Rivista Italiana di Paleontologia e Stratigrafia	volume 118	no. 3	pp. 503-534	November 2012

FACIES PARTITIONING AND SEQUENCE STRATIGRAPHY OF A MIXED SILICICLASTIC-CARBONATE RAMP STACK IN THE GELASIAN OF SICILY (S ITALY): A POTENTIAL MODEL FOR ICEHOUSE, DISTALLY-STEEPENED HETEROZOAN RAMPS

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Received: March 15, 2012; accepted: July 24, 2012

Key words: Distally steepened ramps, Heterozoan carbonate, Icehouse, Palaeoecology, Taphonomy, Sequence stratigraphy.

Abstract. The Gelasian succession of the Capodarso area (Enna-Caltanissetta basin, Sicily, Italy) consists of an offlapping stack of cycles composed of siliciclastic units passing to carbonate heterozoan, clino-stratified wedges, developed from a growing positive tectonic structure. Identification of a number of facies tracts, based on sedimentary facies, biofacies and taphofacies, provided important information about the differentiation and characterisation of systems tracts and key stratal surfaces of sequence stratigraphy. The bulk of carbonate wedges are interpreted as representing the rapid falling-stage progradation of distally steepened ramps. The inferred highest rate of carbonate production during forced regressions was concomitant with active downramp resedimentation by storm-driven downwelling flows, leading to storing of most carbonate sediment on the ramp slope as clino-beds of the prograding bodies. Comparison of the Capodarso ramps with other icehouse carbonate ramps, with particular regard to the Mediterranean Plio-Pleistocene, provides clues for defining some common features. These are inferred to include: (1) brief, rapid episodes of progradation concomitant with orbitally-forced sea-level changes, resulting in limited ramp width; (2) preferential fostering of growth and downramp resedimentation of heterozoan carbonates during glacial hemicycles marked by enhanced atmospheric and marine circulation; (3) building out from positive features of entirely submerged distally-steepened ramps with storm-wave-graded profile and distinctive clinoforms; (4) ramp stacks generally consisting of mixed clastic-carbonate sequences showing an ordered spectrum of distinct frequencies; (5) rapid, continuous changes in environmental parameters, leading to the short-lived persistence of faunal communities, climax communities generally having insufficient time to form.

Riassunto. La successione Gelasiana di Capodarso (bacino di Enna-Caltanissetta, Sicilia) è costituita da cicli in sovrapposizione *offlapping*, composti da unità silicoclastiche passanti a cunei clino-stratificati di carbonati temperati, sviluppati a partire da una struttura tettonica positiva in crescita. La caratterizzazione dei *systems tracts* e delle superfici chiave della stratigrafia sequenziale è basata sull'identificazione di associazioni di facies, definite da caratteri sedimentologici, biofacies e tafofacies. La maggior parte dei cunei carbonatici dal punto di vista volumetrico è attribuita a eventi di regressione forzata, caratterizzati da massima produzione di carbonato in concomitanza con attiva ridistribuzione dei sedimenti da flussi *downwelling* di tempesta, in grado di accumulare il sedimento prevalentemente sul pendio frontale della rampa in progradazione. La comparazione delle rampe di Capodarso con esempi analoghi in contesto *icehouse*, con particolare riguardo al Plio-Pleistocene del Mediterraneo, consente di definire tentativamente alcune caratteristiche comuni: (1) brevi e rapidi episodi di progradazione di rampe di larghezza limitata, in concomitanza con cambiamenti del livello del mare a controllo orbitale; (2) crescita preferenziale e ridistribuzione dei carbonati durante emicicli glaciali caratterizzati da accresciuta circolazione atmosferica e marina; (3) sviluppo, a partire da strutture positive, di rampe *distally-steepened* interamente sommerse, con profilo controllato dalla profondità della *storm wave base*; (4) comune sovrapposizione ciclica di rampe costituite da sequenze miste terrigeno-carbonatiche caratterizzate da uno spettro ordinato di distinte frequenze; (5) rapidi e continui cambiamenti dei parametric ambientali, che si traducono in limitata persistenza delle comunità faunistiche e mancanza del tempo necessario per la formazione di comunità *climax*.

Introduction

The facies and architecture of shallow-water heterozoan carbonate sands are sensitive to changes in accommodation, being able to respond rapidly to base level changes (Schlager 2003; Halfar et al. 2006; Pomar & Kendall 2007). In particular, carbonate sands can easily respond to relative sea-level falls by migrating sea-

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wards and developing a progradational body akin in architecture to that of siliciclastic wedges. Obviously, the high responsiveness to accommodation changes is typical of grainy, shallow-water systems, not of heterozoan factories developing in the oligophotic or aphotic zone.

Wright & Burgess (2005) observed that the sedimentary record of carbonate ramps commonly represents the product of spatially complex and mobile facies mosaics, especially in the case of homoclinal ramps, suggesting the need for moving away from frequently applied sequence stratigraphic models in their analysis. However, in the case of distally steepened ramps (*sensu* Pomar & Kendall 2007), the predominance of hydrodynamic factors in controlling facies associations, and the close genetic relationships of the stratal architecture with relative sea-level changes, allow us to regard the system as comparable from several aspects to a siliciclastic system and therefore to exploit the framework of sequence stratigraphic surfaces to interpret and predict facies architecture.

One might wonder whether such systems, in which a carbonate productivity profile and an ecologically-based zoning are generally missing, should be considered true ramps or simply prograding wedges. The important point to be remarked, however, is that distally steepened ramps in the sense of Pomar & Kendall (2007) are carbonate bodies prograding in a high-energy setting dominated by "physical accommodation", a concept referring to the space available for sediment deposition up to a physical base level exposed to waves and currents which can stir and move carbonate sediments down-ramp. Because of the shallow-water setting and grainy sediment texture, these systems are characterised by large-scale resedimentation processes during the phases of accommodation loss, skeletal material being prone to removal from factory areas by storm-induced flows and redeposited on the frontal slopes of prograding bodies (see also Burchette & Wright 1992). The latter are therefore made up of distinctive clino-bedded lithofacies (e.g., Sonnenfeld & Cross 1993; Braga et al. 2006). This study focuses on the Gelasian Capodarso succession (Sicily, southern Italy), which consists of a stack of distally steepened ramps prograding from a positive tectonic structure in a setting exposed to the full action of storm waves and storm-driven flows. The depositional setting of landlocked Mediterranean waters is obviously different from that of open oceanic shelves. The tidal range is on average very low, and large swell is conspicuously absent. In addition, there is no appreciable upwelling, and fair-weather and storm wave bases are far shallower than on oceanic margins, being respectively less than 5 m and around 20-25 m on average. Hence, carbonate ramps generally consist of relatively shallow-water and shelf-perched deposits.

Both the basic sedimentologic and sequence-stratigraphic analysis of the studied succession, and assessment of the role of trace fossils in reconstructing the growth stages of carbonate wedges have already been treated by Massari & Chiocci (2006) and Massari & D'Alessandro (2009). This paper focuses on (1) defining the facies tracts of the Capodarso cycles, based on analysis of depositional architecture and qualitative study of the composition and taphonomy of faunal assemblages, in order to give support to the sequence-stratigraphic reconstruction; (2) using the composition of macrobenthos as an indicator of how organisms tend to respond to environmental changes, such as those triggered by climatic changes and high-amplitude sea-level fluctuations; (3) tentatively defining a model for high-energy, icehouse heterozoan carbonate ramps, with particular regard to the Mediterranean Plio-Pleistocene, by comparing the Capodarso example with similar case histories.

HP	Photophilic Algae
SFBC	Fine Well-Sorted Sand
SGCF	Coarse Sand and Fine Gravel under Bottom Current
DC	Coastal Detritic Bottoms
VTC	Terrigenous Mud
PE	Heterogeneous Community

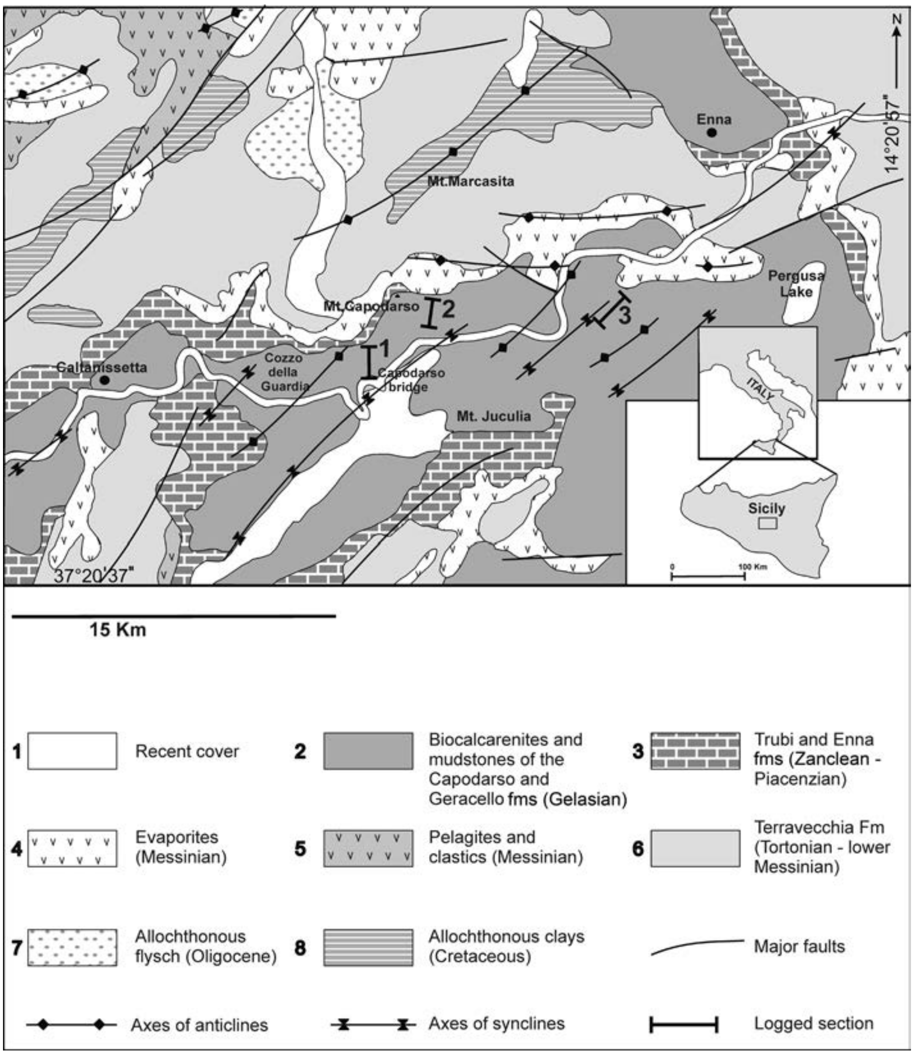
Tab. 1 - Letter code of Mediterranean biocoenoses (Pérès & Picard 1964) mentioned in text.

Methods and nomenclature

Facies analysis, identification of stratal geometry and body architecture based on photomosaics and logged sections were integrated by qualitative taphonomic, palaeo-ecological and taxonomic analyses of macrofossil content, and study of 54 representative thin sections and a number of washed mudstone samples, in order to identify microfacies, texture and skeletal assemblages. Comparisons with present-day communities are based on the work of Pérès & Picard (1964) concerning the biocoenoses of the Mediterranean Sea (Tab. 1) and on palaeoecological papers illustrating upper Neogene to Recent shell assemblages in the Mediterranean area (e.g., Bernasconi & Robba 1993; D'Alessandro & Massari 1997; D'Alessandro et al. 2003; Massari et. al. 2009). The nomenclature of shell concentrations is mainly based on Kidwell et al. (1986), Kidwell (1991) and Kidwell & Bosence (1991). Autochthony/parautochthony and allochthony are predominantly inferred from mixing of organisms having different environmental requirements and taphonomic features.

Due to the character of this paper, concerned on both biofacies-taphofacies and sedimentologic features, we opted for a mixed nomenclature for the physiographic zones. The zone having the lower limit coinciding with the storm wave base, currently defined as "offshore-transition zone" (e.g., Reading & Collinson 1996), is preferably called here "inner shelf", following Bottjer & Jablonski's (1988) scheme, based on physical structures (storm-related event-beds separated by bioturbated interbeds) and taphonomic features. We also use this scheme to define the middle and outer shelf. The term "lower shoreface" is used to indicate the zone where amalgamation of physical structures prevents the differentiation of storm-related episodes. Infralittoral and circalit-

Fig. 1 - Geological sketch-map of Caltanissetta-Enna area (slightly modified from Vitale, 1996). 1: Monte Capodarso section; 2: Morello river section; 3: Serieri valley section. In Serieri valley two sections were measured in northern and southern tracts of the valley.



toral terms refer to the vertical zoning proposed by Pérès & Picard (1964).

Sections were logged and studied at Monte Capodarso, the Morello river and the Serieri valley (Fig. 1). In the latter locality, two sections were measured, in the northern and southern tracts of the valley. Additional observations were made on a small section at Portella Capodarso (located 750 m SSE of the peak of Monte Capodarso). Due to difficult access, the Monte Capodarso section was mainly analysed by photomosaics for facies recognition and reconstruction of stratigraphic architecture, since single-point field observations could only be made near the base and on the uppermost part of the section.

We do not agree with the recent decision to lower the base of the Pleistocene and Quaternary to the base of the Gelasian Stage. This implies unjustified inconsistency with the existing geologic cartography and the huge quantity of previous literature on Plio-Quaternary successions. We therefore follow here the "traditional" habit of placing the base of the Quaternary at the boundary between the Gelasian and the Calabrian.

Geologic setting

Between the late Miocene and the early Pleistocene, high-amplitude fold systems and thrusts developed in growing piggy-back basins in Sicily, located between the emerging Maghrebian thrust belt and the Hyblean foreland (Catalano et al. 1993; Colella & Vitale 1998).

The Gelasian (upper Pliocene) synorogenic Capodarso succession, located in central Sicily, was laid down in the northern marginal belt of the upper Neogene Enna-Caltanissetta basin, a satellite basin developing above a Tertiary roof-thrust complex and infilled with Plio-Pleistocene deposits (Fig. 1). Sedimentation was controlled by the growth of the thrust-cored, NE-trending Marcasita anticline, which formed a positive structure from which the progradation of carbonate wedges began to develop (Lickorish & Butler 1996). The growth of the structure resulted in progressive tilting of the fold limb and the formation of a forestepping stack of 'parasequences', displaying a progressive shallowing of dips recording the tilt history (Fig. 2) (Catalano et al. 1992 a, b; 1993; Butler & Grasso 1993; Catalano et al. 1995; Lickorish & Butler 1996; Vitale 1998). Late orogenic uplift of the basin fill provides spectacular, seismic-scale exposure of the Capodarso succession (Fig. 2). The stacked carbonate bodies form a substantial

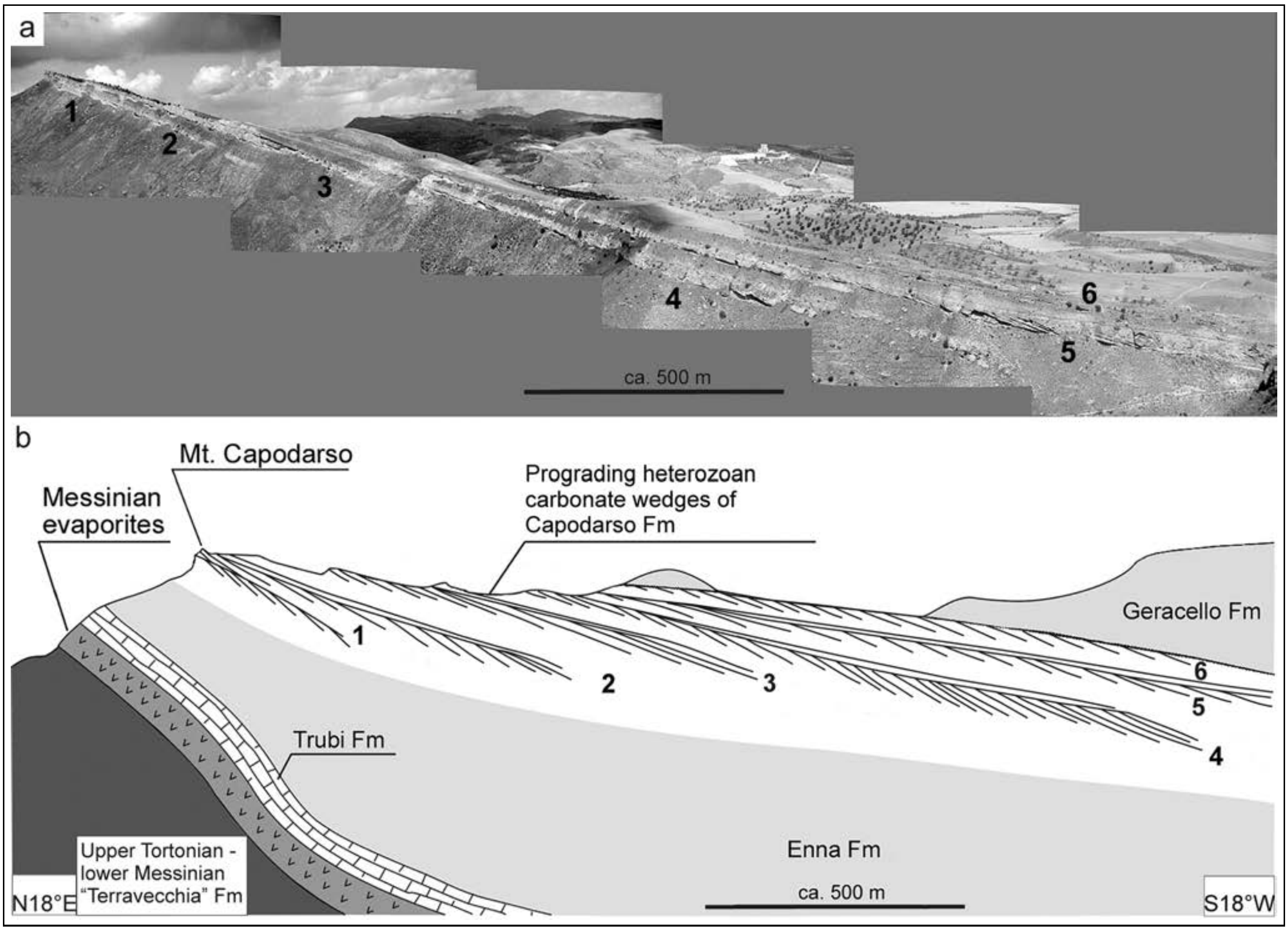


Fig. 2 - Forestepping stack of Gelasian siliciclastic-carbonate cycles in the Monte Capodarso section. (a) Seismic-scale exposure. (b) Simplified stratigraphic cross-section (slightly modified from Vitale, 1998). 1-6: progradational carbonate wedges.

wedge of distinctive lithology at the inner margin of the piggy-back basin, which "shales out" rapidly basinwards, away from the growth anticline, grading into a time-equivalent, basinward-thickening succession of hemipelagic mudstone which accumulated in the depocentral area (Catalano et al. 1993; Vitale 1998).

