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The late Pliocene to early Pleistocene siliciclastic succession of western Emilia (northern Italy) forms part of the infill of the Po Plain-Adriatic foredeep, a collisional basin with active thrusting during deposition, and is characterized by 5-to-20-m-thick fining-upward sedimentary cycles. Late Pliocene cycles were deposited in an inner-to-middle shelf setting at the end of a long-term uplift-denudation cycle controlled by tectonics. Cycles are characterized by shell beds of biogenic origin, particularly abundant in the middle of each cycle. The stacking pattern of paleocommunities, with particular reference to their paleodepths, reflects that each cycle is the product of sea-level variation. In particular, early transgressive deposits are marked by a Nuculana *community, indicating a shelly-sand bottom of the inner shelf; late transgressive deposits and the condensed section are marked by a shelly bottom* Timoclea *community developed at times of lowered clastic input; highstand deposits are characterized by a muddy soft bottom* Pinna *community.*

The situation changed near the boundary of the early Pleistocene, when a new uplift-denudation cycle started, renewing sediment availability and increasing the slope of the nearby mountain front. Local climatic conditions periodically triggered the sudden delivery on the shallow shelf of large amounts of sediment through hyperpycnal flows and related turbidity currents generated by catastrophic river floods. Sandy shelfal lobes form the lower reaches of the delta front. These are characterized by densely packed shell beds and the occurrence of echinoderm obrution deposits. Recurring sedimentological assemblages from sandstones, characterized by the sandy bottom Spisula *and* Ditrupa *communities, and* in situ *faunas from intervening mudstones, characterized by the muddy-bottom, hypoxic* Arctica *(and* Corbula *?) community, suggest that the lower part of a cycle formed during deglaciation following glacial maxima, at times of high input of freshwater and river-borne nutrients and high summer pelagic productivity. Mudstones from the upper part of the cycle, with dispersed remains of the muddy-bottom* Venus *community, indicate return to full interglacial conditions and to humid, low seasonality climates. Thus, early Pleistocene cycles could be correlative to sapropel-non sapropel cycles typical of the eastern Mediterranean deep water successions. Moreover, the western Emilia fossil and sedimentary records suggest that cyclic deposition was controlled by factors other than eustasy, providing a case study for future sequence stratigraphic modeling in active tectonic settings.*

INTRODUCTION

Taphonomy and paleoecology are tools for reconstructing changes of past environments and depositional dynamics. The wide acceptance of the sequence stratigraphic model, as originally formulated and subsequently developed by the Exxon school (Posamentier et al., 1988; Van Wagoner et al., 1990), focused on lithofacies analysis and high-resolution stratigraphy of fossil-bearing shallow-water successions, has led these two disciplines towards sequence stratigraphic-oriented applications (e.g., Beckvar and Kidwell, 1988; Banerjee and Kidwell, 1991; Benvenuti and Dominici, 1992; Abbott and Carter, 1997). Sequence stratigraphy stresses the role of eustasy in shaping depositional sequences and interpretation of the stacking pattern of shell beds and fossil communities observed in fossil-bearing successions. Thus, recurrence of shell beds and fossil associations mainly is regarded as the outcome of sea-level fluctuations and related parameters (e.g., sedimentation, oxygenation, etc.; Brett, 1995, 1998; Abbot and Carter, 1997). However, available literature on sedimentary successions from collisional margins shows that tectonic control on subsidence and sediment supply may lead to deviations from the sequence stratigraphic model (e.g., Mutti and Sgavetti, 1987; Milliman and Syvitsky, 1992; Mutti et al., 1996). This also applies to other active tectonic settings (e.g., Surlyk et al., 1993). In addition, similar deviations can be caused by climatically driven changes in sediment supply (e.g., Martinsen, 1990; Weltje and de Boer, 1993; Blum et al., 1994). Nevertheless, little effort has been made by paleontologists to sort out the tectonic and climatic controls that may cyclically affect the formation of shell beds and the nature of benthic communities.

