitudinal ridges or sandwaves because the lagoonal depression is oriented SW–NE (Fig. 2). Inclined beds and transverse bedforms described by Bosellini (1972) can be explained by tidal currents because of their closer location to the margins of the Trento Platform. Consequently it is quite possible that they formed by unidirectional strong tidal currents as suggested by Bosellini (1972). Conversely, tidal currents are expected to be negligible at the centre of a very wide carbonate platform, in comparison with the situation within the Bahama platform where they are important only in close proximity to the platform margin (Fig. 7). That tidal currents did not play an important role in sedimentation is demonstrated by the lack of high-angle cross bedding in the study area.

Inclined beds are not an exclusive product of fair-weather processes: they were described in storm-generated deposits (Scoffin, 1977; Tagett et al., 1986). Cloyd et al. (1990) also advanced a combination of tidal and storm processes. Some of the storm deposits referred to in the introductory parts of this paper may have been produced by tropical storms or hurricanes. However, known sedimentary structures produced by even strong hurricanes or mid-latitude storms in actual carbonate environments (Ball et al., 1967; Perkins & Enos, 1968) are some order of magnitude smaller than bedforms described above. Hurricane storm tracks are random on a $20 \times 20\,km^2$ wide area (Tannehill, 1960: p. 66) and are unlikely to produce a well-defined paleocurrent trajectory such as that shown in Fig. 2. Fining-upward coquinites (tempestites) similar to those described and attributed to hurricanes by Kreisa (1981) and Aigner (1985) are rare

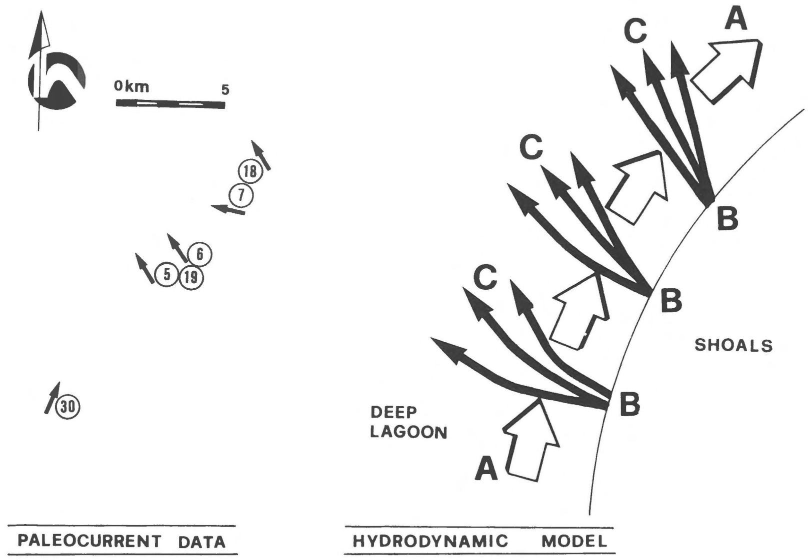


Fig. 9. Paleocurrents obtained from the tsunamite horizon (including other bedforms not described here) and hydrodynamic model. The ray configuration at right consists of a fluid moving at a supercritical speed (A) around a wall (shoal array: cf. Fig. 2: lower right). Discontinuities on the walls (for example, changes in directions) are the point-sources (B) of return current fans (C). This configuration is quite common in nature (Rutherford 1970; Landau & Lifchitz 1971).

or absent. The tempestites found here match swell lags described by Powers & Kinsman (1953) which are interpreted as the result of the passage of long period swells. Hurricanes may produce swell waves, but these are effective against beaches and shorelines unsheltered by barriers or reefs (Terwindt et al., 1984). Based on paleogeographic data (Bernoulli & Jenkins, 1974) and Fig. 3, it is conceivable that the Trento Platform could have been dissected into blocks by synsedimentary tectonism, with the formation of narrow corridors and seaways (cf. Straits of Andros in Eberli & Ginsburg, 1987: Figs 2 and 3) which enhanced the velocity of tidal currents and hurricane swells. However, the existence of a corridor facilitating the intrusions of oceanic currents (Flemming, 1978) is discounted by a lack within the whole Trento Platform of pelagic fossils (ammonoids, etc.) which would have been transported into the lagoon. A direct connection to the open sea would have triggered the formation of marginal bays populated by a high-diversity lagoonal fauna, rather than a semirestricted environment populated by an abundant, low-diversity fauna such as *Lithiotis* (Broglio Loriga & Neri, 1976). Faunal diversity of lagoons prospicient to Exuma Cays is low due to stress induced by strong tidal currents, but semipermanent strong currents take place only close to the barrier island system, being constricted by shoals and islands; other than oceanic waters, they would have transported pelagic skeletons onto the platform which have not been found.