Previous studies concerning the stratigraphy and architecture of the Capodarso succession are those of Lickorish & Butler (1996), Vitale (1996, 1998), Colella & Vitale (1998), Massari & Chiocci (2006) and Massari & D'Alessandro (2009).

In the local stratigraphic succession (Fig. 2) deep-water pelagic lower Pliocene chalk deposits (the Trubi Formation), pass upwards into slope to outer-shelf, siliciclastic mudstone deposits of the Enna Formation, the upper part of which is referred to the *Discoaster pentaradiatus* Zone (Di Stefano, pers. comm. 2005). The overlying Capodarso Formation consists of a stack of up to six mixed siliciclastic-carbonate sequences (Fig. 2). Biostratigraphic data allow this formation to be ascribed to the lower part of the Gelasian (Di Stefano & Sprovieri, pers. comm. 2005; Massari & Chiocci 2006). The overlying Geracello Formation predominantly consists of offshore siliciclastic mudstone, attributable to the upper Gelasian.

Capodarso Formation

The mixed siliciclastic-carbonate Capodarso Formation is composed of an offlapping stack, about 180 m thick, of up to six sequences consisting of bluish-grey, siliciclastic, inner to middle shelf mudstone units (weathering to light yellow), overlain by progradational yellow-brown carbonate wedges. The latter have internal architecture characterised by distinctive, basinward-dipping clino-beds (Fig. 2) with complex sigmoidal-oblique configuration and height ranging from a few metres to a maximum of 27 m (height is intended as vertical relief between the surfaces bounding the clino-stratified set), which interfinger with and downlap onto offshore siliciclastic silt and clay.

The carbonate bodies are elongated, linear lithosomes located on the southern limb of the Marcasita thrust-cored anticline (Fig. 2). They may be regarded as thrust-top platforms *sensu* Bosence (2005), defined as elongated bodies a few km wide, fringing compres-

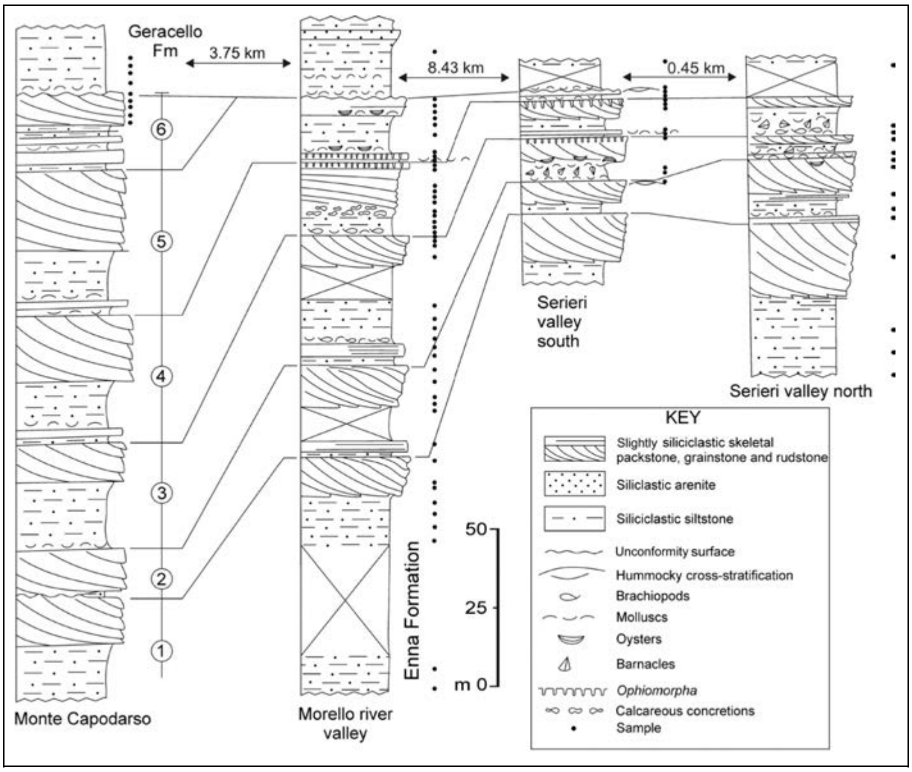


Fig. 3 - Cross-correlation of logged sections through the Capodarso succession. For sake of representation, shingled carbonate wedges are projected on a single vertical.

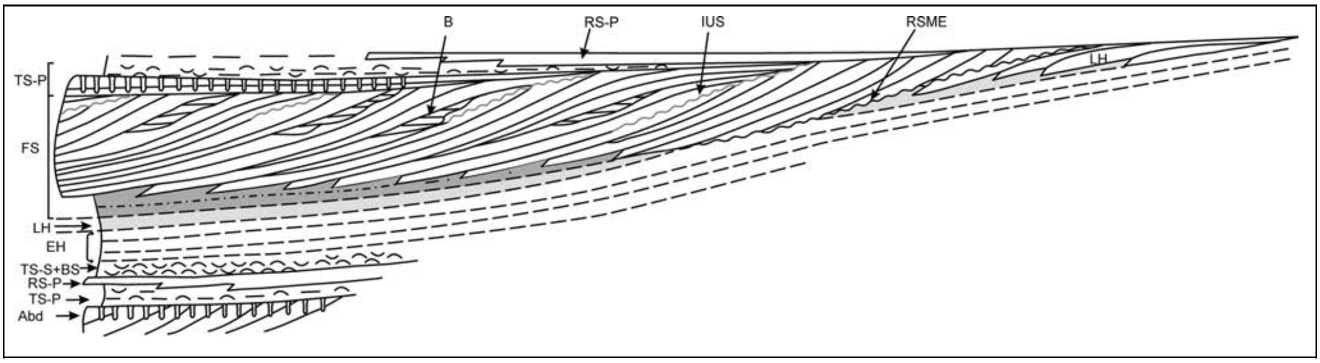


Fig. 4 - Outline of organisation of Capodarso cycles, with indication of identified facies tracts (not to scale). TS-P Facies Tract (TS-P for brevity) is either bipartite, comprising a shell concentration underlain by a thin carbonate package lapping on the top surface of prograding wedge (upper part of sketch), or simple, consisting of a shellbed directly lying on this surface (lower part of sketch). TS-P is overlain by RS-P (carbonate unit) as a rule. Shellbeds of TS-S, locally amalgamated with shellbeds of BS, are transitionally overlain first by aggrading silty mudstone of EH and then prograding sediments of LH and FS, consisting of clino-bedded carbonate deposits downlapping on mixed/siliciclastic deposits (the latter indicated respectively with light grey and dark grey shading). LH records an early, short-term stage of aggrading progradation (extreme right); FS the main phase of progradation, characterised by offlapping sigmoidal-oblique clinoforms bounded updip by an erosional surface (RSME: Regressive Surface of Marine Erosion) and showing internal unconformity surfaces (IUS, in grey) and sets of backset beds (B). Intensely burrowed Abd is characterised by vertical *Ophiomorpha* shafts crossing the topmost part of clino-bedded prograding wedge (lowermost part of the sketch).

sional folds in convergent margin settings. According to Vitale (1996), individual lithosomes extend along strike for up to 20 km, and 1-2 km downdip, wedging out gradually updip, and rapidly basinwards. The carbonate wedges may be defined as distally steepened ramps dominated by physical accommodation, *sensu* Pomar & Kendall (2007). The ramp slope reflects the clinoform geometry of the prograding front, recording the interaction between sediment input and hydrodynamic processes of erosion, transport and resedimentation. This

TS-P - RS-P couplet	Parasequence or small-scale sequence of the Transgressive Systems Tract
TS-S	Transgressive deposits locally overlain by BS
BS	Backlap shellbeds
EH	Early Highstand Systems Tract
LH	Late Highstand Systems Tract
FS	Falling Stage Systems Tract
Abd	Abandonment stage

Tab. 2 - The acronyms used for the facies tracts (FTs) refer to their sequence-stratigraphic position. Their meaning is anticipated here for sake of clarity.

Facies tract	*Lithology and fossils*	*Biogenic structures*	*Physical structures and stratal pattern*	*Biofabric and life habit*	*Interpretation*
Abd	Thin, upw.-fining package of bioclastic grainstone. Local conc. of corallines and/or shells.	Heavy bioturb. (*Dactyloidites* and *Scolicia*) crossed by *Ophiomorpha* omission suite.	Massive or subdivided into event-beds with local shell conc.	Domichnia of susp.-f. and fodinichnia of detr.-f. Sparse indigenous shells of susp.-f.	Stacked storm beds. Very low sed. rate. Conc. of corallines may reflect mesotrophy.
TS-P	Silty packstone upw.-fining into bioclastic siltstone. Typical: corallines, pectinids. Sparse infaunal molluscs.	Bioeros. and encrust. on epifaunal skeletons. Rare extrinsic biogenic conc.	Stratification absent or poorly distinct, poor sorting. Thin shell conc.	Mixed, loosely to densely packed shell conc. Disartic. valves, commonly stacked or nested. Indigenous: mainly sessile and vagile, semi-infaunal and epifaunal susp.-f.	Storm-related events. Deposition near normal storm wave base. Stable soft-firm bottom. Upw.-decreasing energy.
RS-P	Grainstones to fine skeletal rudstones, locally packstones. Low species diversity. Remains of pectinids and barnacles. Debris of corallines and amphisteginids.	*Thalassinoides*-like, *Piscichnus, Scolicia*. Few bioeros. on bivalve shells.	Base gradual or abrupt. Massive or subdivided into event-beds. Hummocky/swaley cross-stratification. Thin shell conc. Local evidence of upw.-thickening.	Sed. conc. of mostly exotic, loosely to densely packed shells. Susp.-f., vagile and sessile epifaunal organisms.	Inner shelf (storm layers) to lower shoreface (amalgamation of storm deposits).
TS-S	Bioclastic silt grading into muddy silt. Typical components: pectinids, brachiopods and barnacles, locally corallines.	Encrust. and bioeros. on epifaunal skeletons. Rare extrinsic biogenic conc.	Stratification absent, poor sorting. Sparse thin shell lenses and discontinuous pavements.	Mixed, loosely to densely packed conc. of disartic., commonly stacked or nested valves of epifaunal susp.-f. Opportunistic taxa in oligotypic associatons.	Middle inner shelf to middle shelf. Moderate energy, with occasional storm events. Periods of mesotrophic conditions.
BS	Bioclastic to marly silt, with *Neopycnodonte cochlear*. Typical: *C. concavus* and *T. terebratula*.	Bioeros.; local encrust. by lamellar bryozoans.	No physical structures.	Intrinsic, loosely packed biogenic conc. of autochth. and parautochth., sessile, epifaunal susp.-f. Conc. result from gregarious behaviour or colonization by opportunistic species.	Low-energy, well oxygenated soft-firm bottoms and sediment starvation. Deep middle shelf or shallow outer shelf. Mesotrophy.
EH	Siliciclastic mudstone. High species diversity (pectinids, glycymerids, cardiids).	Few encrust. Sparse bioturb. Some extrinsic biogenic conc.	Generally massive, with local thin, lens-like or layered shell conc., mainly in upper part.	Shallow-infaunal and vagile organisms. Mostly parautochth. in lower part. Sed. conc. in upper part contain mostly exotic, concordant, convex-up and -down, stacked or nested shells.	Middle shelf, shallowing into inner shelf. Softground. Low to moderate energy. Upw. increase in sed. rate. Stirring by storm flows and wave winnowing in upper part.

Facies tract	*Lithology and fossils*	*Biogenic structures*	*Physical structures and stratal pattern*	*Biofabric and life habit*	*Interpretation*
LH	Heavy, upw.-decreasing bioturb. LH-A: nodular silty packstone with brachiopods and barnacles rarefying upw. LH-B: bioclastic silty packstones with abundant macrofauna.	Bioturb. Index (BI): 5-6 to 4, upw.-decreasing (*Thalassinoides* networks in the lower part, *Scolicia* in the upper part). Local encrust. by laminated bryozoans or barnacles.	'Climbing' progradational stratal pattern. Upw.-shoaling into generally planar-laminated clino-beds. Mixed-origin conc. in middle part, sed. conc. in upper part.	Whole, unabraded, artic. and disartic. shells in mixed assemblages. Trace fossils of infaunal tracemakers. Obrution events. Dominant: epifaunal and shallow- to semi-infaunal sessile susp.-f. Loosely packed concordant shells in sed. conc. Among autochth. components: *Lutraria* and buried portions of pinnids.	Initial facies belts of prograding wedges. Trend gradually shallowing-upw. LH-A: deep middle shelf to inner shelf. LH-B: storm layers, largely blurred by bioturb. in the lower part, better defined in upper part. Inner shelf.
FS-A clino-beds	Upw.-coarsening from packstone to grainstone and fine-grained skeletal rudstone. Dominant pectinids. Local clusters of *Glycymeris*. Sparse infaunal echinoids.	Common *Scolicia* and sparse *Dactyloidites* in clino-beds. Pectinids locally encrusted by lamellar bryozoans. Laminated to bioturb. bedding style.	Traction structures: pervasive in low-relief, upramp clino-beds; restricted to uppermost slope in high-relief downramp clino-beds, passing downslope into gravity-flow structures.	Densely packed sed. conc. of artic. and disartic. valves, commonly whole, concordant, locally imbricated. Mainly exotic, subord. indigenous elements. All organisms: mobile bottom dwellers. Except for echinoids, body fossils are epifaunal and shallow-infaunal susp.-f.; ichnomakers are detr.-f.	Distally steepened ramps with top surface in the inner shelf, close to storm wave base. Storm-related beds. Offshore dispersal by means of three-dimensional dunes. Change of traction flows into gravity flows down the slope of high-relief downramp clinoforms.
FS-A silt	Bioclastic siltstone, usually massive. Thin, lenticular layers with cardiid cores, mitilids and pinnids. *Panopea glycymeris* in life position, with upper part truncated. Autochth. *Venus multilamella*	Umbonal, artic. parts of *Atrina pectinata* commonly encrusted by laminar bryozoans	Local interbedding with upw.-thickening carbonate bottomset layers.	Sed. conc. of loosely to densely packed, variably fragmented and abraded shells, disartic., with concordant and hydrodynamic stable orientation. Both exotic and indigenous skeletons, the latter mostly shallow-infaunal and semi-infaunal, both sessile (e.g., pinnids, ostreids) and sedentary (e.g., glycymerids).	Redeposition into deep inner shelf of remains sourced from nearshore to shallow inner-shelf. Processes: density flows, and current–associated scouring and winnowing of sea floor, followed by rapid burial. Local derivation of exotic skeletons from erosion of temporarily emerged areas.
FS-B	Silty to sandy packstone/grainstone. At base: clumps of large-sized *Ostrea*. Within the main body: laminated to bioturb. beds with pectinids, venerids and small-sized *Corbula*, cardiids, and mytilids.	Some bioeros.; encrust. by lamellar bryozoans and polychetes. A burial event in lowermost part. Few extrinsic biogenic conc.	Massive basal unit, overlain by planar-laminated pavements/lenses with shell conc.	At base: autochth. clumps of mostly sessile epifaunal organisms. Above: densely-packed sed. conc. of mostly disartic. shells, whole and fragmented, convex-up and -down. Exotic fauna dominant, with some indigenous shells. Shallow- and semi-infaunal organisms, subord. epifaunal, mostly susp.-f, subord. detr.-f.	Middle inner shelf, grading to shallow inner shelf with evidence of periodic storm layers. Generally soft bottoms. Erosion at base generated a firmground on which ostreids could settle.

Tab. 3 - List of essential features of identified facies tracts. Nomenclature of Kidwell et al. (1986) is followed for description of shell concentrations. FS-A facies tract includes: carbonate clino-beds (FS-A clino-beds), and siltstone and mixed deposits with which clino-beds interfinger (FS-A silt). Conc.: concentration(s); sed.: sedimentologic, sedimentation; bioturb.: bioturbation, bioturbated; bioeros.: bioerosion; encrust.: encrustation(s); autochth.: autochthonous; allochth.: allochthonous; parautochth.: parautochthonous; mixed: assemblages including exotic and indigenous elements; artic.: articulated; disartic.: disarticulated; susp.-f.: suspension feeders; detr.-f.: detritus feeders; upw.: upward; subord.: subordinately.