This paper presents the results of a taphonomic and paleoecologic study conducted on a semi-enclosed basin, the paleo-Adriatic, forming part of a collisional margin. The depositional time interval, the late Pliocene and early Pleistocene, is marked by important climatic and eustatic changes and registers a local phase of thrust propagation. Previous studies (Mutti, 1996; Molinari, 1997) suggest that shallow-marine deposition is controlled by the interplay of tectonic, climatic, and eustatic factors. The aim of the study is to verify whether shell beds and benthic paleocommunities can help to unravel the tectonic and climatic influence on deposition, as compared to the pattern expected from simple sea-level variations.

GENERAL SETTING

Climate and Water Circulation in the Paleo-Adriatic Sea

The Adriatic Sea is an elongate and narrow, semi-enclosed sea subdivided into a north-central shelf province

and a southern basin (Rebman, in Stanley, 1972). Marine processes are strongly influenced by the continental climate of surrounding land masses. Summers are warm, winters cold and dry, and precipitation is concentrated in the spring and fall. High summer evaporation and winter convection under the action of cold and arid winds from the northeast trigger the formation of deep currents that ensure oxygen renewal to the bottom (Zore-Armanda, 1963; Lacombe and Tschernia, 1972). Currents from the Adriatic flow at depth southwest into the Ionian Sea, bringing warm and oxygenated waters into the eastern Mediterranean. At the end of the last deglaciation (7–9 ky BP), organic carbon-rich sediments (sapropel) accumulated in the eastern Mediterranean (Thunnel and Williams, 1989; Myers et al., 1998, and references therein). It is generally agreed that, during sapropel formation, bottom waters were dysoxic. Sea surface salinity was greatly reduced due to high freshwater fluxes. Seasonality and river runoff increased following maxima in Northern Hemisphere summer insolation due to precessional forcing of the African monsoon (Rossignol Strick et al., 1982; Rossignol Strick, 1985; Rohling, 1994). The hypothesis of humid interglacials and arid glacials is confirmed by paleontological, geochemical, and palynological data from late Quaternary successions of the eastern Mediterranean (Schmiedl et al., 1998, and references therein).

Regularly spaced sapropel beds occur in late Pliocene and early Pleistocene sediments of the Mediterranean region. Conditions comparable to those occurring during the higher amplitude mid- and late Pleistocene climatic oscillations also characterized the late Pliocene and the early Pleistocene. Patterns of planktonic foraminiferal faunal change in the Mediterranean between 2.8 and 1.2 Ma reveal 41-kyr, obliquity-related variability related to glacial cycles (Lourens et al., 1992, 1996). During this interval, sapropel formation coincides with maxima in summer temperatures and decreased winter insolation (i.e., high seasonality), maxima in productivity connected to increased input rates of river-borne nutrients, and minima in $\delta^{18}O$.

Geological and Stratigraphical Setting

The late Pliocene to early Pleistocene succession outcropping in western Emilia forms part of the northwestern extension of the paleo-Adriatic sea. This area was a satellite basin of the Po Plain foredeep, a complex foredeep in continuity with the north-central Adriatic basin, with deep-seated active thrusts (Fig. 1A). Several basin-wide, unconformity-bounded sedimentary cycles, recognized from the Apennine outcrops to the subsurface of the Po Plain and the central Adriatic, characterize the basin infill (Fig. 1B,C; Ricci Lucchi et al., 1982; Pieri, 1983; Ricci Lucchi, 1986; Ori et al., 1986). The late Pliocene sequence (P_2) is a regressive succession marked by the transition from outer shelf to inner shelf deposits. At approximately the Pliocene-Pleistocene boundary, marked in the Mediterranean by the arrival of cold boreal immigrants such as the bivalve *Arctica islandica* (Raffi, 1986; Ricci Lucchi, 1986), local uplifts during a tectonic phase produced marginal unconformities. Sequence Qm (acronym for "Quaternary marine," early to mid-Pleistocene) is formed by shelfal, nearshore, and transitional deposits in a shallowing-up-

ward trend. Seismic reflection profiles show that Qm is transgressive over sequence P_2 in marginal areas of the foredeep (Fig. 1C; see also Pieri, 1983; Ricci Lucchi, 1986; Ori et al., 1986; Di Dio et al., 1997). Qm is topped by a weathered erosional surface representing a regional unconformity of tectonic origin and is, in turn, overlain by a mid-Pleistocene continental sequence (Qc). Smaller unconformities permit Qm to be divided into sequences Qm_1 (early Pleistocene), Qm_2, and Qm_3 (middle Pleistocene; Amorosi et al., 1998a, b).