Common biogenic mounds described by Bosellini (1972) from other areas in the Trento Platform are symmetrical as is expected in areas not subject to semipermanent unidirectional currents; they are also low-relief features, less than 1 m high and 4 to 5 m wide. Shells of *Lithiotis* within *Lithiotis* bioherms are vertically oriented and typically occur as fanning upward clusters (Göhner, 1980). Consequently, 'giant ripples' and bedform 1 are not the product solely of biogenic parameters. In addition, 'giant ripples' occur in micrite lithologies, other than in *Lithiotis* wackestones. It is not excluded that 'giant ripples' and undulated bedforms were produced by an accentuation of the relieves of former biogenic mounds, through interference between swell action (as formerly hypothesized by Bosellini, 1972) and an irregular topography.

A tsunami origin for these bedforms is supported by: 1) a formation of bedforms 1, 2 and 3 by impulse-generated surface waves and local vertical pressure pulses on the sea-floor; 2) a great lateral extent of individual bedforms (hundreds of metres); and 3) a restriction of bedforms to the same stratigraphic horizon.

Profiles of coset boundaries mimic those of surface waves produced by local impulses on an undisturbed surface which show a decrease in deformation away from the source of the impulse (Fig. 8). This is reflected by upcurrent, well-pronounced erosional troughs, together with a downcurrent decrease in height of mounds and an increase in bedform wavelength. These variations suggest the action of an alongshore storm current progressing as pulsating bursts of energy on patches which decreased in intensity in a downcurrent direction, away from the local source of the impulse. Shell fabrics within bedforms, such as those sketched in Figs 4 and 5, resulted from a strong bottom shear stress which produced a better sorting in troughs than in the domes, lamination and fragmentation (Madsen, 1976).

It is not clear how vertical pressure pulses and horizontal shear acted on or below the sedimentary interface; in some cases (not described in this paper) deformation of beds underlying interpreted tsunami-generated beds would indicate that a pressure pulse on the sea-floor preceded the shear stress-induced shell imbrication. The intensity of the shear stress was probably independent of depth, as expected for tsunami waves. Variations in external and internal characters of bedforms were not so much a function of water depth, as they were a function of complex interactions between current directions and physiography. Surface waves probably impinged upon shoals in the east (cf. Fig. 2) and were refracted (cf. refracted wave patterns shown in Fig. 2). A complex current pattern during tsunamis is inferred from variability and rapid transitions between bedforms. Inferred paleocurrent measurements from the interpreted tsunami horizon (Fig. 9) are in accordance with the cumulated paleocurrent trends of Fig. 2 because of the existence of a current directed parallel (NE–SW) and another oblique (NW–SE) to the strike of the lagoonal corridor. The tsunami flow field is similar to that documented by Swift et al. (1983). The possibility that tsunamis produced a similar current pattern was suggested by Klein & Marsaglia (1987). Landau & Lifchitz (1971: p. 498) demonstrated that properties of impulse waves such as those produced by tsunamis at a shallow water depth, are analogous to those of compressible fluids travelling at supercritical speeds.

A hypothetical scenario could be represented by the trajectory of refracting impulse waves around a convex obstacle (Rutherford, 1970), represented in this case by the shoal array shown in Fig. 2. Consequently, bedform 1 would have been produced by first-order impulse waves progressing discontinuously (cf. Fig. 8) along the lagoonal corridor; bedforms 2 and 3 would be the end-product of strong bottom return flows activated by centripetal refracted current fans.

The similarity between the storm flow field produced by tsunamis and the flow system documented by Swift et al. (1983) suggests the possibility that water movements produced by tsunamis could couple within a shallow water environment, as effectively with the water column, as geostrophic flows and related current components, along continental shelves (Swift et al., 1983).