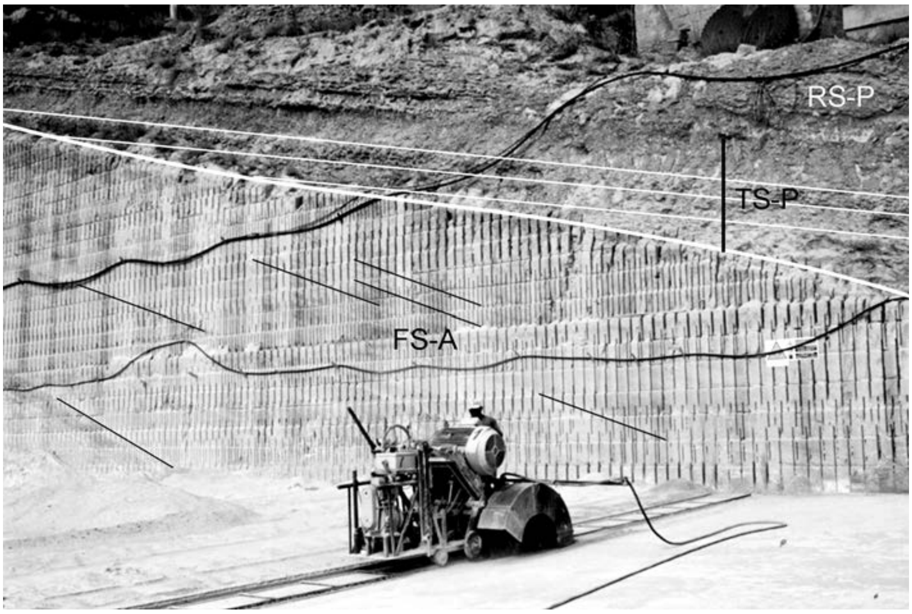


Fig. 5 - The top of a clino-stratified unit (FS-A) is overlain by a TS-P - RS-P couplet, of which TS-P unit consists of a heavily bioturbated package lapping at low-angle on top surface of the clino-stratified unit, grading into a more erodible shellbed. Active quarry at the southern foot of Monte Capodarso.

concept differs from that of Read (1985) and Burchette & Wright (1992), who attributed the steepening of outer ramps to tectonism, slope inheritance, or drowning of earlier rimmed shelves.

The Capodarso carbonate deposits are tightly cemented and dominated by debris of bivalves and foraminifers, with associated whole, commonly unabraded shells and subordinate amounts of bioclasts of mainly heterotrophic organisms, such as serpulids and barnacles, and sparse debris of brachiopods, gastropods, bryozoans, echinoids and coralline red algae (hereafter corallines). In Lees & Buller's (1972) classification they would be called foramol. Following James (1997), we use the term heterozoan association. In the strict sense, the deposits are mixed, as they contain a siliciclastic fraction. However, as this is largely subordinate, not exceeding 5 % in most cases, we simply refer to them as carbonate deposits.

Although showing changes in thickness, physical facies and biofacies, the sequences can be reliably correlated by means of litho- and biostratigraphy across the examined sections (Fig. 3). A succession of six sequences is only found in the westernmost Monte Capodarso section, since erosive truncation below the ravinement surface at the base of the Geracello Formation removed the last cycle in the Morello river area and the last two cycles in the Serieri valley area (except for the lowermost part of the fifth cycle in the southern tract of this valley) (Fig. 3). These truncations are attributed to the greater syndepositional growth of the Marcasita anticline in the eastern area.

The Capodarso cycles can be subdivided into a number of facies tracts (FT for brevity) (Fig. 4, Tabs. 2 and 3), based on sedimentary facies, biofacies and taphofacies. The term facies tract is intended to refer to individual facies or facies associations occurring in response to physical and biological processes, and stacked to form distinct facies-tract patterns having a distinctive meaning in terms of sequence stratigraphy, as will be detailed below.

TS-P facies tract

TS-P FT (Figs. 4 - 6), a few dozen centimetres to 2.5 m thick, lies both sharply and unconformably above the planar, erosional top surface of the clino-bedded wedge. As a rule, it underlies the RS-P FT. In terms of general geometry, TS-P FT shows sheet-like geometry with high lateral continuity (Fig. 4). More complete successions are bipartite, with a lower calcarenitic unit and an upper, more erodible, richly fossiliferous siltstone unit (Fig. 5). The former is locally missing and in this case the fossiliferous unit directly overlies the top of the clino-bedded wedge (Fig. 6). The lower unit, up to 1.8 m thick, is a poorly to distinctly stratified, bioturbated grainstone/packstone lapping at low angles on the top surface of the wedge. Bioturbation is intense, consisting either of dense, vertical *Ophiomorpha* shafts, locally crossing a former generation of traces, or an intricate network of indeterminable burrows. In the former case the upper surface of the unit is sharp, in the latter is gradational and made irregular by bioturbation.

The upper unit, up to 75 cm thick, is an unstratified bioclastic siltstone containing simple and composite shell concentrations (Figs 6, 7a) consisting of loosely to densely packed, commonly disarticulated and variably fragmented shells, concordant and locally stacked or nested, convex-up and -down (mostly *Pecten flabelliformis* and *Aequipecten scabrella*), associated with branches of corallines and small rhodoliths, in a matrix of comminuted bio-debris, more abundant in the lower

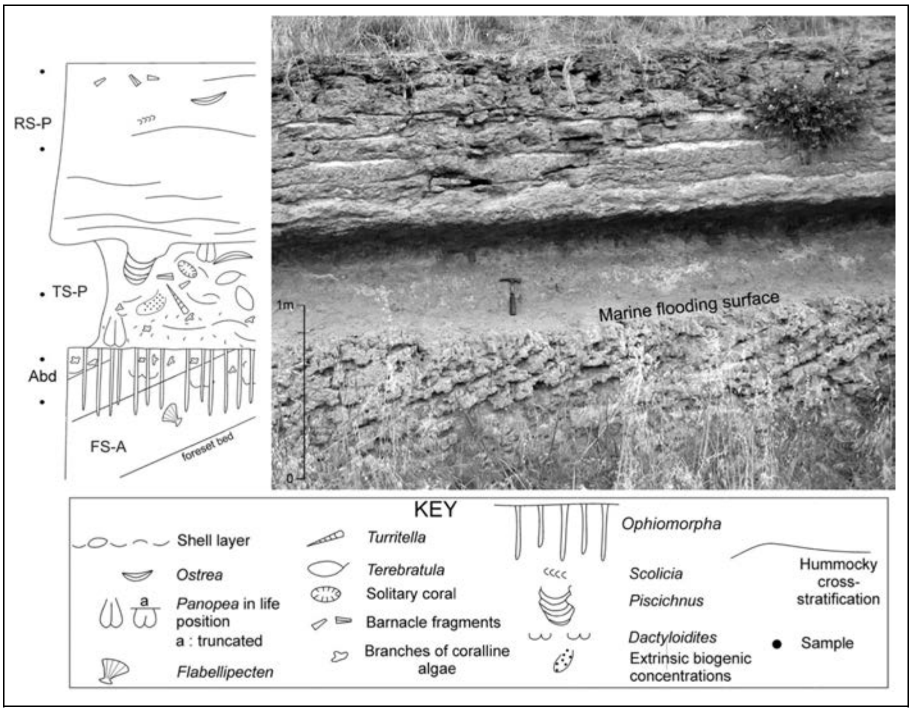


Fig. 6 - Bipartite bed package (TS-P - RS-P) on top of clino-stratified unit: field view and interpretive drawing, with details of faunal assemblages. Oblique clinoforms (lower part of photograph) are crossed near top by *Ohiomorpha* shafts (Abd), and truncated by an erosional surface covered by a silty bioclastic shellbed (TS-P). This is sharply overlain by a carbonate bed package (RS-P). Top of cycle 4 and basal part of cycle 5, Serieri valley, southern section.

part. The fossils may be considered allochthonous and parautochthonous. Crowns of *Concavus concavus*, *Terebratula terebratula* and subordinately a few azooxanthellate corals (arrow in Fig. 7a), semi-infaunal elements (e.g. *Modiolus* cf. *barbatus*), and shallow-infaunal forms (e.g., cores and moulds of cardiids, *Corbula gibba*) are randomly dispersed. In cycle 4 of the Morello river section sparse large fragments of the bryozoan *Celleporaria palmata* include numerous specimens of its symbiotic coral *Culicia parasita* (a form characteristic of shallow circalittoral zone). Indigenous organisms (i.e., autochthonous and parautochthonous) are mainly sessile and vagile, epifaunal and semi-infaunal suspension feeders. Some remains of epifaunal organisms are bioeroded and/or encrusted by lamellar bryozoans or, rarely, small barnacles (*Actinobalanus stellaris*). Small extrinsic biogenic bioturbations (biodebris-filled pits) produced by bottom-feeding organisms are locally present. The deep-burrowing *Panopea glycymeris* locally occurs in life position within this FT and at its top, where it may be truncated at the contact with the RS-P FT (Fig.6).

Environmental interpretation

The *remanié* elements are a residual (lag) concentration, eroded from older sediments. A greatly reduced net sedimentation rate in an inner shelf setting is indicated by heavy bioturbation. *Ophiomorpha* shafts crossing a former generation of burrows represent an omission suite. Local concentrations of corallines, heralding the similar, or even denser concentrations occurring in some layers of the TS-S FT, suggest a change in environmental conditions with respect to the underlying prograding body, possibly an increase in nutrient availability (see below). The shell concentrations of the upper unit, dominated by vagile organisms, pertain to various fossil communities, mainly equivalent to the modern Pérès & Picard' biocoenoses (1964) Coarse Sand and Fine Gravel under Bottom Current (SGCF) or shallow Coastal Detritic Bottoms (DC) (Tab. 1). They suggest the action of episodic, storm-related, moderate flows stirring up epifaunal elements and redepositing them into a stable soft-firm bottom of the deep inner shelf or shallow middle shelf. The upward changes are consistent with a decrease in energy level.

RS-P facies tract

TS-P and RS-P couplets form characteristic, sheet-like packages on top of the clino-stratified units (Figs 4-6). At first sight, they may be mistaken for topset beds of the clino-stratified wedges. RS-P FT is a carbonate package 2.5-4.2 m thick, either stratified or massive, consisting of grainstone to fine-grained skeletal rudstone, locally packstone, with debris of macrofaunal organisms, branches of corallines, planktonic and benthic foraminifers, and a sparse quartz fraction in the silt to fine sand grades. It shows gradual wedging-out both basinwards and landwards, in the latter case closing updip of the TS-P FT pinch-out (Fig. 4). The base is either transitional or sharp and erosional (Fig. 6). In the latter case, erosion is documented by truncation of *Panopea*, formerly settled in the top layer of the underlying TS-P FT, and leads to a firmground state, with colonisation by *Thalassinoides*-like traces and rare

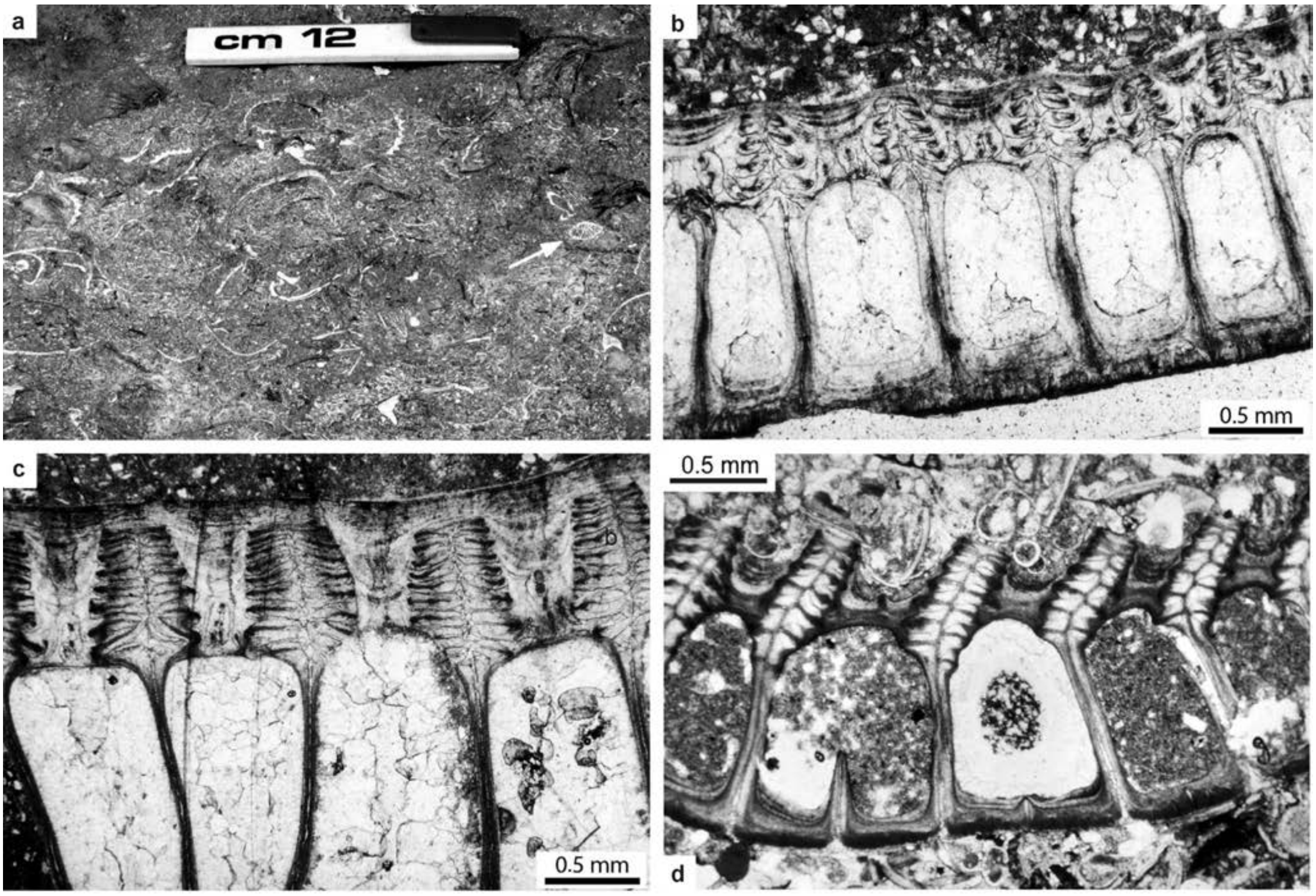


Fig. 7 - (a) Detail of silty bioclastic shellbed (TS-P) of section shown in Fig. 6. Note random arrangement of disarticulated valves, and solitary coral (arrow) (basal part of cycle 5, Serieri valley, southern section). (b), (c), (d) Thin-section photomicrographs of internal structure of barnacle compartmental plates. (b) *Concavus concavus* (TS-S, cycle 4, Morello river section). (c) *Megabalanus tintinnabulus* (BS, cycle 4, Morello river section). (d) *Megabalanus tulipiformis* (BS, cycle 4, Morello river section).

Piscichnus (the latter attributed to the well-known feeding behaviour of rays), piping downwards from the base of the RS-P FT (Fig. 6).

The most common internal structure is hummocky/swaley cross-stratification. In the case of internal subdivision into strata, erosionally based and in places normally graded layers are separated by finer-grained interbeds, locally bioturbated. Some RS-P units show an upward change from planar-parallel stratification to a massive, hummocky-amalgamated interval or, in one case (distal part of cycle 5, Monte Capodarso section) to a sand-wave cross-set 1.6 m thick, with laminae dipping basinwards.

Shell concentrations, mostly loosely packed to dispersed, occur as sparse pavements or lenses. Low-diversity macrofauna is mainly represented by parautochthonous and allochthonous epifaunal elements (*Pecten flabelliformis* and *Aequipecten opercularis*). The valves are mostly disarticulated, concordant, mainly convex-up, and locally stacked or imbricated. Minor components are oysters (slightly bioeroded), barnacles, echinoids and *Ditrupa arietina* tubes. In the cycle 5 of the Morello river section, densely packed, monotypic concentrations of barnacle compartments and crowns, selected by size, occur as infills of small erosional scours, passing laterally to thinner pavements or shallow lenses.

Environmental interpretation

Inner shelf grading locally upwards to lower shoreface. Most skeletons of mixed assemblages were probably exported by storm-driven flows from areas located near the fair-weather wave base, where they underwent fragmentation in a periodically high-energy setting, into a deeper inner-shelf environment. They probably derive from palaeocommunities equivalent to the modern biocoenoses SGCF (Coarse Sand and Fine Gravel under Bottom Current) and SFBC (Fine Well-Sorted Sand) (Pérès & Picard 1964).