Two sections have been studied from the outcrops of the Arda and Stirone valleys, about 8 km apart in an E-W direction (Fig. 1B). Facies analysis was carried out in the upper part of sequence P_2 and in sequence Qm_1 (Fig. 2; Molinari, 1997; Dominici and Molinari, 1997). Chronostratigraphy for the upper Pliocene is based on correlations with the Rio Riorzo outcrop from the Arda area, studied and dated by Monegatti et al. (1997), that shows striking lithofacies similarities with the upper P_2 of the Stirone area. The base of Qm_1 is placed in both sections at the first appearance datum of *Arctica islandica*. The Qm_1-Qm_2 bounding surface is placed at the base of fluvial and lagoonal deposits typical of Qm_2 of the Stirone area, and correlative deposits of the Arda area (Fig. 2).

Small-scale Sedimentary Cycles

Sedimentary cycles, characterized by littoral, lagoonal, and alluvial deposits, have been described in the upper part of sequence Qm and interpreted as mid-Pleistocene (0.9–0.65 Ma) depositional sequences formed during eustatic cycles of 100-ka periodicity (Amorosi et al., 1998a). Small-scale sedimentary cycles are present both in the upper Pliocene and the lower Pleistocene. Unfortunately, the lack of detailed biostratigraphic and magnetostratigraphic control (see Mary et al., 1993; Iaccarino, 1996; Monegatti et al., 1997) prevents their correlation with known isotope stages.

The basal part of the Stirone succession (Fig. 2) and the upper part of the Rio Riorzo outcrop (Monegatti et al., 1997, also shown in Fig. 2) exemplify the development of upper P_2 cycles. Each cycle is about 20 m thick, fines upward, and is characterized by: (1) a basal sandstone facies, (2) a bioturbated calcareous silty sandstone, (3) a fining-upward shelly interval, and (4) an upper mudstone facies. The boundary of a cycle is either sharp or gradual. The basal sandstone has a coarser grain size and a lower degree of bioturbation with respect to under- and overlying deposits.