The storm system, rather than actively transporting sediment, determined near-bottom oscillating currents acting through strongly pulsating bursts of energy. It is suggested that earthquakes within the platform produced sudden oscillations of water which incorporated the whole water column.

Concluding considerations

Despite the evidences furnished above, a tsunami interpretation presents some problems.

A mechanism whereby tsunamis might influence the formations of the three bedforms hampers the applications of a comparative approach because they have no known counterpart among modern sediments. Rather, the conclusions are in accordance with the principles of catastrophic uniformitarianism put forth by Ager (1981). If the earthquake hypothesis is right, then what is the source of earthquakes? General paleogeographic considerations (Bernoulli & Jenkins, 1974) lead to a confinement of the formation of earthquakes within the Trento Platform. Independent data such as synsedimentary faults, seem to confirm this possibility. The exact knowledge of the seismicity of passive margins would provide a test for the tsunami hypothesis. Cisne (1987) calculated a 40.000-yr periodicity of stick-slip faulting movements for the Upper Triassic Hauptdolomite of the Northern Calcareous Alps. The occurrence of two tsunami horizons over 60 m of stratigraphic thickness in the study area would evidence for a long-term periodicity for these very large tsunamis.

Acknowledgements

This paper is a part of a larger study originally prepared as a PhD thesis under the supervision of Prof. G. B. Vai, Prof. A. Castellarin and D. Masetti gave helpful views during field excursions in the Venetian Alps. Dr. C. G. St. C. Kendall generously provided facilities and an aircraft during a trip at the Bahamas and Lee Stocking Island. Various reviews of previous manuscript draughts by various referees were also helpful. Final remarks by Prof. A. Bosellini led me towards more dispassionate reasoning.

References

Ager, D.V. 1981 The nature of the stratigraphic record – Halsted Press (New York): 122 pp

Aigner, T. 1985 Storm depositional systems – Springer (New York): 174 pp

Ball, M.M., E.A. Shinn & K.W. Stockman 1967 The geological effects of Hurricane Donna in south Florida – J. Geol. 75: 583–597

Barbujani, C., A. Bosellini & M. Sarti 1986 L'oolite di San Vigilio nel Monte Baldo (Giurassico, Prealpi Venete) – Annali Univ. Ferrara IX (2): 19–47

Bascom, W. 1964 Waves and beaches – Anchor Books Doubleday & Co, Inc. (Garden City, New York): 195 pp

Bernoulli, D. & H. Jenkins 1974 Alpine, Mediterranean, and central Atlantic Mesozoic facies in relation to the early evolution of the Tethys – Soc. Econ. Paleontol. Mineral. Spec. Pub. 19: 129–160

Bernstein, J. 1954 Tsunamis – Sci. Am. 191: 60–64

Bosellini, A. 1972 Paleoecologia dei calcari a *Lithiotis* (Giurassico inferiore, Prealpi Venete) – Riv. Ital. Paleont. 78: 441–464

Bosellini, A. 1973 Modello geodinamico e paleotettonico delle Alpi Meridionali durante il Giurassico-Cretaceo. Sue possibili applicazioni agli Appennini – Accad. Naz. Lincei 183: 163–205

Bosellini, A., D. Masetti & M. Sarti 1981 A Jurassic 'Tongue of the Ocean' infilled with oolitic sands: the Belluno Trough, Venetian Alps, Italy – Mar. Geol. 44: 59–95

Bosence, D. 1988 Trends in recent shallow-water carbonate mounds (Abstract) – 9th Reg. Mtg Sediment. Leuven 1988: 26–27

Bourgeois, J., T.A. Hansen, P.L. Wiberg & E.G. Kaufmann 1988 A tsunami deposit at the Cretaceous – Tertiary boundary in Texas – Science 241: 567–569

Bourrouilh-Le Jan & J. Talandier 1985 Sédimentation et fracturation de haute énergié en milieu récifal: Tsunamis, ouragans et cyclones et leurs effects sur la sédimentologie et la géomorphologie d'un atoll: motu et hoa, à Rangiroa, Tuamotu, Pacifique SE – Mar. Geol. 67: 263–333

Broglio Loriga, C. & C. Neri 1976 Aspetti paleobiologici della facies a *Lithiotis* (Giurese inf.) – Riv. Ital. Paleont. 82: 651–706