TS-S Facies Tract

TS-S FT is located at the base of the siliciclastic mudstone unit of the cycle (Fig. 4). It is an unconformably-based unit, either underlain by the TS-P - RS-P couplet or directly by the clino-bedded carbonate wedge. Similarly to the TS-P FT, more complete successions are bipartite, including a lower calcarenitic unit,

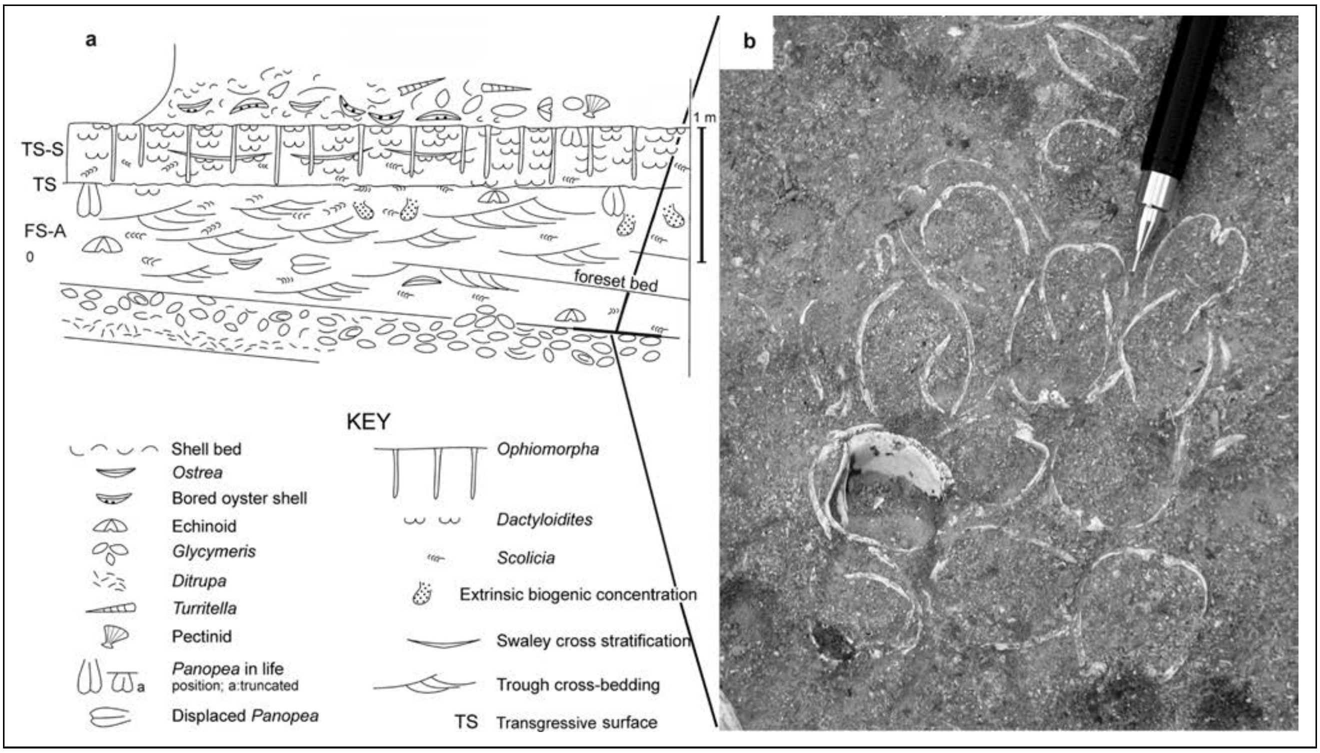


Fig. 8 - Drawing and detail of uppermost part of clino-stratified unit of cycle 6 (FS-A), overlain by highly bioturbated, slowly aggrading TS-S with vertical *Ophiomorpha* shafts crossing a former generation of trace fossils (*Dactyloidites* and *Scolicia*), in turn covered by fossiliferous transgressive deposits of base of Geracello Formation (Monte Capodarso section, near Capodarso bridge). (a) Faunal assemblages, taphofacies, ichnofacies and sedimentary structures. (b) Horizontal section parallel to stratification, showing monotypic sedimentologic concentration of *Glycymeris* valves.

locally missing, and a more erodible, bioclastic, fossiliferous siltstone unit.

The lower unit, 0.5 to 0.9 m thick, is either massive or subdivided into upward-thinning layers, lapping at low-angles on the top surface of the wedge. The beds appear in places as erosionally based event-beds, with a few dispersed cores of cardiids, *Ditrupa* tubes and commonly moderate concentrations of rounded fragments of the thalli of *Lithophyllum* sp., *Titanoderma* sp. and *Mesophyllum* cf. *alternans*, accompanied by small rhodoliths. Typical is the presence of sparse *Panopea glycymeris* in life position. Bioturbation is intense (Bioturbation Index BI= 4-5). Dense, vertical *Ophiomorpha* shafts up to 75 cm long locally cross a former generation represented by *Dactyloidites peniculus* structures and *Scolicia* (Massari & D'Alessandro 2009) (Fig. 8). Trace fossils are domichnia and fodinichnia, probably produced by suspension and deposit feeders.

The upper unit, on average 35 cm thick, is typically fossiliferous, and, in case of lack of a lower unit, may contain at the base a few *remanié* elements, i.e., eroded from older sediments. This unit may be defined in the lower part as a skeletal concentration with shells floating in a matrix of finely bioclastic silt or muddy silt (Fig. 9). Loosely to densely packed exotic and indigenous fossils are represented by disarticulated valves, both convex-up and -down, commonly fragmented, some abraded, usually stacked or nested, concentrated in thin lenses. The fossils mostly belong to pectinids (*Aequipecten scabrella, A. opercularis*, *Chlamys varia*, *Ch. multistriata*, *Amusium cristatum, Pecten jacobaeus*), typical of a circalittoral environment (DC - Coastal Detritic Bottoms), associated with rounded fragments of corallines and abraded tubes of *Ditrupa arietina*. Some epifaunal skeletons are poorly encrusted by lamellar bryozoans and/or bioeroded by *Entobia* isp. In cycle 4 of the Morello river section (Fig. 9), the basal part is characterised by numerous *Concavus concavus* crowns (Fig. 7b) and scattered *T. terebratula* (mainly articulated specimens of variable size). Numerous although sparsely occurring other forms, probably exotic, show high species diversity but low abundance. Between shell concentrations, dispersed indigenous elements are intercalated, such as semi-infaunal (*Modiolus* spp.) and infaunal molluscs (i.e., cores of *Venus* spp., cardiids, *Pelecyora brocchi, Dosinia orbicularis*). In the cycle 3 of Serieri valley (northern section) a finely bioclastic layer, about 40 cm thick, containing numerous branches of corallines, is dominated by autochthonous and parautochthonous valves of *Modiolus barbatus*. In cycle 5 of the Morello river section, an upward-fining coarse silt, above a thin lag concentration, contains discontinuous pavements of loosely to densely packed, concordant, parautochthonous *Turritella tricarinata* cores (the modern species, *T. communis*, is characteristic of VTC - Terrigenous Mud), laterally replaced by numerous, moderate-size cardiid cores.

In the upper part of the FT, the fauna shows an upward progressive sparseness, with disarticulated and randomly arranged valves of epifaunal taxa, accompanied by rare infaunal echinoids and autochthonous elements (such as *Panopea glycymeris*, *Lutraria* sp., *Venus* sp., *Solecurtus scopulus*, and *Tellina serrata*), as well as a few extrinsic biogenic concentrations attributable to bottom-feeding organisms.

Environmental interpretation

The environmental setting is similar to that of TS-P FT. *Ophiomorpha* shafts crossing a former generation of burrows in the lower unit represent an omission suite. Faunal composition and taphonomic features indicate a background setting of low to moderate energy, deepening from inner shelf to middle shelf. Low sedimentation rate is suggested by the presence of bioeroded and/or encrusted skeletons of epifaunal organisms. Upward decreasing physical concentrations record high-energy events, during which barnacles and brachiopods were mixed with bivalves. Episodes of water turbidity are suggested by lenses of opportunist *Ditrupa*, and local high terrigenous input by numerous *Turritella tricarinata* moulds.

BS Facies Tract

BS FT is characterised by monotypic or oligotypic shell concentrations directly superimposed on TS-S shellbeds (Fig. 4). Due to the poor outcropping conditions of the finer-grained parts of the cycles, this FT has only been identified in a few cases. It is clearly expressed in cycle 3 (Serieri valley, southern section) and cycle 4 (Morello river and Portella Capodarso sections).

The indigenous macrofauna is dominated by sessile epifaunal suspension feeders in a marly siltstone matrix, locally bioclastic, with angular quartz in the silt grade. Planktonic forms are more common than benthic ones in the foraminiferal assemblage.

In the Serieri valley (southern section), loosely to densely packed autochthonous clumps of the gregarious *Neopycnodonte cochlear* are associated with some dispersed reworked crowns of *Concavus concavus* and a few disarticulated valves of pectinids and brachiopods, probably exotic. In the Morello river section, a fine-grained interval contains oligotypic associations, consisting of loosely to densely packed crowns of *Concavus concavus* (Fig. 7b), locally associated with rare *Megabalanus tintinnabulum* and *M. tulipiformis* (Fig. 7c, d; determinations based on microscopic structure of compartments, following Menesini 1965). Barnacles, autochthonous to parautochthonous, occur in clumps or isolated specimens. The skeletons, poorly bioeroded or slightly encrusted by lamellar bryozoans, are commonly attached to disarticulated valves of pectinids (*Aequipecten scabrella*, *Chlamys varia*, *Amusium cristatum*), brachiopods, or barnacle compartments. Abundant, parautochthonous, articulated shells of *T. terebratula* occur in the upper part as oligotypic associations, and are locally associated with a few remains of *Ditrupa arietina* (characteristic of PE - Heterogeneous Community), *Dentalium sexangulum*, and cores of venerids.

Environmental interpretation

The fossil assemblages are interpreted as time-averaged biologic accumulations. The *Neopycnodonte* association indicates a well-oxygenated setting of deep middle shelf or shallow outer shelf. Transition from the underlying TS-S FT to this FT is accompanied by water deepening and a decrease in energy level. Extensive colonisation took place in a setting characterised by soft-firm bottoms, sediment starvation or significant reduction of sediment input and low-moderate hydrodynamic energy. Prolonged residence on the seafloor is indicated by shell degradation, bioerosion and encrustation. Shell concentrations of the underlying TS-S FT provide a firm, stable substrate for barnacle attachment and colonisation by epifaunal taxa (feedback mechanism).

Barnacles are thought to be *r*-selected forms characteristic of mesotrophic conditions (e.g., Kamp et al. 1988; Halfar et al. 2004; Aguirre et al. 2008; Radwańska & Radwański 2008). *T. terebratula* may be considered a moderate *r*-selected species, since it is well represented only in oligotypic associations. The predilection for relatively high trophic levels seems to be a characteristic commonly shared by Phanerozoic brachiopods (e.g., Kowalewski et al. 2002). The monotypic or oligotypic concentrations of indigenous *r*-selected species therefore suggest environmental stress related to mesotrophic levels.

EH Facies Tract

EH FT (Figs 4, 9) consists of dominantly terrigenous, poorly fossiliferous, grey siltstone or bluish-grey mudstone (weathering to light yellow), in places with nodular concretions (Fig. 9). It contains a variable proportion of silt-sized angular quartz and mica grains, and coarsens upwards, with minor grain-size fluctuations, into coarse siltstone, in places finely bioclastic. The lower part (e.g., cycle 4 of the Morello river section; Fig. 9) contains dispersed autochthonous *Venus multilamella* in life position (at the present time preferentially occurring in VTC - Terrigenous Mud), accompanied by scattered, parautochthonous *Nucula sulcata*,

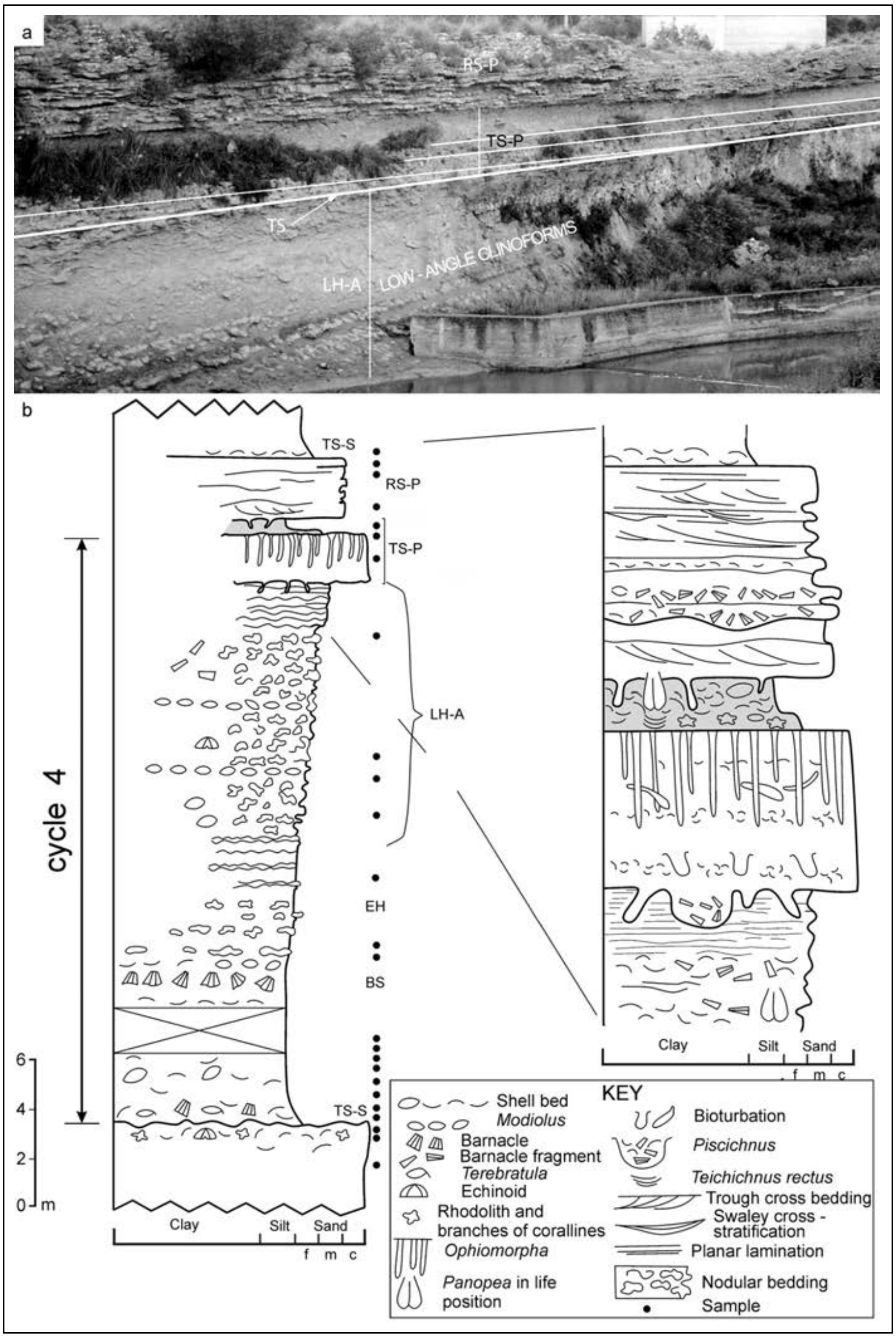


Fig. 9 - Cycle 4 and basal deposits of cycle 5 in Morello river section. (a) Field view, with indication of FTs. (b) Stratigraphic log, measured a few dozen meters from section depicted in (a) (See Fig. 4 for relative position of facies tracts).

rare allochthonous barnacle crowns, and locally numerous small fragments of corallines.

The upper part consists of poorly sorted sediment, locally including thin lenses or layers composed of pectinids, unidentified bivalve shells, and coralline fragments. In cycle 4 of the Morello river section, a poorly fossiliferous silty mud contains sparse juvenile valves of *Aequipecten opercularis* associated with rare disarticulated valves of brachiopods, *Spatangus lamberti* and *Lutraria* in life position.

Foraminiferal microfauna (cycle 4 of the Serieri valley, northern section) yielded assemblages including benthic forms (*Ammonia beccarii*, *Cassidulina neocarinata*, *Asterigerina planorbis* and *Cibicides lobatulus refulgens*), and planktonic foraminifers (*Orbulina universa*, *Turborotalia quinqueloba*, *Globigerinoides ruber*, together with clearly *remanié* forms, such as *G. margaritae*).

Environmental interpretation

In the lower part, the macrofauna suggests a background palaeocommunity equivalent to the modern VTC (Terrigenous Mud) of the middle shelf, inhabiting a soupy, rarely soupy-soft, bottom below the normal storm wave base, with moderate sedimentation rate. Suspension feeders are more common than deposit fee-

Fig. 10 - (a) Burrowed low-angle clino-beds in proximal belt of sixth carbonate wedge (LH-B), with pervasive bioturbation almost completely obliterating physical structures (Monte Capodarso section). Encircled 15 cm pencil for scale. (b) Longitudinal section of clino-stratified unit, about 11 m thick, composed of high-angle, oblique clinoforms (FS-A), underlain by siliciclastic mudstone (lower right) and unconformably overlain by bipartite bed package (TS-P and RS-P). Cycle 4 and lower part of cycle 5, Serieri valley, southern section.

ders. The trend is shallowing upwards into inner shelf with increased sedimentation rate and moderate hydrodynamic energy. The thin lenses or layers may be the result of scouring and winnowing of the sea floor by storm waves, followed by rapid burial.

The foraminiferal assemblages show a mixing of ecologically and biostratigraphically incompatible forms, suggesting a certain degree of reworking and redeposition.

LH Facies Tract

The sediments of this FT record the initial stage of progradation. In the most updip portions of the progradational wedges, the initial clinoforms show a prograding-aggrading stratal pattern ("climbing" progradation) with low dip angles, and asymptotic downlap onto offshore siltstone (Fig. 4). The clino-beds are characterised by bioturbated, grey to yellow-brown, skeletal packstone layers with a fraction of well-sorted quartz silt, interbedded with bioclastic siltstone. Planktonic foraminifers are generally abundant and are associated with benthic foraminifers, including various morphotypes of epiphytic genera. The LH FT displays a certain facies variability. Two end-members (LH-A, LH-B) were chosen as representative of the range of physical facies and taphofacies. The former is typically represented in cycle 4 of the Morello river section (Fig. 9) and the latter in cycle 6 of the Monte Capodarso section (Fig. 10a).