Small-scale Qm_1 cycles are well developed in both areas. In the Arda area, three lower cycles, with an overall thickness of about 40 m, are interpreted to onlap on the P_2-Qm_1 unconformity to the East (Fig. 2). Basal Qm_1 surfaces also are seen from seismic reflection profiles to onlap towards the south (Fig. 1C), suggesting that the Salsomaggiore area was a positive, and possibly emergent, relief during the deposition of the lower part of Qm_1. The upper part of Qm_1 is laterally continuous, about 45 m thick in the Stirone section and 70 m thick in the Arda section. Four cycles are recognized; they are 5–20 m thick and separated by sharp, unweathered surfaces. From bottom to top these cycles are formed by four lithofacies. Facies 1 is characterized by 5-15-cm-thick cross-bedded or massive sandstones
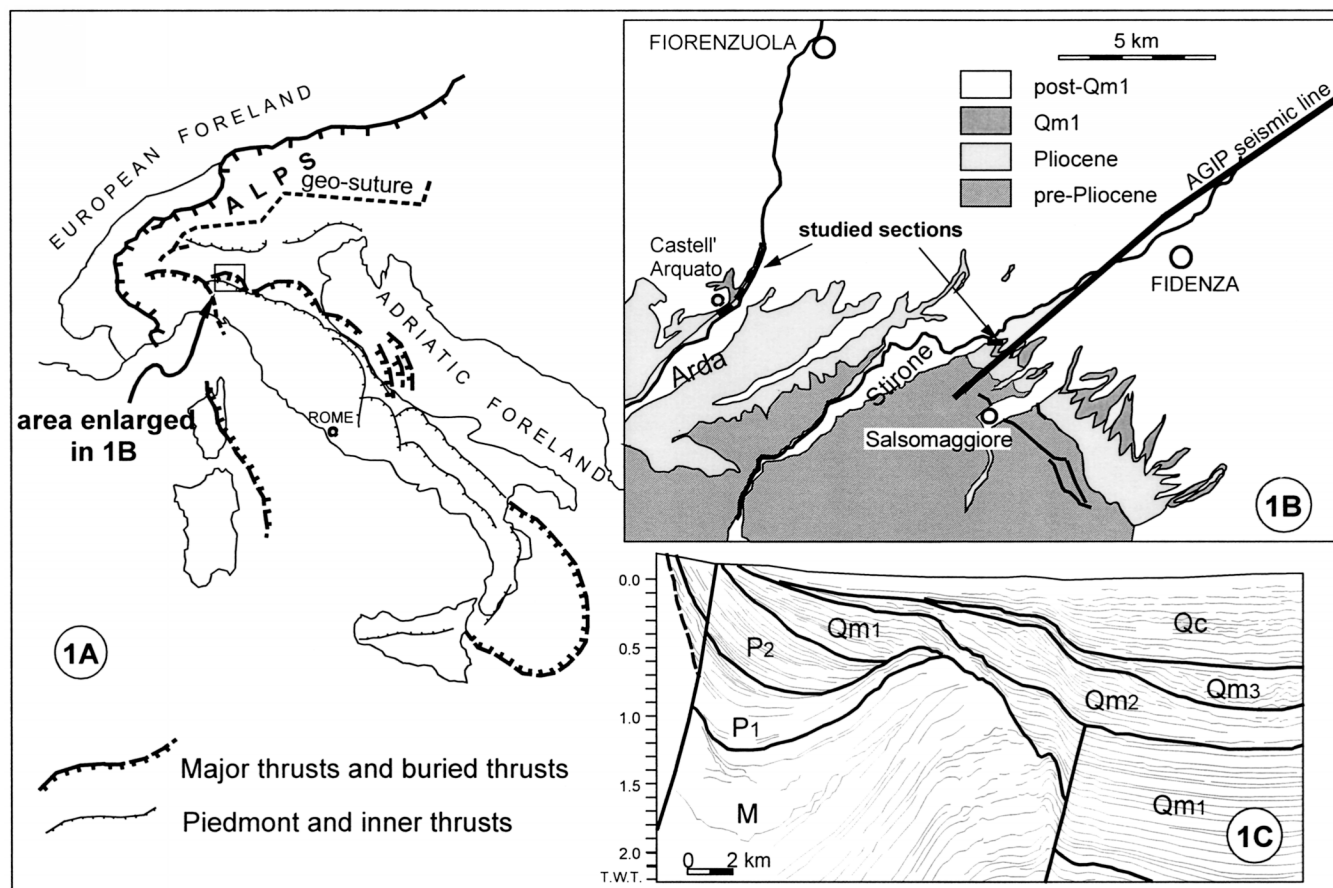
FIGURE 1—General location and geology of western Emilia. (A) Structural sketch map of Italy. The boxed area shows the apenninic side of western Emilia, in the northwestern extension of the Po Plain-Adriatic foredeep (modified after Ricci Lucchi, 1986). (B) Geological map of the western Emilia Apennine foothills. The Arda and Stirone sections are shown by dashed lines. Note the approximate location of the AGIP seismic line shown in C, and the inverse faults east of the Salsomaggiore village. (C) AGIP seismic line. The line cuts at approximately right angles the piedmont thrust outcropping east of Salsomaggiore, and the buried thrust located northeast of Fidenza (see Fig. 1B; modified after Di Dio et al., 1997).