Cisne J.L. 1987 Earthquakes recorded stratigraphically on carbonate platforms – Nature 323: 320–322

Clari, P. 1975 Caratteristiche sedimentologiche e palentologiche di alcune sezioni dei Calcari Grigi del Veneto – Mem. Ist. Min. Univ. Padova 31: 2–63

Cloyd, K.C., R.V. Demicco & R.J.V. Spencer 1990 Tidal channel levee, and crevasse-splay deposits from a Cambrian tidal channel system: a new mechanism to produce shallowing-upward sequences – J. Sediment. Petrol. 60: 73–83

Coleman, P.J. 1968 Tsunamis as geological agents – J. Geol. Soc. Aust. 15: 267–273

De Mowbray, T. & M.J. Visser 1984 Reactivation surfaces in subtidal channel deposits, Oosterschelde, SW Netherlands – J. Sediment. Petrol. 54: 811–824

De Raaf, J.F.M., J.R. Boersma & A. Van Gelder 1977 Wave-generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork Ireland – Sedimentology 24: 451–483

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

Duringer, P. 1984 Tsunamis, a possible explanation for upper Muschelkalk (Trias of east France) alternating marls-limestones – Terra Cognita 3: 228

Eberli, G.P. & R.N. Ginsburg 1987 Segmentation and coalescence of Cenozoic carbonate platforms, northwestern Great Bahama Bank – Geology 15: 75–79

Edwards, M.B., K.A. Eriksson & R.S. Kier 1983 Paleochannel geometry and flow patterns determined from exumed Permian point bars in north central Texas – J. Sediment. Petrol. 53: 1261–1270

Fairbridge, R.W. & J. Bourgeois 1978 Tsunami sedimentation. In: Fairbridge, R.W. & J. Bourgeois (eds): The encyclopedia of sedimentology. Dowden, Hutchison, Ross, Inc. (Strassbourg): 828–831

Flemming, B.W. 1978 Underwater sand dunes along the southeast African continental margin – Mar. Geol. 26: 177–198

Galli, G. 1988 Rampe di intrapiattaforma con esempi dalle Alpi Meridionali e dalla Florida: applicazioni di concetti di sismostratigrafia nella ricostruzione di geometrie carbonatiche di mare basso – Doct. Thesis, Univ. Bologna: 133 pp

Göhner, D. 1980 'Covel dell'Angiolono' – ein mittelliassisches Lithiotis – Schlammbioherm auf der Hochebene von Lavarone (Provinz Trento, Norditalien) – Neues Jahrb. Geol. Paläont. Monatsh. 10: 600–619

Göhner, D. 1981 Beiträge zur Kenntnis des Sudalpinen Juras mit besonderer Berücksichtigung der unterjurassischen Lithiotis-Fazies. I. Stratigraphie, Microfazies und Paläontologie – Universität Stuttgart: 164 pp

Hardie, L.A. & P. Garrett 1977 General environmental setting. In: Hardie, L.A. (ed.): Sedimentation on the modern tidal flats of northwest Andros Island – Johns Hopkins Studies in Geology, – Johns Hopkins University Press (Baltimore) 22: 12–49

Harms, J.C., J.B. Southard, D.R. Spearing & R.G. Walker 1975 Depositional environments as interpreted from primary sedimentary structures and stratification sequences – Soc. Econ. Palentol. Mineral. Short Course: 166 pp

Houbolt, J.J.H.C. 1968 Recent sediments in the southern bight of the North Sea – Geol. Mijnbouw 47: 245–273

Johnson, H.D. 1977 Shallow marine sand bar sequences: an example from the late Precambrian of North Norway – Sedimentology 24: 245–270

Kastens, K.A. & M.B. Cita 1981 Tsunami – induced sediment transport in the abyssal Mediterranean Sea – Geol. Soc. Am. Bull. 92: 845–857

Kendall, C.G.St.C., R.F. Dill & E. Shinn 1989 Guidebook to the giant subtidal stromatolites and carbonate facies of Lee Stocking Island, Bahamas – Dept. Geol. Univ. South Carolina: 74 pp

Klein, G. De V. & K.M. Marsaglia 1987 Hummocky cross stratification, tropical hurricanes, and intense winter storms, Discussion – Sedimentology 34: 333–359