LH-A FT is characterised by silty-packstone nodular concretions (Fig. 9) surrounded by a siltstone matrix. The macrofauna is mostly articulated and locally common. Epifaunal shells are slightly encrusted by laminated bryozoans or attached barnacles. The lower part of the FT shows alignments of small clumps of autochthonous *Modiolus barbatus* shells, and scattered *T. terebratula* shells, *Concavus concavus* crowns (both significantly decreasing in abundance upwards) and disarticulated valves of pectinids (mostly *A. scabrella*). The vagile fauna is recorded by some skeletons of *Spatangus lamberti*. In the middle part, the sediment becomes more bioclastic, and contains a few pavements of loosely packed complete allochthonous valves of *P. flabelliformis*, commonly disarticulated, concordant and convex-up. Intrinsic biogenic and mixed-origin concentrations occur in both the lower and middle parts. The bioclastic fraction increases in the upper part, where the nodular facies disappears. The sediment coarsens into fine bioclastic grainstone with some meniscate galleries, and contains small burrows infilled with fragments of barnacle compartments and rare thin lenses of *M. barbatus*, *T. terebratula* and pectinid valves. The dispersed fauna is represented by *Modiolus* sp., *A. scabrella*, *Chlamys* spp., *Glans rhomboidea*, *Anadara diluvii*, *Acanthocardia* sp.

LH-B FT (Fig. 10a) consists of intensely bioturbated silty packstone with interbeds of bioclastic siltstone, grading upwards to low-angle clino-beds consisting of laminated to bioturbated couplets. The lower part shows dense *Thalassinoides* isp. systems (max. BI = 5-6), largely obliterating physical structures and, locally, some *Piscichnus waitemata*. Commonly, the fossils are randomly disposed, due to biologic and/or physical action. They include fragments of corallines, articulated cardiid cores, *Glycymeris insubrica*, pectinid valves, sparse *Megabalanus tulipiformis* crowns and mesoskeletons of *Sphaerechinus* sp., *Echinolampas* sp., and *Spatangus* sp. A layer, a few centimetres thick, contains some articulated *G. insubrica*, associated with *Pinna nobilis*, the latter recorded by some basal parts of the shell, still in life position, probably truncated by a subsequent, storm-related high-energy event. Vagile shallow-infaunal suspension feeders are dominant, associated with some deposit feeders, and rare epifaunal and sessile elements. Local extrinsic biogenic concentrations are probably feeding-related. In the upper part a decrease in the intensity of bioturbation is accompanied by transition to grainstone and an increase in sorting and the importance of physical structures, with sedimentologic shell concentrations occurring in laminated to bioturbated beds with *Scolicia* meniscate galleries.

Environmental interpretation

LH-A: The intrinsic biogenic concentrations (locally preserved by obrution events) and composition of macrofauna suggest a middle shelf depositional setting in the lower part, with relatively stable bottoms, episodically affected by distal storm flows *sensu* Fürsich & Oschmann (1993). The obrution events were followed by short-term colonisation by burrowing ichnomakers. Nodular concretions are regarded as resulting from selective diagenesis of *Thalassinoides*-like irregular mazes (BI= 4-5). In the upper part, sedimentologic and taphonomic features, and the faunal ecology suggest a soft biotope with higher hydrodynamic energy and a shallowing trend from deep middle shelf to inner shelf. This matches the change from DC (Coastal Detritic Bottoms) to DC/SFBC (Coastal Detritic Bottoms / Fine Well-Sorted Sand) in terms of modern biocoenoses. Burrows infilled with bioclasts may represent either feeding-related extrinsic biologic concentrations, or tubular tempestites (Wanless et al. 1988).

LH-B: The fossil assemblages suggest upward transition from stable soft bottoms of a middle shelf environment, probably with patchy seagrass meadows, to shifting bottoms of inner shelf, bioturbated by vagile shallow burrowers. The latter setting is indicated by palaeocommunities comparable to the modern DC transitional to SFBC biocoenosis. Layers with recognisable physical structures are thought to be event-beds emplaced by storm-driven flows. A sporadic aeolian contribution, followed by hydraulic reworking in a shallow-marine environment, is suggested by the well-sorted fraction of quartz silt present in both varieties of the LH FT.

FS Facies Tract

The FS FT includes those parts of the clino-bedded wedges, largely predominant in volume with respect to the LH FT, which developed downdip of the LH FT, when stratal geometry changed from 'climbing' progradational to offlapping, with complex sigmoidal-oblique clinoforms. FS-A and FS-B are differentiated according to the composition of the clino-beds, which are essentially carbonate in the former, by far the most common (Figs 4, 10b), and comprise a moderate siliciclastic fraction and more varied macrofauna in the latter. In addition to the carbonate clino-beds, the FS FT includes the time-equivalent, fine siliciclastic or mixed facies onto which the clino-beds downlap, and with which they interfinger (Fig. 4, dark grey toe and bottomsets). The latter is only treated in connection with the FS-A FT, owing to better conditions of outcrop exposure.

FS-A Facies Tract

FS-A clino-bedded facies: composition, biofacies and taphofacies

The contact between LH FT and FS-A FT is marked by an erosional surface and textural coarsening, accompanied by the local presence of rip-up mudstone clasts. This surface dips at a gentler angle than the clinoforms, and extends with erosional character to the base of the clino-stratified wedge in the proximal part of the FS-A FT, where the height of clinoforms does not exceed the depth of the storm wave base. It becomes gradational and conformable basinwards, where higher clinoforms interfinger transitionally at the toe with fine-grained offshore siliciclastic silt laid down below the storm wave base (Fig. 4).

FS-A clino-bedded facies (Figs 4, 10b) is represented by yellowish-brown, prograding carbonate units showing a trend coarsening upwards, from fine-grained packstone to grainstone and fine-grained skeletal rudstone, with interstitial micrite occurring in the uppermost decimetres of the prograding bodies. The clino-beds consist of generally well-sorted skeletal material, commonly disarticulated and fragmented. Minor constituents are sparse quartz, locally bimodal in grain size distribution (silt-size, well-sorted angular fraction, associated with larger rounded grains or broken rounds), rare feldspar, mica, and glauconite grains. Foraminifers and debris of bivalves are dominant, accompanied by subordinate amounts of serpulids and barnacles (Fig. 11b), and sparse debris of brachiopods, gastropods, bryozoans, echinoids and corallines (including *Lithophyllum*). The bioclastic matrix contains whole, commonly unabraded shells. Millimetre-sized, well-rounded extraclasts of a micritic facies with small planktonic foraminifers reminiscent of the Lower Pliocene Trubi are sparsely present. Common *Scolicia* and sparse *Dactyloidites peniculus* occur in the clino-beds.

No significant modifications in average composition occur in the proximal-to-distal direction, as local changes are mainly linked to grain size. Bioclasts are

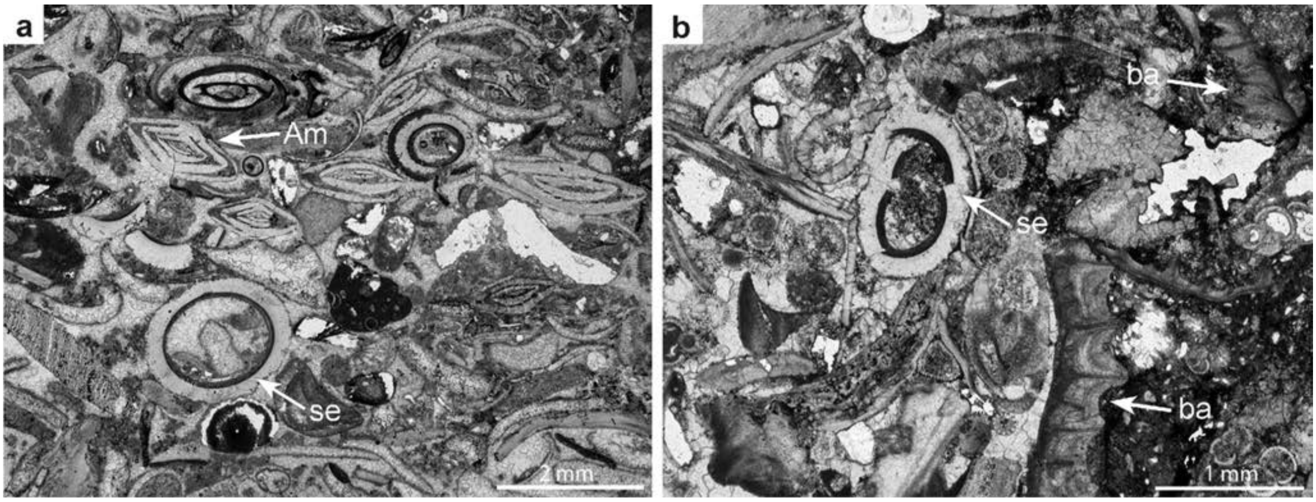


Fig. 11 - Thin-section photomicrographs of Capodarso heterozoan limestone. (a) Grainstone/packstone with serpulids (se), *Amphistegina* (Am), and debris of bivalves and echinoids. Note micrite envelopes around skeletal debris and spar-filled molluscan moulds. RS-P of cycle 3 (Morello river section). (b) Packstone/grainstone with debris of bivalves, barnacles (ba), serpulids (se), and foraminifers. Clino-stratified unit (FS-A) of cycle 6 (Monte Capodarso section). Note effects of mechanical and chemical compaction in both photomicrographs.

moderately abraded, variably rounded, partly according to size. Thin-section analysis reveals common small peripheral borings, although not particularly dense or invasive, and very thin micrite envelopes surrounding the bioclasts. Skeletal material ranges from fresh-looking to variably macerated, with common, brown Fe-hydroxide staining.

The macrofauna is dominated by mostly exotic vagile epifaunal suspension feeders. Together with some parautochthonous elements, they form loosely to densely packed concentrations or pavements with shells, articulated and disarticulated (Fig. 8a, b), commonly unbroken, concordant, convex-up and -down, aligned and locally imbricated. Pectinids, rarely encrusted by lamellar bryozoans, are dominant [most common *P. flabelliformis,* current-related, locally accompanied by *A. scabrella*, *P. jacobaeus*, exclusively occurring in DC (Coastal Detritic Bottoms), and *Amusium cristatum*, negatively related to depth]. *Remanié* valves (e.g., *Pecten bipartitus* in the Serieri valley section) are exceptional.

Skeletal elements inferred to be parautochthonous, i.e., mobilised from nearby areas, and belonging to the same palaeocommunity, are represented by small scattered clumps of *Ostrea lamellosa* and articulated specimens of *G. insubrica* (characteristic at the present time of SFBC - Fine Well-Sorted Sand), as well as rare, horizontally disposed valves of the deep infaunal *Panopea*. The latter occurs locally even in life position, although eroded in its siphonal part. Due to mechanical size and shape sorting, sedimentologic concentrations are commonly dominated by elements belonging to a single species, e.g., pavements of parautochthonous juvenile *G. insubrica* valves, mostly half-open and commonly nested, and lenses of *D. arietina* tubes (Fig. 8a, b). Autochthonous elements are rare, mostly belonging to infaunal and shallow-infaunal suspension feeders; the presence of deposit feeders is recorded by trace fossils and a few infaunal echinoids (*Echinolampas hoffmani*, *Schizechinus chateleti*).

Foraminifers include both benthic (most commonly Textulariidae, Trochamminidae, Verneuilinidae) and planktonic forms. *Amphistegina* sp., abundant in the lower cycles, rapidly decreases in abundance upwards. Epiphytic foraminifers, both motile and sessile forms, including *Elphidium* sp., *Triloculina* and *Quinqueloculina* groups, *Lobatula* sp., and *Planorbulina mediterranensis*, are sparse, but almost systematically present.

FS-A clino-bedded facies: physical structures, stratal patterns and dispersal processes

Prograding wedges of FS-A FT are characterised by oblique and sigmoidal clinoforms, generally with asymptotical toesets (Fig. 12). The dip of clinoforms is distinctly unimodal (Fig. 13), changing very little along the strike, indicating an approximately linear front.

In the FS-A clino-bedded facies two belts may be distinguished in the proximal-to-distal direction. They grade transitionally into each other and show different stratal organisation (Figs 4, 14).

(1) The upramp facies belt shows lower and less inclined clino-beds, characterised by pervasive traction structures, mainly planar lamination and trough cross-bedded intrasets. The latter indicates that the dominant mode of transport was by extensive offshore-migrating three-dimensional dune fields. The dunes migrated seawards on the top of the prograding ramp and down the gentle clinoform slopes. The dip directions of the lami-

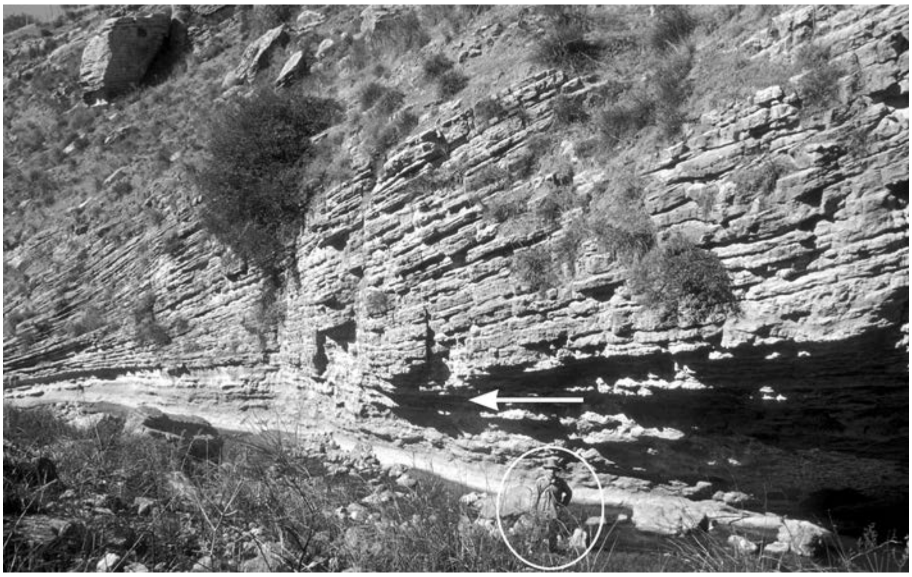


Fig. 12 - Foreset beds passing asymptotically downdip (arrow) into toeset and bottomset beds interfingering with siliciclastic mudstone (FS-A, cycle 2, Serieri valley, southern section). Encircled person for scale.

nae of the trough cross-bedded intrasets are slightly divergent, by 22° on average, with respect to the dip of the clinoforms (Fig. 13), indicating that the dunes migrated obliquely down the surfaces of the foresets, probably as a result of a tendency to diversion from offshore-directed into along-shelf flow. Individual clino-beds (foresets) are bipartite, with a lower division dominated by physical laminae, grading upwards into a bioturbated division. The transition from foresets to toesets and bottomsets is marked by downdip increasing bioturbation intensity. As observed by Quiquerez & Dromart (2006), the slope angles of these clinoforms are not simply correlated with sediment grain size and fabric, and may record hydrodynamic equilibrium profiles.

(2) Farther basinwards, clinoforms increase progressively in height and steepness (up to 19°) (Fig. 14), as progradation of the carbonate body encroaches on increasingly deeper waters. In contrast with the pervasive presence of traction structures in the inner-belt clino-beds, the transition to the outer belt is marked by the gradual restriction of these structures to the uppermost part of the body (Figs 8a, 15), that is, the upper slope of clinoforms, showing nearly flat or only slightly inclined geometry. In this part of the body, physical structures, mainly represented by hummocky and swaley cross-stratification, trough cross-bedding and planar lamination, show an increasing degree of amalgamation in the downramp direction, contrasting with the laminated-to-bioturbated pattern characteristic of the event-beds of the inner belt.

Downdip of the upper foreset slope, the physical structures in the middle and lower foreset slope, toeset and bottomset are dominated by normal grading and pervasive planar lamination. The thickness ratio between the laminated and bioturbated portions of the beds decreases on average from the foresets to the bottomsets. These stuctures and stratal patterns indicate that, beyond a certain threshold of steepness and height of clinoforms, offshore-directed storm-induced traction flows changed into sediment gravity flows, as the dense suspensions were driven beyond the slope break and conveyed down the ramp slope. In this case, the high dip angles of clinoforms are correlated with the sediment grain size and fabric, owing to the importance of gravity resedimentation processes (Quiquerez & Dromart 2006). The laminated to bioturbated bedding style indicates peak and waning stages of high-energy events,

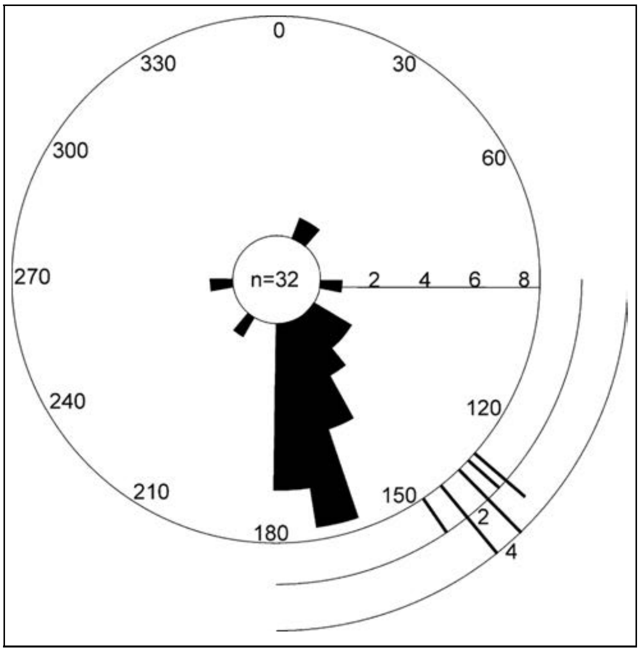


Fig. 13 - Rose diagram representing dip azimuths of laminae of trough cross-sets (inner part), and dip azimuths of clinoforms (outer part), the former mostly measured in cycle 6 of the Monte Capodarso section Note divergence of about 22° between two groups of measurements.