with rip-up clasts and shell debris, planar- and ripple-laminated fine sandstones and/or fine sandstones with hummocky cross stratification (HCS). Sandstones are either minimally or not bioturbated (e.g., isolated *Ophiomorpha* and? escape structures are recovered in otherwise unbioturbated sandstones). Shell beds are abundant and form accumulations of transported mollusc shells mixed with mudstone rip-up clasts. Facies 1 alternates with facies 2, which is dominated by massive or small-scale cross-stratified, centimeter-thick, fine sandstones interbedded with mudstones. Shell beds often are present, either at the base of the sandstone beds, or intercalated with mudstones. Facies 3 is a fining-upward bioturbated sandstone or siltstone, sometimes topped by a shell lag. Facies 4 is a 1-to-6-m-thick bioturbated mudstone. Sandstone facies (facies 1 and 2) may be overlain abruptly by the mudstone facies (4). Upper Qm_1 cycles are asymmetric, the sandstone members forming the thickest part. A survey of the literature suggests that Qm_1 marine cycles can be traced throughout western Emilia, to the west (Molinari, 1997; Taviani et al., 1997) and east of the study area (Pelosio and Raffi, 1973; Iaccarino and Monegatti, 1996; pers. observ.). Sandstones pinch out in eastern Emilia (see Annovi et al., 1979), while isolated shell beds within thick mud-

stone successions occur in equivalent stratigraphic position further east (see Amorosi et al., 1998b). Thus, towards the east, cycles are expressed as progressively thicker and muddier sequences.

No attempt has been made so far to frame P_2 and Qm_1 cycles within a sequence stratigraphic context. The cyclothemic nature of sequence P_2 has been recognized in various parts of the Apenninic foredeep and interpreted as the product of high-frequency fluctuations of sea level (Ricci Lucchi, 1986; Monegatti and Raffi, 1996). Sedimentologic data suggest that Qm_1 cycles were formed through changes of clastic input controlled by cyclic tectonic and climatic change (Mutti, 1996; Molinari, 1997). The sandstones are shelfal lobes deposited in a shallow marine basin by hyperpycnal flows and related turbidity currents generated by catastrophic river floods. These sandstones form the seaward extension of fan-delta systems essentially built by catastrophic floods that occurred when large volumes of water were generated as the result of heavy rain fall, ice and snow melt, or the failure of naturally dammed lakes (Mutti et al., 1996, 1998). In this hypothesis, the upper part of each cycle would represent a return to normal, muddy deposition in an inner-shelf setting, during climatic conditions similar to the present day.
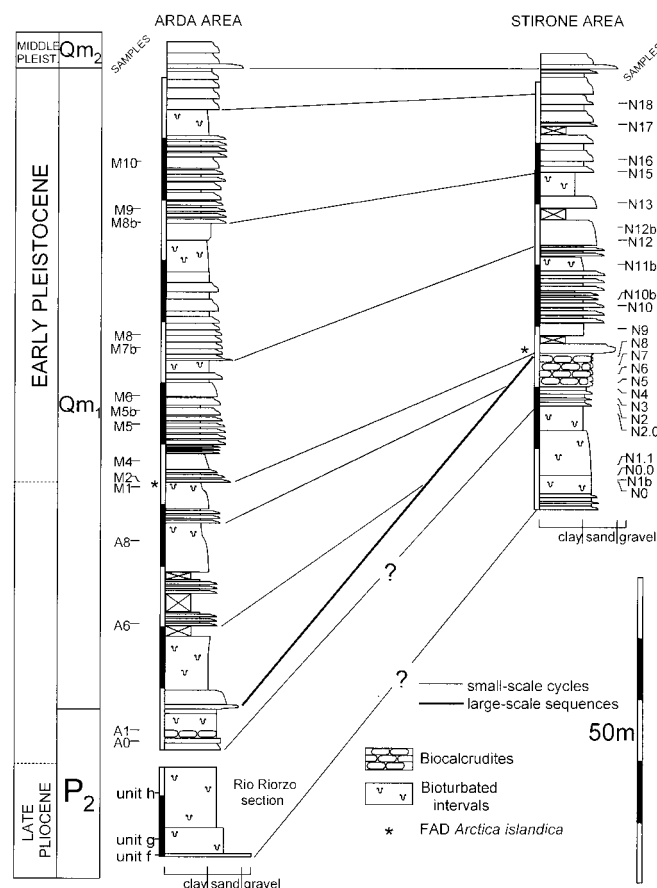
FIGURE 2—Stratigraphic sections from sequences P_2 and Qm_1 in the Arda and the Stirone areas. Positions of samples are indicated. The meters-thick fining-upward sedimentary cycles within the upper part of sequence P_2 and sequence Qm_1 are correlated between the two sections. The uppermost late Pliocene cycle of the Rio Riorzo section, located 2 km west of Castell'Arquato (see Fig. 1B), is shown at the bottom of the Arda section. The paleoecological study of Monegatti et al. (1997: their units f-h) formed the base used here for the tentative correlation with the Stirone section. Lowermost Qm_1 cycles onlap on the tectonic unconformity at the top of the Pliocene. The base of the early Pleistocene is placed at the FAD of *Arctica islandica.* The dating of the late Pliocene is based on data from Monegatti et al. (1997).