Komar, P.D. & M.C. Miller 1975 The initiation of oscillatory ripple marks and the development of plane-bed at high shear stress under waves – J. Sediment. Petrol. 45: 697–703

Kreisa, R.D. 1981 Storm-generated sedimentary structures in subtidal marine facies with examples from the middle and upper Ordovician of southwestern Virginia – J. Sediment. Petrol. 51: 823–848

Lamb, H. Sir 1945 Hydrodynamics – Dover Publ. (New York): 738 pp

Landau, L. & E. Lifchitz 1971 Mechanique des fluides – MIR Editions (Moscow, U.R.S.S.): 669 pp

Loucks, R.G. & J.H. Anderson 1980 Depositional facies and porosity development in Lower Ordovician Ellenburg Dolomite, Puckett Field, Pecos County, Texas. In: Halley, R.B. & R.G. Loucks (eds): Carbonate reservoir rocks: Soc. Econ. Palentol. Mineral. Core Workshop (Tulsa, Okl.) 1: 1–31

McGowen, J.H. & L.E. Garner 1970 Physiographic features and stratification types of coarse-grained point bars: modern and ancient examples. Sedimentology – 14: 77–111

Madsen, O.S. 1976 Wave climate of the continental margin: elements of its mathematical description. In: Stanley, D.J. & D.J.P. Swift (eds): Marine sediment transport and environmental management – Wiley (New York): 65–87

Marsaglia, K.M. & G. De V. Klein 1983 The paleogeography of Paleozoic and Mesozoic storm depositional systems – J. Geol. 91: 117–142

Nio, S.D. 1977 Marine transgressions as a factor in the formation of sandwave complexes – Geol. Mijnbouw 55: 18–40

Nio, S.D. & J.C. Siegenthaler 1978 A lower Eocene estuarine-shelf complex in the Isabena Valley – State Univ. Utrecht, Sedimentology Group, Rept 18: 1–44. In: Walker, R.G. (ed.) 1980 Facies models – Geosc. Canada, Repr. Ser. 1: 211 pp

Perkins, R.D. & P. Enos 1968 Hurricane Betsy in the Florida-Bahamas area – geological effects and comparison with Hurricane Donna – J. Geol. 76: 710–717

Powers, M.D. & B. Kinsman 1953 Shells accumulations in underwater sediments and their relation to the traction zone – J. Sediment. Petrol. 23: 229–234

Riding, R. & V.P. Wright 1981 Paleosols and tidal-flat/lagoon sequences on a carboniferous carbonate shelf: sedimentary associations of triple disconformities – J. Sediment. Petrol. 51: 1323–1339

Rine, J.M. & R.N. Ginsburg 1985 Depositional facies of a mud shoreface in Suriname, South America – a mud analogue to sandy, shallow – marine deposits – J. Sediment. Petrol. 55: 633–652

Rutherford, D.E. 1970 Fluid dynamics – University mathematical texts – Oliver and Boyd Ltd.: 247 pp

Scoffin, T.P. 1977 Sea-level features on reefs in the northern Province of the Great Barrier Reef – Third Int. Coral Reef Symp. (Miami, Fl): 319–324

Swift, D.J., A.G. Jr. Figueiredo, G.L. Freeland & G.F. Oertel 1983 Hummocky cross stratification and megaripples: a geological double standard? – J. Sediment. Petrol. 53: 1295–1317

Szulc, J. 1988 Seismically controlled carbonate sedimentary basin: an example from the middle Triassic, southern Poland (Abstract) – 9th Regional Mtg Sediment. (Leuven): 243–244

Tagett, M.G., H.R. Wanless & D.J. Cottrell 1986 Gradients in carbonate mudbank stratigraphy and dynamics: Florida Bay, south Florida (Abstract) – Soc. Econ. Palentol. Mineral Ann. Midyear Mtg. (Raleigh) 3: 108

Tannehill, I.R. 1960 Hurricanes – Princeton University Press:

Terwindt, J.H.J., C.H. Hulsbergen & L.H.M. Kohsiek 1984 Structures in deposits from beach recovery, after erosion by swell waves around the southwestern coast of Aruba (Netherlands Antilles) – Mar. Geol. 60: 283–311