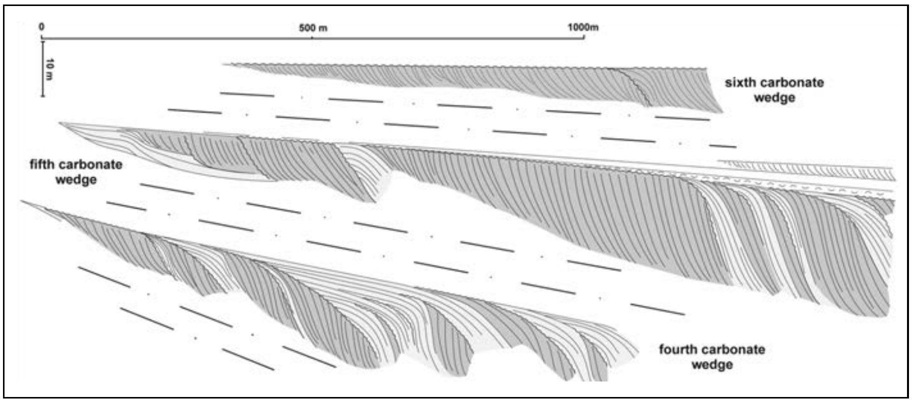


Fig. 14 - Vertical exaggeration (X10) of internal architecture of fourth to sixth carbonate wedges alternating with siliciclastic mudstone (Monte Capodarso section), showing average downramp increase in clinoform dip and presence of internal unconformity surfaces bounding shingled units with sigmoidal to oblique clinoforms (highlighted by differential shading). Basis for this processing was a photomosaic. Depiction of sheet-like packages on top of wedges and downlap terminations of clinobeds is incomplete, due to scree or vegetation cover. Note sand-wave cross-set (RS-P) on top of fifth cycle (right) (slightly modified from Massari & Chiocci 2006).

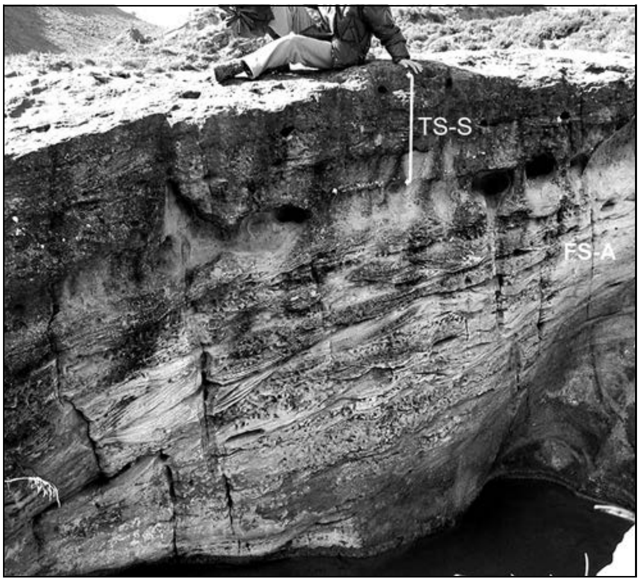


Fig. 15 - Trough cross-bedding and swaley cross-stratification (upper part of FS-A), overlain by intensely bioturbated TS-S package. Compare with Figure 8a. Monte Capodarso section, near Capodarso bridge, uppermost part of sixth carbonate wedge. Person for scale.

followed by bottom recolonisation by benthic organisms. At the transition into toesets and bottomsets, foreset beds are tangentially based (Fig. 12) or, less commonly, angularly based. Skeletal hash transported down the foreset slope was rapidly dumped in the bottomset beds, which consequently pinch out rapidly seawards over distances of a few dozen metres, interfingering with siliciclastic mudstone.

Scour-based backset beds are particularly common in the foreset of the distal belt (Figs 4, 16). They appear as infills of large bowl-shaped scours up to several decimetres deep and several metres in width and length. They are interpreted as the record of upslope migrating hydraulic jumps affecting downdip-accelerating, sediment-laden suspensions flowing down the steep front of the prograding body (Massari 1996; Massari & Chiocci 2006). Owing to the considerable energy involved in the process, they may have been generated by flows produced by major storms, as supported by the common updip convergence of the surfaces bounding the sets of backset beds into erosional surfaces truncating at low angles the upper slope of clinoforms.

The steepening of the clinoforms and related increasing gravitational instability locally resulted in slope failure, expressed by large spoon-shaped scars truncating the clinoforms, in places accompanied by the accumulation of contorted beds in the toesets. The scars were either infilled with clino-beds during continuing progradation or, in places, with fossiliferous deposits of the TS-P or TS-S facies tracts, indicating in this case that infill occurred after the end of progradation.

Wave climate, tidal range and general oceanographic conditions occurring at the time of deposition of the carbonate wedges were most probably very similar to those occurring today on the southern Sicilian coast, including long fetch, windward orientation of the ramps into the Mediterranean, and exposure to periodic high-energy storms. Dispersal of the skeletal hash is thought to have been mainly effected by storm-driven downwelling flows (cfr. dispersal model of Chiocci & Orlando 1996 and Chiocci et al. 2004), i.e., offshore-flowing near-bottom return currents, compensating the onshore piling-up of water caused by onshore-directed storm winds, and tending to farther change into alongshelf flows. Roy et al. (1995) observed that the steepness of the substrate is critical in onshore vs. offshore sediment fluxes. On substrate slopes steeper than 1.0°, which are assumed to have been the case of the Capodarso ramps, sand-size sediment probably moved offshore under the influence of storm-driven downwelling currents.

As stressed by Sonnenfeld & Cross (1993), Pomar & Tropeano (2001) and Pomar & Kendall (2007), in a setting dominated by physical accommodation, the depth (base level) of sediment accumulation is controlled by storm waves and storm-driven flows, and defines a shelf surface of dynamic equilibrium between sediment supply and removal, i.e., a storm-wave-graded equilibrium profile, a concept already anticipated by

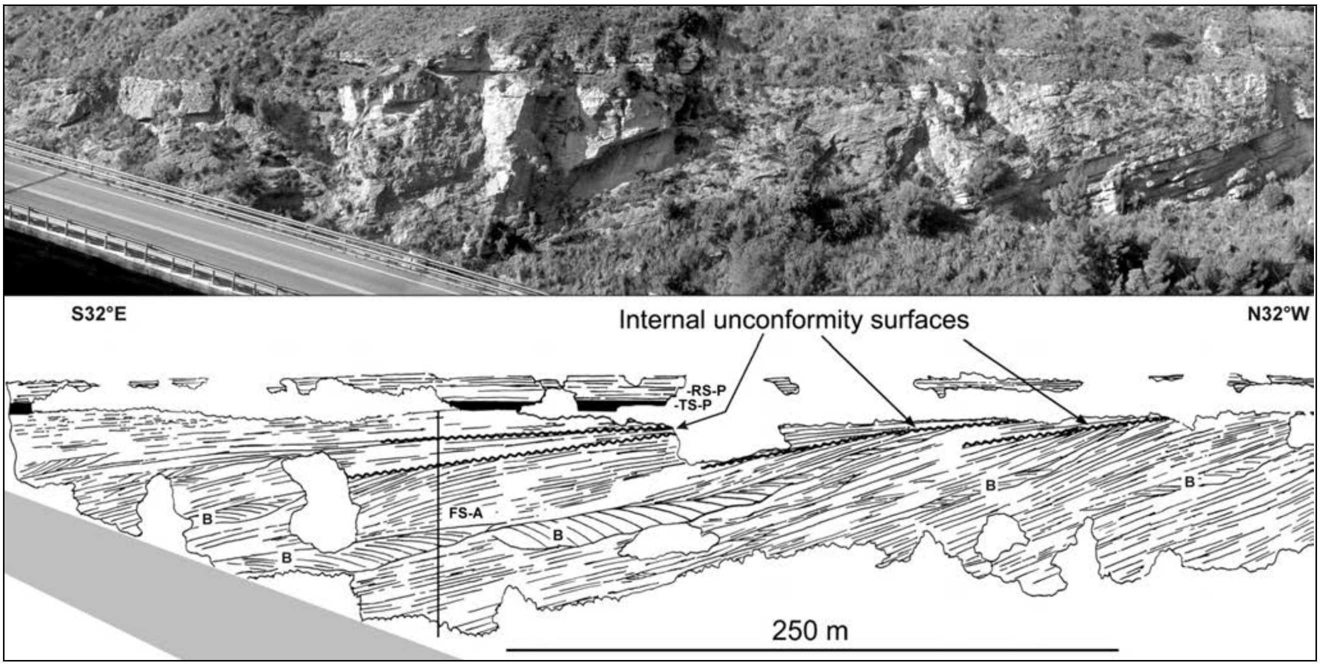


Fig. 16 - Photograph and drawing of oblique-longitudinal section of fifth carbonate wedge. Note internal unconformity surfaces and sets of backset beds (B) in FS-A, and poorly outcropping sheet-like bipartite bed package at top (TS-P, in black, overlain by RS-P) (near Capodarso bridge, eastern flank of Cozzo della Guardia). Vertical exaggeration of drawing: 1.5 X (slightly modified from Massari & Chiocci 2006).

Rich (1951) and further elaborated by Swift & Thorne (1991). We suggest that, during storms and particularly in conditions of accommodation loss, loose skeletal material was shed basinwards and deposited on the ramp slope, so that the clino-beds represent the locus of preferential accumulation and preservation of skeletal material.

A dispersal mechanism dominated by storm-related events is indicated by the pervasive laminated-to-bioturbated pattern of event-beds, high mechanical size- and shape-sorting, and predominance of allochthonous skeletons. Changes in the proportions of the variously sized grains and related compositional changes were essentially regulated by sorting, and do not reflect variation in source area (Aurell et al. 1998). Together with loose skeletal grains, whole shells constituting the coeval palaeocommunities, probably living on the top of the ramp, were commonly entrained in storm-generated flows and mixed with elements eroded from formerly deposited sediments. Selective transport resulted in efficient bypassing of winnowed fine-grained particles, including terrigenous silt and clay, as well as lime mud inferred to derive mostly from abrasion of skeletal debris in a shallow-water setting, and, to a lesser degree, from bioerosion. Fines were mainly later incorporated in offshore muds, indirectly contributing to the relative coarsening of the deposits of the prograding wedge (Light & Wilson 1998).

A close siliciclastic counterpart of the Capodarso carbonate bodies is represented by the Holocene "Infralittoral Prograding Wedges" of Hernandez-Molina et al. (2000), subjected to storm-generated downwelling flows and typically detached from the shoreline.

The FS-A prograding bodies are dominated by oblique clino-beds, particularly in the proximal belts. However, in the intermediate and outer belts, this stratal geometry is commonly replaced by a composite, oblique-sigmoidal internal architecture already identified by Colella & Vitale (1998) and Massari & Chiocci (2006). This is highlighted by the subdivision of the wedge into a series of adjoining, shingled sets of clino-beds, bounded by unconformable surfaces with high-angle toplap terminations below and downlap terminations above (Figs 14, 16). These surfaces dip at gentler angles than the clinoforms and are erosional in their updip parts, becoming conformable downdip. Within individual shingled sets, the offlap break trajectory shows first an upstepping and then a downstepping pattern, resulting in a transitional change in clinoform geometry from sigmoidal to oblique (Fig. 14).

FS-A prograding carbonate body: environmental interpretation

The ecological and taphonomic features of indigenous elements indicate that the tops of prograding ramps were inhabited by organisms preferring the setting of a well-oxygenated inner shelf. Event-bedding highlights the periodic influence of storms, during which the most severe episodes undermined even deep-burrowing bivalves or eroded the upper part of their shells.

Amphistegina indicates minimum water temperatures of 14° according to Langer & Hottinger (2000) or

16°-17°C according to Betzler et al. (1995). Di Bella et al. (2005) noted that *Amphistegina* is much more tolerant of low temperatures than other larger rotaliine foraminifers. Its presence suggests uniform trophic and salinity conditions, as 'larger' foraminifers do not generally tolerate high seasonal variations in nutrients and salinity (Renema & Troelstra 2001). Algal symbiosis may be indicative of relatively low trophic levels (Hallock 1987). The rapid upward decrease in abundance of this larger foraminifer throughout the successive carbonate bodies might reflect a cooling trend, or a decrease in light penetration.

FS-A siliciclastic/mixed facies: description

In the intermediate and distal segments of the wedges, where progradation encroaches on progressively deeper waters, the carbonate toesets and bottomsets interfinger with siliciclastic mudstone (Fig. 4, dark grey), resulting in an upward-thickening alternation a few metres thick, developing below the storm wave base. The facies was examined in the cycle 2 of the Morello river section and cycle 6 of the Monte Capodarso section, both providing fairly well-exposed outcrops. In the former locality, poorly cemented grey bioclastic siltstone, generally massive, with epiphytic foraminifers and bryozoans, abundant plant remains and dispersed, thick-shelled ostreids, contains a few, thin, lenticular concentrations of loosely to densely packed, variably fragmented and abraded shells. These are mainly cardiid cores, mitilids and pinnids, the latter probably represented by *Atrina pectinata*, also recorded by articulated umbonal parts of the valves, commonly encrusted by laminar bryozoans. In association are scattered cores of *Acanthocardia* spp., disarticulated shells of *Glycymeris* cf. *insubrica* (SFBC - Fine Well-Sorted Sand), *Dosinia* cf. *exoleta* (rheophilous, characteristic of SGCF - Coarse Sand and Fine Gravel under Bottom Current), disarticulated *Modiolus barbatus* (DC - Coastal Detritic Bottoms) and *Laevicardium oblongum* (now exclusively occurring in DC). The sedimentologic concentrations contain both exotic and indigenous faunal components, the latter mostly represented by shallow infaunal and semi-infaunal organisms, both sessile (e.g., pinnids, ostreids) and sedentary (e.g., glycymerids). A specimen of *Panopea glycymeris* (preferentially occurring in SFBC and SFBC-DC), still in life position, is truncated, probably by erosion linked to a high-energy event.

In cycle 6 of the Monte Capodarso section, near the Capodarso bridge, the facies consists of bluish-grey, massive mudstone, including autochthonous *Venus multilamella* associated with dispersed parautochthonous shells of *Amyclina* gr. *semistriata* and some *Nucula sulcata*, and allochthonous *Amusium cristatum*. Some thin lenses consist of loosely to densely packed parautochthonous and allochthonous skeletal remains, the latter commonly covered by a reddish patina. The shells are variably fragmented and abraded, completely disarticulated, with concordant and stable hydrodynamic orientation, mostly belonging to the same taxa as those occurring in the surrounding sediment, together with some *Ditrupa arietina* tubes, *Corbula gibba*, *Saccella commutata*, rare *Amyclina gigantula*, *Odostomia conoidea*, and exotic pristine white shells of the freshwater gastropod *Rhombostoma* sp.

FS-A siliciclastic/mixed facies: environmental interpretation

Ecological and taphonomic signatures in cycle 2 of the Morello river section suggest redeposition to the deep inner shelf of remains sourced from nearshore to shallow inner-shelf environments (possibly partly from inter-mats of *Posidonia* meadows). Epiphytic foraminifers and bryozoans, inferred to have been originally attached to *Posidonia* leaves, were obviously abandoned after the decay of dead leaves.

The background setting in cycle 6 of the Monte Capodarso section is a muddy bottom inhabited by a VTC-like palaeocommunity. The shellbeds are inferred to result either from physical emplacement by sediment gravity flows dumping their load in the bottomset area, or from current-associated scouring and winnowing of the sea floor, followed by rapid burial. The presence of a continental faunal element and a reddish patina on some skeletal remains suggests the partial derivation of exotic skeletal material from erosion of temporarily emerged areas, as a result of severe erosion during a base-level drop.

FS-B Facies Tract: description

FS-B FT is specific to the regressive unit of cycle 5 of the Morello river section (Fig. 17), and has distinct features with respect to the much more common FS-A FT, being characterised, as noted above, by a significant terrigenous fraction. It consists of yellowish-brown silty to sandy packstone/grainstone. A basal erosional surface, marked by abrupt coarsening above underlying silty mudstone, is covered by a massive, coarse silty, finely bioclastic unit, 1.5 m thick (unit 1 in Fig. 17), having at the base a time-averaged concentration consisting of clumps of large-sized valves of autochthonous *Ostrea lamellosa* poorly bioeroded (*Oichnus* isp.) and encrusted (lamellar bryozoans), accompanied by a few cores and moulds of *Pelecyora brocchii*, *Dosinia exoleta* and *Venus casina* (both specific to SGCF - Coarse Sand and Fine Gravel under Bottom Current). This assemblage was rapidly buried by a thin concentration containing loosely-packed convex-up *Flabellipecten* valves. Above this concentration, unit 1 contains scattered *Pelecyora brocchii*, *O. lamellosa*, pectinids and venerids,

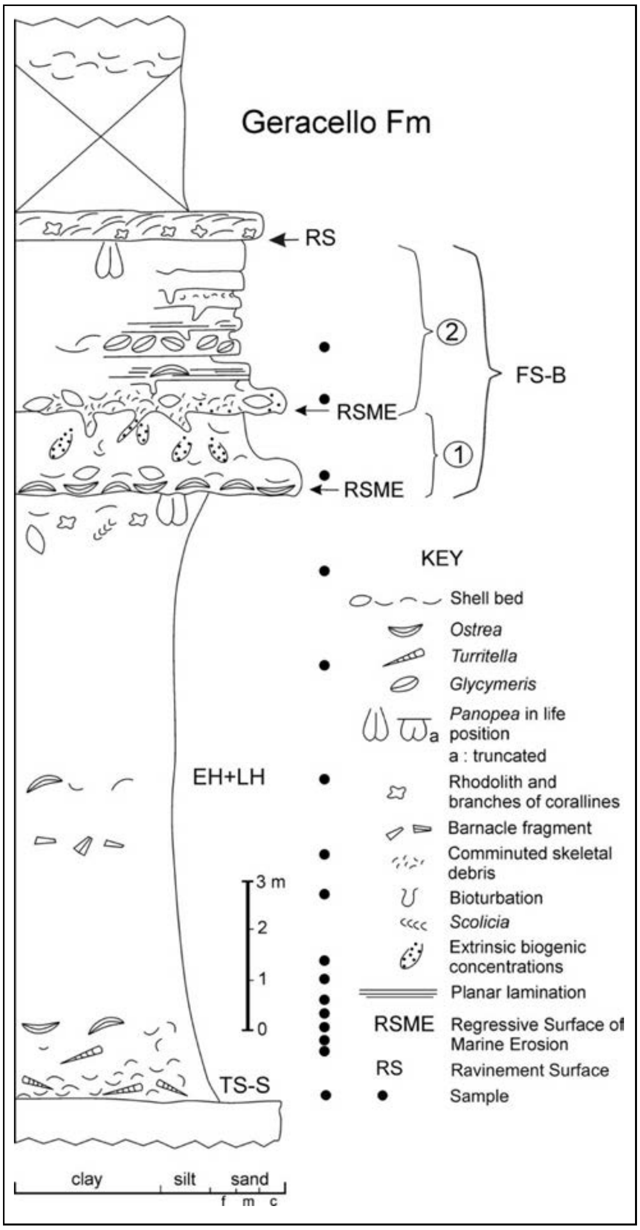


Fig. 17 - Stratigraphic log of cycle 5 in Morello river section.

accompanied by small extrinsic, feeding-related biogenic concentrations.