METHODS

The taphonomic study described herein employed the classifications of Kidwell et al. (1986) and Kidwell and Holland (1991) for field description of bioclastic fabric (bioclast orientation, articulation, packing, and sorting), as well as shell-accumulation geometry and internal structure. Fossil preservation was estimated through the analysis of bioclast abrasion, bioerosion, and encrustation from sampled shelly material. Taphonomic analysis also was conducted on the echinoderm Lagerstätten housed at the Museum of the Università di Parma, collected in Qm_1 sandstones from the Stirone section (Pelosio and Raffi, 1977; Pelosio, pers. commun.; 1996; recent surveys failed to record new occurrences, although asteroids and ophiuroids are reported by Iaccarino and Monegatti, 1996, in nearby outcrops). The degree of time-averaging was estimated through a comparison with time-scales proposed by

Kidwell and Bosence (1991) for coastal and shelfal shelly assemblages.

Bulk samples (0.5 liters) were collected in major shell beds to document taxonomic composition. The vertical spacing between samples varied from 1–2 m along intervals with better developed P_2 and Qm_1 cycles, to 5–20 m in other parts of the sections (Fig. 2). Each sample was washed through a 1.0-mm-mesh sieve, and coarse residues were picked. The taxonomic composition of the residue was determined for paleoecological analyses. A half-liter sample was considered diagnostic of a given shell bed if it contained at least 300 specimens. If this was not the case, a second sample was analyzed and so on, until either 300 specimens or a two-liter volume was reached (in the majority of the collections N = 300–1500 specimens; otherwise, 70<N<300). Bulk samples from mudstones were difficult to wash and contained very few specimens; hence, they were excluded from numerical treatments.

Twenty-three shell beds were sampled in the Stirone section and 15 in the Arda section, for a total of 38 collections. The residues include molluscs (the most abundant fossils), bryozoans, echinoids, brachiopods, corals, calcareous algae, and serpulids. Two hundred and thirty-five taxa (229 species of molluscs) have been recognized at this stage of the analysis. The total number of individuals is 22,725. The abundance of bryozoans, rodoliths fragments, and echinoderms spines and plates was evaluated on a semi-quantitative scale, and not included in cluster analyses. The bryozoans were described following the morphological approach of Bone and James (1993). Collections are deposited in the Museo di Geologia e di Paleontologia of the Università di Firenze. The complete macrofossils dataset is available from the author on request.

To facilitate the recognition of recurring associations, Q-mode and R-mode cluster analysis was executed on the data matrix, performed with a SPSS+PC package. The total number of taxa recognized in the first step was reduced to 93 by grouping rare taxa into higher order units (i.e., genera or families). This made the matrix size manageable for the software used, with 38 rows (collections) and 93 columns (taxa). Abundance of each taxon was converted into percentage within a given sample to make the clustering independent on the size of the collections. Q-mode analysis groups collections of comparable taxonomic composition, whereas R-mode analysis groups taxa that co-occur within assemblages. Of all the iterations tested during cluster analyses, the most easily interpreted Q-mode dendrogram was achieved using Ward's method of Minimum Variance (distance metric Euclidian distance), whereas the best R-mode dendrogram was obtained using the Average Linkage (distance metric 1-Pearson correlation coefficient). Indices of diversity were measured by use of the Shannon-Weaver Index and equitability (Dodd and Stanton, 1990).