Another sharp grain-size break marks the contact with the overlying interval, 3.5 m thick (unit 2 in Fig. 17), consisting of laminated to bioturbated couplets (event beds), particularly manifest in the lower part, where they consist of discontinuous, roughly planar-laminated pavements/broad lenses of densely-packed concentrations, composed of randomly disposed, or locally imbricated, commonly disarticulated and fragmented bivalve shells, mainly belonging to *Modiolus phaseolinus* and *M. adriaticus* (both typical of DC - Coastal Detritic Bottoms). Intercalated, more terrigenous lenses enclose large fragments of mitilids, celleporiform bryozoans and thin lenses of small densely-packed bivalves of uniform dimensions (*Palliolum* sp., *Corbula gibba*, specific to PE - Heterogeneous Community -, and *Saccella commutata*). Some of these lenses contain exogenic fossils of similar dimensions, mostly belonging to one single species. Characteristic are patchy concentrations of articulated (closed or half-open) indigenous valves of *Glycymerys insubrica insubrica* (the modern sub-species is typical of SFBC - Fine Well-Sorted Sand). Minor components are scattered shells of *Pecten jacobaeus*, *P. planariae* (DC - Coastal Detritic Bottoms), *Chama placentina*, *Venus casina*, *Solen marginatus* (SFBC), *Gibbula magus* (preferentially occurring at the present time in DC), cardiids, venerids, and large sparse fragments of *Pinna* cf. *nobilis* (HP - Photophilic Algae and SFBC).

The vagile fauna and size-sorted valves within physical concentrations are probably exotic and mostly belong to shallow- or semi-infaunal, subordinately epifaunal, organisms. The indigenous components are predominantly shallow-infaunal. From the trophic viewpoint, suspension feeders are more common, followed by some vagile shallow-infaunal deposit feeders (e.g., echinoids) and rare carnivores (naticids).

FS-B Facies Tract: environmental interpretation

Deposition generally occurring on soft sea bottom may be envisaged, except at the base, where erosion exhumed a firmground on which a time-averaged assemblage was preserved by an abrupt burial event. The two closely spaced grain size and faunal breaks occurring at the bases of units 1 and 2 (Fig. 17) are thought to mark abrupt shallowing steps. Unit 1 indicates a shelf setting near the normal storm wave base. A transition to a shallow inner shelf in Unit 2 is indicated by the predominance of storm-related sedimentological concentrations of exotic elements typical of infralittoral and, subordinately, shallow-circalittoral palaeocommunities. Compared with FS-A, FS-B facies tract is characterised by higher terrigenous input, as also supported by the presence of local lenses with *Corbula gibba*, suggesting events of water turbidity.

Abd Facies Tract

Abd FT is a characteristic, non-depositional horizon of intense bioturbation, marked by dense, vertical *Ophiomorpha* shafts up to 75 cm long (Massari & D'Alessandro 2009), crossing the topmost part of the clino-bedded wedge (Figs 4, 6), and occurring with higher density in the distal segments of the carbonate bodies. The shafts are superimposed on former *Dactyloidites peniculus* structures, and show reinforced walls, suggesting penetration into soft sediment. They are truncated by an erosional surface at the contact with TS-P or TS-S FTs (Fig. 6), implying removal of, at most, a few dozen centimetres of sediment.

Environmental interpretation

Ophiomorpha shafts crossing the first generation of burrows represent an omission suite. Erosional truncation of *Ophiomorpha* shafts led to exhumation of a firmground.

An integrative sequence stratigraphic - facies model

The biofacies, examined together with the palaeoecologic and taphonomic attributes of skeletal assemblages and ichnofabrics, are an important tool supplementing sedimentologic evidence in the recognition of facies changes and characterisation of the basic elements of sequence stratigraphy, such as systems tracts and related key surfaces (Kidwell et al. 1986; Norris 1986; Banerjee & Kidwell 1991; Brett 1995). (Fig. 4).

The top surfaces of clino-bedded wedges mark the turn-around between progradational and backstepping stages and are regarded as sequence boundaries (Fig. 4), due to their easy identification in the field and high lateral persistence (e.g., Caron et al. 2004). The first signature of transgression in the Capodarso sequences is lime mud infiltration into flooded and commonly truncated surfaces at the top of the clino-bedded packages (see also Pedley & Grasso 2002).

The TS-P - RS-P couplets (Figs 4, 6, 9, 10b) are interpreted as parasequences or small-scale sequences belonging to the TST of the higher-rank cycle. In the case of more complete successions (Figs 5, 9), the onlapping lower unit of the TS-P Facies Tract records the backstepping stage, the overlying shell concentration a condensed mid-cycle shellbed *sensu* Abbott (1997) and the RS-P FT the regressive unit. Conversely, in the absence of the lower unit (Fig. 6), the shell concentration of the TS-P FT is regarded as onlap shellbed. Sharp- or transitionally-based RS-P units respectively record forced or normal regression. They probably pass laterally into one another in a proximal-to-distal direction, representing the response to slight downramp changes from decreasing to increasing accommodation.

The TS-S FT, when occurring above a TS-P - RS-P couplet, develops above a second flooding surface and its organisation is similar to that of TS-P FT, both recording greatly reduced sedimentation rate (Naish & Kamp 1997). Local concentrations of corallines is regarded as typical of the TST, as suggested by Corda & Brandano (2003), who noted that corallines are among the primary producers in this stage, concomitantly with increased nutrient availability. Enhanced trophic levels during the TST were also noted by Arnaud-Vanneau & Arnaud (1990), Raspini (1998), and Wright & Burgess (2005), among others.

The confinement of clearly recognisable parasequences in the TST is not unusual in the carbonate ramps. Burchette & Wright (1992) and Sanders & Pons (2001) pointed out that whereas parasequences a few metres thick occur in the early TST of some high-energy carbonate ramps, they are less clearly defined in late transgressive and highstand systems tracts.

The shellbeds of the BS FT are thought to indicate prolonged residence on a starved sea floor with low hydrodynamic energy. They are believed to represent time-averaged biologic accumulations, corresponding to the backlap shell beds of Kidwell (1991), and the sediment-starved shell beds of Hendy et al. (2006). The offshore depositional setting commonly results in an amalgamation with transgressive shellbeds, leading to condensed onlap-backlap compound shellbeds. The oligotypic (in some cases monotypic), mainly autochthonous associations of barnacles and brachiopods, generally regarded as r-selected opportunists, may be the biotic fingerprint of relatively high nutrient availability (e.g., Kowalewski et al. 2002; Aguirre et al. 2008; Radwańska & Radwański 2008).

The aggrading stratal pattern and gentle shallowing trend of EH FT (Fig. 4), coupled with evidence of a progressive increase in sedimentation rate, are consistent with its attribution to the early Highstand Systems Tract (HST).

LH FT (Fig. 4) characterises the initial stage of progradation, marked by shoaling sedimentation from middle to inner shelf environments, and the appearance of "climbing" clinoforms downlapping with low dip angles onto offshore mudstone. It may therefore be ascribed to the late HST (see also Butler et al. 1997; Massari & Chiocci 2006).

With progressive loss of accommodation in the subsequent stage, sedimentation starts to build up to a higher-energy environment. The transition from slowly aggrading progradation to pure progradation with toplap geometry, implying both sedimentary bypassing and/or erosional truncation, is thought to indicate the onset of the Falling Stage Systems Tract (FSST), represented by the FS FT (Fig. 4). Bottom orbital velocities of storm waves can stir and lift both fine-grained sediments and sand-sized skeletal fragments, with potential for lateral transport by superimposed linear, downwelling flows. Excess grainy sediments are shed basinwards, feeding the clino-beds on the front of the prograding body, where they are ultimately stored and buried. Basinward increase in the height of clinoforms is afforded by the divergence between the offlap break trajectory and the bathymetric profile of the foundation of the prograding body, so that the offlap break faces successively deeper waters as progradation proceeds (Helland-Hansen & Hampson 2009).

The above noted proximal-to-distal changes of stratal organisation in the uppermost part of the body indicate the increasing energy of the depositional setting at the ramp top, concurrently with progradation, and hence a gradual reduction in the depth of the water column above the ramp top. This would also result in enhanced erosion potential, at the expense of formerly deposited sediments. It is argued that the amount of sediment removed and resedimented during the falling stage was significantly higher than during the base level rise, considering the gentle erosion recorded by the truncation of *Ophiomorpha* shafts at the top of the clino-bedded wedges during the backstepping stage, and the limited lag component in the shell concentrations of TS-P and TS-S Facies Tracts.

As noted above, downramp of the LH FT, the FS FT appears to be dominated in its proximal part by oblique clinoforms with distinct toplaps (Figs 4, 10b, 14), whereas the intermediate and outer belts commonly show composite internal architecture, consisting of a subdivision into a series of unconformity-bounded, shingled sets of sigmoidal to oblique clinoforms (Figs 4, 14, 16). This implies cyclical, small-scale changes in accommodation, producing first ascending and then descending paths of the offlap break trajectory within individual shingles, involving oscillation amplitudes of a few metres. In this case, the trajectory-based analysis proposed by Helland-Hansen & Hampson (2009) is particularly useful in identifying subtle changes in depositional responses. These short-term changes do not substantially alter the average trajectory of the offlap break, so that even the wedge tracts recording them are included in the FSST. They are thought to record minor relative sea-level fluctuations punctuating the process of forced regression. The related, minor, internal unconformity surfaces bounding the shingled clinoform bundles (Figs 4, 14, 16) should not be mistaken for the "master" RSME surface (Regressive Surface of Marine Erosion) bounding the FS FT at its updip margin (Fig. 4). Similar small-scale sequences have been highlighted in dip seismic profiles of prograding terrigenous deposits (Bertoni & Cartwright 2005; Lobo et al. 2005).

The characteristic bioturbated horizon marked by dense, vertical *Ophiomorpha* shafts crossing the topmost part of the clino-bedded wedge (Figs. 4, 6), and indicated as Abd FT, is thought to record the "abandonment" stage after a progradational episode.

The Capodarso carbonates

Most of the skeletal carbonate deposits making up the carbonate lithofacies are grainstone and fine-grained rudstone, whereas packstone is subordinate. Grainstone cement is mostly heterogranular, and locally syntaxial around echinoid remains. Packing is usually dense, with evidence of compaction-induced collapse of particles (Fig. 11), particularly in serpulids and corallines, and local interpenetrating grain fabrics due to pressure solution, both indicating that carbonates entered the burial history as uncemented sediments. Conversely, the low degree of mutual grain interpenetration indicates relatively early cementation at shallow burial depths. Mouldic porosity is commonly observed in bivalves and gastropods, with voids generally filled by calcite spar (Fig. 11) and moulds outlined by very thin micritic envelopes. In addition to moulds, bivalve remains may show neomorphic fabrics, represented by pale brown inclusion-bearing spar, partially preserving the original shell microstructure (e.g., Caron & Nelson 2009), sometimes associated in the same skeleton with evidence of partial dissolution, leaving voids which may or may not host calcite precipitates. These various fabrics, ranging from mouldic voids filled with calcite to neomorphic fabrics, are interpreted as representing various degrees of aragonite transformation (Caron & Nelson 2009). Selective removal of aragonite skeletons prior to burial, due to seabed alteration processes, could therefore not have occurred to a significant extent. This may have been due to the rapidity of successive processes of production, transport and burial of skeletal material, which thus escaped prolonged exposure on the sea floor, an assumption also supported by limited evidence of bioerosion and encrustation.

Unconformity surfaces, particularly the topmost layers of clino-bedded units, lack evidence of either hardground formation on the sea floor or of subaerial exposure. This is indicated on the one hand by persisting evidence of compaction-induced collapse of particles in these layers, and by truncation of *Ophiomorpha* shafts, and, on the other hand, by lack of freshwater cements and rip-up intraformational lithoclasts in the overlying deposits.

Although Gillespie & Nelson (1997) and Smith & Nelson (2003), by means of carbon dating, demonstrated that a macerated appearance is not proof of the recycled nature of skeletons, we infer that the common association of fresh-looking biofragments with iron-stained and worn bioclasts and intraclasts showing variable degree of alteration, indicates mixing of fresh with exhumed skeletal material.

The carbonate factory

Carbonate production started developing on offshore shoals located on the submerged high of the growing thrust-cored Marcasita anticline. The growth of a positive structure, coupled with relatively high gradients of the sea floor were effective in focusing wave energy and diverting terrigenous sedimentation, thus creating ecologically suitable sites for loose grain-producing biota and the formation of widespread heterozoan carbonate blankets (Hayton et al. 1995; Henrich et al. 1995; James 1997; Caron et al. 2004). In conditions of accommodation loss, intense bottom winnowing by storm waves initially removed and swept away any fine-grained sediments, potentially exhuming coarse shell debris. This provided a suitable substrate for the carbonate factory to develop, and led to increasing rates of carbonate production (Caron et al. 2005). In this high-energy environment skeletal material was subjected to disarticulation and fragmentation, and was episodically exported basinwards. Destructive agents were mainly physical processes, as evidence of bioerosion is quite scanty. Judging from the limited numbers of epiphytic foraminifers in the composition of skeletal hash, it may be argued that seagrass patches were small, compared with open sandy bottoms in the area of carbonate production.

Active ramp margin progradation during forced regression expanded the width of the ramp top, thus enlarging and displacing the carbonate factory basinwards. The presence in the clino-beds of parautochthonous, non-fragmented shells of adult benthic forms (such as oyster clumps, pectinids and glycymerids) having a bathymetric range compatible with the inferred depth of the ramp top, does indicate that fully grown populations could develop there between successive resedimentation events. Prolific carbonate production is therefore thought to have been maximised in the falling stage, together with storm-induced periodic offshore export of both continuously forming and recycled skeletal material. Ultimately, grainy sediments which had been removed were stored on the frontal slope of the prograding clino-stratified body. As a result, the autochthonous skeletal component is largely subordinate with respect to allochthonous and parautochthonous material. In this setting, loss of information on the composition of the original communities is essentially the result of physical processes, including both breakdown and mechanical destruction of less resistant carbonate particles and subsequent selective sorting of particles during storm-driven displacement and mixing of grains derived from different sources.

Due to the overwhelming importance of hydrodynamic processes, leading to a compositionally quite uniform carbonate body, an ecologically-based subdivision into inner, middle and outer belts is hardly applicable to the studied example, except with reference to the peculiar depth of different physical processes. Specifically, the downramp transition from the proximal belt showing "climbing" progradation to the offlapping tract cannot be interpreted within the framework of ramp zoning, since it is essentially a response to relative sea level change.

Should the studied carbonate systems be considered ramps or simply prograding wedges? Actually, an important role of autochthonous organisms, leading to a definite carbonate productivity profile and an ecologically-based zoning is clearly missing in the investigated examples, due to the importance of reworking and introduction of derived material. The important point to be stressed in our opinion, however, is that distally steepened ramps in the sense of Pomar & Kendall (2007), are carbonate systems dominated by physical accommodation, commonly developing clino-bedded prograding wedges by shedding most sediment during sea-level falls or lowstands (see also Burchette & Wright 1992).

Interaction between tectonic and eustatic controls

The offlapping Capodarso sequence stack records the progressive tilting of the limb of the Marcasita anticline (Fig. 2) (Vitale 1996, 1998). The marked angularity between successive carbonate bodies, coupled with the progressive decrease in their dip angle, indicates that the blind thrust beneath the anticline was growing during deposition, with total tilt estimated at 5° by Lickorish & Butler (1996).

However, a subtle tectonic-driven effect is thought to have occurred even at the level of individual sequences. Gradual syndepositional rotation of fold limbs led to generation of accommodation space beyond the inflexion point, and concurrent loss of accommodation along the crest of the anticline. This is made clear by the amalgamation of the first and second carbonate wedges near the anticline crest (Vitale 1996, 1998) (Fig. 2), where the regressive surface of marine erosion at the base of the second body cuts into the first body. In addition, the creation of accommodation space beyond the fold inflexion point probably allowed the stratigraphic recording of high-frequency and low-amplitude base level fluctuations (Fig. 14), which are not registered in the inner belt, dominated by oblique clinoforms.

Although it is always difficult to disentangle the overlapping effects of tectonics and eustacy, the link of the forced-regressive wedges of the Capodarso sequences with eustatic sea-level falls is demonstrated by the fact that their internal architecture is maintained over both the cores of growth anticlines and synclines throughout the Enna-Caltanissetta piggy-back basin (Lickhorish & Butler 1996). Coeval stacks of carbonate bodies with similar stratal pattern, separated by mudstone intervals, also occur as a regional pattern across the foreland basin of southern Sicily, away from the thrust belt (Wezel 1965; Roda 1965, 1968), indicating that cyclicity is linked with a supra-regional process and is independent of tectonics. Therefore, the hypothesis that forced regressions were triggered by fold amplification may reasonably be ruled out. We are led to admit that periodic accommodation losses, although tectonically-modulated, were essentially triggered by eustacy. The amplitude of base level oscillations involved in the formation of the Capodarso cycles was estimated by Lickorish & Butler (1996) in the 30-50 m range.

Orbital and climatic forcing

The internal sequence architecture and sequence stacking pattern of the Capodarso succession reflect the response of the depositional system to changes in accommodation on several scales. The Capodarso Formation and the overlying Geracello Formation (Fig. 2) have respectively been interpreted as the carbonate-dominated Lowstand Systems Tract (LST) and the siliciclastic-dominated TST and HST of a fourth-order sequence, attributed to a ~400 Ka eccentricity cycle, approximately extending from 2.51 Ma to 2.1 Ma (Catalano et al. 1998; Colella & Vitale 1998; Vitale 1998). Although high resolution of biostratigraphic data (Di Stefano & Sprovieri, pers. comm., 2008) is unfortunately not available, the time-span involved in the basic cyclicity of the Capodarso Formation can be indirectly inferred. The HO (Highest Occurrence) of *Discoaster pentaradiatus* (2.52 Ma, approximately corresponding to the transition from Marine Isotope Stage 101 to 100) has been confidently identified in the siliciclastic mudstone of cycle 2. The upper cycles of the formation are ascribed to the lower part of the *Discoaster brouweri* Zone. The LO (Lowest Occurrence) of *Globorotalia inflata* (2.09 Ma according to Gradstein et al. 2004) has been identified in the upper part of the Geracello Formation, and is a reliable bio-event, occurring in outer-shelf to upper bathyal sediments rich in planktonic foraminifers (Di Stefano & Sprovieri, pers. comm. 2008). The time-span between these bio-events is 0.43 Ma. As this time-span includes a substantial interval of the Geracello Formation, it is reasonable to infer that the Capodarso Formation is made up of fifth-order sequences.

Orbitally-driven sea-level changes have been considered as the dominant forcing function for the Capodarso sequences by Lickorish & Butler (1996), Catalano et al. (1998), Colella & Vitale (1998), Vitale (1998), Roveri & Taviani (2003) and Massari & Chiocci (2006). Specifically, in a study of the upper Pliocene to lower Pleistocene marine record of the central Mediterranean, Catalano et al. (1998) concluded that individual parasequences can be correlated with 41 Ka obliquity cycles on the basis of high-resolution chronology. Obliquity forcing was confirmed for the interval between 2.8 and 2.3 Ma by Versteegh (1994) in a chronologically well-constrained palynological study of a Pliocene succession in Calabria (southern Italy) and by Haywick et al. (1992) and Naish & Kamp (1997) for the upper Pliocene to lower Pleistocene mixed siliciclastic-heterozoan carbonate cyclothems of New Zealand. Specifically, Naish & Kamp (1997) demonstrated obliquity forcing by means of biostratigraphy, magnetostratigraphy and the numerical ages of tephra layers. Raymo et al. (1989) also showed that glacio-eustatic changes during the Gelasian were controlled by obliquity, as indicated by the $\delta^{18}O$ record from North Atlantic DSDP Site 607, primarily reflecting changes in global ice volume. This was confirmed by Raymo & Nisancioglu (2003) and Raymo et al. (2006), who stressed that large ice volume changes at the precessional period are missing between ~3 and 1 Ma.

In conclusion, although the identification of specific orbital cycles in shallow-water, commonly gap-riddled sediments is generally equivocal and remains inferential (Fischer et al. 2009), the Capodarso sequences may reasonably be attributed to obliquity forcing, and small-scale internal cyclicity to higher-frequency phases of space accommodation/subtraction, due to repeated changes in the factors controlling the growth and the equilibrium profile of the platform. An important consequence is that progradation rates were probably extremely high, as progradation over a distance of 1.5-2 km may have occurred during a fraction of an obliquity cycle. Although accumulation rates do not correspond to production rates, the former differing in the various systems tracts and responding to the nature of dispersal processes and available accommodation, it does seem reasonable that high accumulation rates of sediment exported from nearby sources also required exceptionally high production rates.

The sharply transitional passage from the outer-shelf sediments of the Enna Formation to the relatively shallow-water Capodarso Formation is consistent with widespread evidence of a significant sea-level drop at about Marine Isotope Stage (MIS) 100, as documented by Raymo et al. (1989). The major climatic change recorded at this time in both the Atlantic Ocean (Mudelsee & Raymo 2005) and the Mediterranean (Sprovieri et al. 2006), is usually considered to mark the end of a cyclic but steady increase in northern hemisphere glaciation (Raymo et al. 1989; Mudelsee & Raymo 2005).

Becker et al. (2006) argued that concomitantly with the extension of glaciers and sea ice in the northern hemisphere, polar air masses expanded southwards, cooling the European continent during MIS 100 and subsequent glacial stages. They pointed out that the turnover near MIS 100 was accompanied by rapid changes in Mediterranean sea-surface temperatures, thermohaline circulation, and African dust supply, as a result of transmission of North Atlantic oceanographic and atmosphere changes by some combination of surface water inflow and Atlantic-Mediterranean atmospheric pressure gradients.

It seems reasonable to assume that the change from the siliciclastic-dominated Enna Formation to the carbonate-dominated Capodarso Formation reflects this major turnover. This is supported by the observation that the offshore siliciclastics of the Geracello Formation (inferred TST and HST of the fourth-order sequence), which overlie the bundle of carbonate wedges, may be correlated with the warming episode which lasted from 2.35 to 2.094 Ma (Lourens et al. 1996), as documented by pollen evidence from Europe (Suc 1984), and significant decrease in the $\delta^{18}O$, coinciding with the increased amplitude of insolation cycles and precession-driven increases in seasonality, precipitation and runoff in the Mediterranean (Lourens et al. 1996).

We believe that climatic control of a similar nature was active even on the scale of cyclical changes from terrigenous to carbonate sedimentation observed in the individual Capodarso sequences. In our opinion, they do not simply represent the Walther's Law effect of periodic lateral facies migration across the shelf in response to changing sea level. The influence of a dry vs. wet rhythm has been assumed as the factor modulating sedimentation in a number of studies on the upper Pliocene succession in southern Italy. Versteegh (1994) reconstructed an alternation of cool-dry and warm-wet climates with 41 Ka periodicity in the Mediterranean Pliocene between 2.8 and 2.3 Ma. A similar conclusion was reached on the basis of pollen assemblages and stable isotopes in southern Italy, which document the cyclic behaviour of vegetation at the beginning of the northern hemisphere glaciations, implying evolution from warm, humid interglacial stages to cold, dry glacial ones (Suc 1984; Rossignol-Strick & Planchais 1989; Combourieu-Nebout & Vergnaud-Grazzini 1991; Bertini 2003).

We therefore suggest that the greater efficiency of the Capodarso heterozoan carbonate factory occurred during glacial hemicycles marked by cooler, drier conditions (a certain aridity is supported by the presence of a silt-sized, well-sorted quartz fraction of inferred aeolian origin in LH and FS FTs), although glacial stages were probably recorded by a temperate-cool climate in the Gelasian of southern Italy. Decreases in sea surface temperatures and increases in the frequency and magnitude of storm events may be expected during these stages, and lead to intensified wave and geostrophic current action on the shelf, in turn augmenting turnover rates of shallow-water masses and the transfer of oxygen and nutrients to the sea floor (see also Roveri & Taviani 2003). These conditions may play a critical role in causing efficient winnowing and bypassing of fines and increasing the efficiency of heterozoan carbonate production (e.g., Schlager 2003).

Conversely, the change from carbonate to siliciclastic sedimentation in the Capodarso cycles probably occurred concomitantly with transition to a warmer climate, characterised by strong seasonal contrasts in humidity, enhanced rates of continental runoff, and more sluggish thermohaline circulation. These conditions probably caused terrigenous sediment input to exceed critical levels, thus leading to smothering and poisoning of the heterozoan association together with a fall in the hydrodynamic energy of the environment. A similar climatic modulation of heterozoan carbonate-siliciclastic cycles was assumed by Ferland & Roy (1997), Lukasik et al. (2000) and Feary et al. (2004).

Icehouse carbonate ramps

Read (1998) observed that typical features of icehouse ramps include limited width and significant gradients of the ramp top (from 30 cm/km to more than 1 m/km), due to high-amplitude sea-level changes, orbital control, and a tendency to the development of mixed carbonate-clastic cycles. He noted that high gradients of the ramp top may result in wave-dominated settings over much of the ramp itself, leading to widespread grainstone blankets, while the greater depth of the storm wave base in comparison with greenhouse ramps induces intense bottom winnowing which sweeps away fine-grained sediment. In addition, the ramps constantly attempt to equilibrate to the rapidly fluctuating water depths, which causes rapid lateral migration of lithotopes and depositional environments. Fourth-order sequences (lasting 100 to 400 Ka), consisting of shingled fifth-order progradational bodies separated by deeper-water facies are commonly generated (Read 1998). This contrasts with low-gradient greenhouse ramps, which are commonly several dozen km wide, and generate layer-cake successions with subtle clinoforms and long-term drowning events (Burchette & Wright 1992).

Examples comparable to the Capodarso carbonate bodies are known from submerged Pleistocene wedges which have been seismically investigated along the Mediterranean margins, particularly along the steep margins of the Tyrrhenian Sea (Chiocci & Orlando 1996; Chiocci et al. 2004; Massari & Chiocci 2006). Progradational bodies of mixed composition have been identified, commonly 10-30 m thick, containing abundant debris of heterozoan organisms and boreal faunas of glacial affinity. They extend for many kilometres parallel to the coast and up to a few km in the dip direction, and show oblique and sigmoidal clinoforms dipping consistently offshore at angles ranging from 4° to 20°. The wedges are particularly located where shelves are reduced or missing, with progradation commonly starting from tectonic or morphologic highs. The general architecture is controlled by the gradient of the substrate, which generally ranges from 0.5° to 2°. The largest and thickest bodies are found at depths between 100 and 150 m, and are interpreted to have formed during the last glacio-eustatic lowstand (Marine Isotope Stage 2), a conclusion supported by radiometric and biostratigraphic dating (Chiocci et al. 2004; Massari & Chiocci 2006). Younger bodies are remarkably smaller in size and formed during phases of substantial standstill of sea level which accompanied the overall sea-level rise since the MIS 2. The bodies are thought to have formed as entirely submarine, shore-detached wedges, at a depth controlled by the base level of storm waves. Redistribution of sediments essentially occurred in response to meteo-marine events of high energy generating downwelling currents balancing storm wave surges and carrying sediments offshore and alongshore. Chiocci et al. (2004) argued that this kind of wedges, poorly described in the literature, may be a characteristic feature of "Mediterranean" setting.

The comparison may be extended to other cases, from both the Plio-Pleistocene and Cenozoic to Palaeozoic icehouse times (e.g., Kamp & Nelson 1987; Kamp et al. 1988; Haywick et al. 1992; Sonnenfeld & Cross 1993; Brachert et al. 1996; Hanken et al. 1996; Ferland & Roy 1997; Naish & Kamp 1997; Catalano et al. 1998; Hansen 1999; Massari et al. 1999; Pomar et al. 2002; Feary et al. 2004; Caron et al. 2005; Piccoli & Simo 2005; Braga et al. 2006). Several examples describe relatively narrow wedges controlled by high-frequency, Milankovitch cyclicity, mostly developing from positive submarine features, and highlight the importance of heterozoan carbonate production, resedimentation and accumulation in downramp settings during periods of decreasing shelf accommodation, in some cases identified as corresponding with glacial stages. Piccoli & Simo (2005) specifically observed that transgressions and early highstands are preferentially characterised by homoclinal ramps, whereas distally steepened ramps are favoured by low accommodation conditions existing through the late highstand, falling stage and lowstand systems tracts.

The ecologically suitable sites for heterozoan carbonate production and ramp development are commonly described as topographic or structural positive submarine features, in areas characterised by long fetch and high sea floor gradients which prevent significant energy loss by impinging storm waves and favour the diversion of terrigenous sedimentation to the troughs and "exportation" of skeletal material (e.g. Nelson et al. 1982; Kamp & Nelson 1987; Nelson 1988; Hanken et al. 1996; Mutti et al. 1996; Pedley & Grasso 2002; Roveri & Taviani 2003; Beavington-Penney et al. 2005).

Conclusions

The upper Pliocene Capodarso succession is a forestepping stack of distally steepened ramps, showing a distinctive cyclic alternation of fine-grained terrigenous offshore units and heterozoan, clino-stratified carbonate wedges, consisting of generally well-sorted skeletal hash, prograding from a growing thrust-cored antiform. The biofacies, examined within the framework of the palaeoecologic and taphonomic attributes of the skeletal assemblages, proved to be important in identifying environmental processes and, together with analysis of stratal patterns and sedimentary structures, in characterising a number of facies tracts useful for distinguishing the basic elements of sequence stratigraphy.

Falling-stage processes are thought to have exerted critical control on overall ramp architecture, by favouring ramp progradation, increasing the size of the factory and creating a favourable setting for maximised production, redeposition and accumulation of carbonate. Progradation was dominated by high-energy dispersal processes triggered by episodic storm events, during which any fine-grained material was winnowed out, and skeletal material was easily lifted by storm waves and transported by downwelling flows, ultimately to be stored on frontal ramp slope.

Biostratigraphic data demonstrate that the siliciclastic-carbonate cycles are fifth-order sequences, most probably forced by obliquity. In addition, higher-frequency alternating phases of space accommodation/subtraction are recorded by the oscillating paths of the offlap break trajectory of clinoforms, due to repeated changes in the factors controlling the growth and the equilibrium profile of the platform.

In view of the inferred extremely rapid progradation, rates of accumulation and burial of skeletal hash were probably exceptionally high, as also indicated by the apparent lack of evidence of selective removal of aragonite prior to burial.

The most favourable conditions for high rates of benthic carbonate productivity and wedge progradation probably occurred during drier and cooler hemicycles correlated with glacial stages, characterised by vigorous atmospheric and marine circulation and increased frequency and magnitude of storm events, leading to intensified turbulent mixing in the water column and efficient winnowing of fines. Conversely, periodic "drowning" and demise of the heterozoan carbonate factory may have occurred as a result of the change to warmer and wetter interglacial climate, with terrigenous sediment input exceeding critical levels, leading to smothering and poisoning of the heterozoan association together with a fall in hydrodynamic energy of the environment.

Climatic-eustatic control of cycles resulted in rapid, continuous changes in environmental parameters. These in turn led to short-lived faunal communities, as climax communities generally had insufficient time to form.

Some features specific to icehouse ramps, partly inspired by Read's (1998) work, are tentatively identified by means of comparisons of upper Pliocene Capodarso carbonate bodies with other examples of ramps forming in icehouse times, as in the Permo-Carboniferous and Plio-Quaternary. Specifically: (1) enhanced atmospheric and thermohaline circulation during glacial hemicycles produces a high-energy wave climate with the increased frequency and magnitude of storm events, which presumably foster production and offshore resedimentation of heterozoan carbonate, to form conspicuously clino-bedded wedges; (2) during icehouse times homoclinal ramps (e.g., Fornos & Ahr 1997) are likely to form in interglacial hemicycles, whereas distally-steepened clino-bedded ramps are probably typical of glacial hemicycles, characterized by higher production and resedimentation of heterozoan carbonate; (3) carbonate factories commonly develop on topographic or structural positive submarine features, from which skeletal material is exported and resedimented on the ramp slope by storm-driven flows, leading to distally steepened ramps with storm-wave-graded profiles, generally shore-detached; (4) high-amplitude, orbitally-forced sea-level changes result in relatively brief, rapid episodes of progradation, and limited ramp width; (5) the short duration of forcing orbital cycles and the associated rapidity of sea-level changes imply that faunal communities are continually forced to adapt to frequent, rapid changes in environmental conditions, with the result that climax communities do not have sufficient time to form, as shown by the common high abundance and generally low diversity of faunal assemblages; (6) icehouse ramps are commonly superimposed to form ramp stacks consisting of mixed clastic-carbonate sequences, commonly with an ordered spectrum of distinct frequencies.

Although some of these comments may have general value, the above conclusions particularly concern the shelf-perched, relatively shallow-water icehouse ramps of Mediterranean settings.

Acknowledgements. We are deeply indebted to Francesco Vitale for field assistance and useful information on the stratal architecture of the Capodarso succession, to Rodolfo Sprovieri and Enrico Di Stefano for biostratigraphic data, to Daniela Basso for identification of red coralline algae, and to Alessandra Asioli for determination of foraminifers. The paper benefitted from reviews of a former draft by L. Pomar, C.S. Nelson and S. Longhitano, to whom the authors are deeply grateful for significant help in improving the text and refining interpretations. The paper was revised by C. G. St. C. Kendall and another anonymous reviewer, who are thanked for their suggestions and critical remarks. M. Gaetani, editor of the "Rivista Italiana di Paleontologia e Stratigrafia" is gratefully acknowledged for help in editing the work. The English was accurately checked by Mrs Gabriel Walton. Support in drawing and digital processing of figures was given by Nicola Michelon and Stefano Castelli. This work was supported by a grant from the Italian Ministry of University and Research (F. Massari, PRIN 2006) and the University of Bari (2005 and 2006 grants).

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