TAPHONOMY OF MACROFOSSIL ASSEMBLAGES

Three main types of shell concentrations have been recognized and described (Table 1). Type 1 shell beds are characterized by shells of varying sizes dispersed in fine sandy (Type 1a) or muddy matrix (Type 1b). In these concentrations, many bivalves and spatangoid echinoderms are found in life position, or with their skeletons articulated; specimens always show little or no alteration. Type 1a

TABLE 1—Taphonomic attributes of shell beds. Descriptive terminology according to Kidwell et al. (1986) and Kidwell and Holland (1991).

Shellbed type	Biofabric			Geometry	Internal structure	Alteration	Assemblage type	Concentration type
	Orientation	Packing	Size sorting					
1a	Life position	Dispersed	Unsorted	Irregular	None	Fresh shells	Autochthonous and parautochthonous	Mostly biogenic
1b	Life position	Dispersed	Unsorted	Irregular	None	Fresh shells, some exceptional preservation	Autochthonous and parautochthonous	Biogenic
2	Mostly concordant, some oblique and perpendicular, nested shells	Both loose and dense packing	Poorly sorted	Pods and thin lenses	Complex	Abundant bioeroded bioclast, some encrustation. Some pristine shells	Parautochthonous	Biogenic
3a	Concordant, convex-up shells some oblique imbrication, stacked shells	Dense packing	Unsorted Bimodal Unimodal	5–20 cm beds, thin beds, lenses	Complex	See Table 2	Allochthonous	Sedimentologic
3b	Concordant, convex-up shells, some articulated shells	Loose and dense packing	Sorted	Pavements	Simple	See Table 2	Allochthonous	Sedimentologic

beds are often punctuated by isolated pods of densely packed biofabric, or by thin shell pavements. Type 1b beds are up to several meters thick. Type 1b assemblages, with large specimens of *Arctica islandica* in life position, were found in 10-to-15-cm-thick mudstones interbedded within Qm_1 sandstone intervals (Fig. 3A).

Type 2 shell beds are 5–15 cm thick and have irregular boundaries; fossils are unsorted and loosely packed in a silty sand matrix, or densely packed and nested, within pods connected in complex microstratigraphies (Fig. 3B).

Although bivalves, regular and irregular echinoids, cemented epibenthos, and brachiopods locally are found in life position, most bioclasts are disarticulated, randomly oriented, and more or less altered by bioerosion and encrustation.

Type 3 shell beds include all skeletal accumulations associated with sedimentary structures. Type 3a shell beds are densely packed accumulations of disarticulated shells, mixed to various degrees with mud rip-up clasts and fine gravel (Figs. 4A–C). Accumulations are 5–20 cm thick and
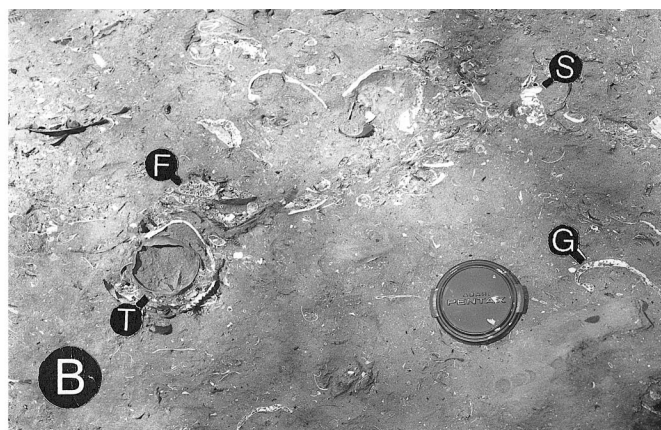
FIGURE 3—Types of biogenic shell beds. (A) Mudstone with a monospecific association of *Arctica islandica* in life position (arrows). The large arrow points at a specimen showing the empty interior of the valves. The match box is 6 cm (Qm_1, Stirone section, shell bed Type 1b). (B) Completely bioturbated silty sandstone (sample N0, large-scale sequence P_2, Stirone section) with loosely packed shell bed and pockets of densely packed shells (shell bed Type 2). The assemblage is characterized by encrusters, like *Flabellum* (F) and serpulids (S), and by reclining epibionts, like *Glycymeris* (G) and *Terebratula* (T). Lens cap is 5 cm.
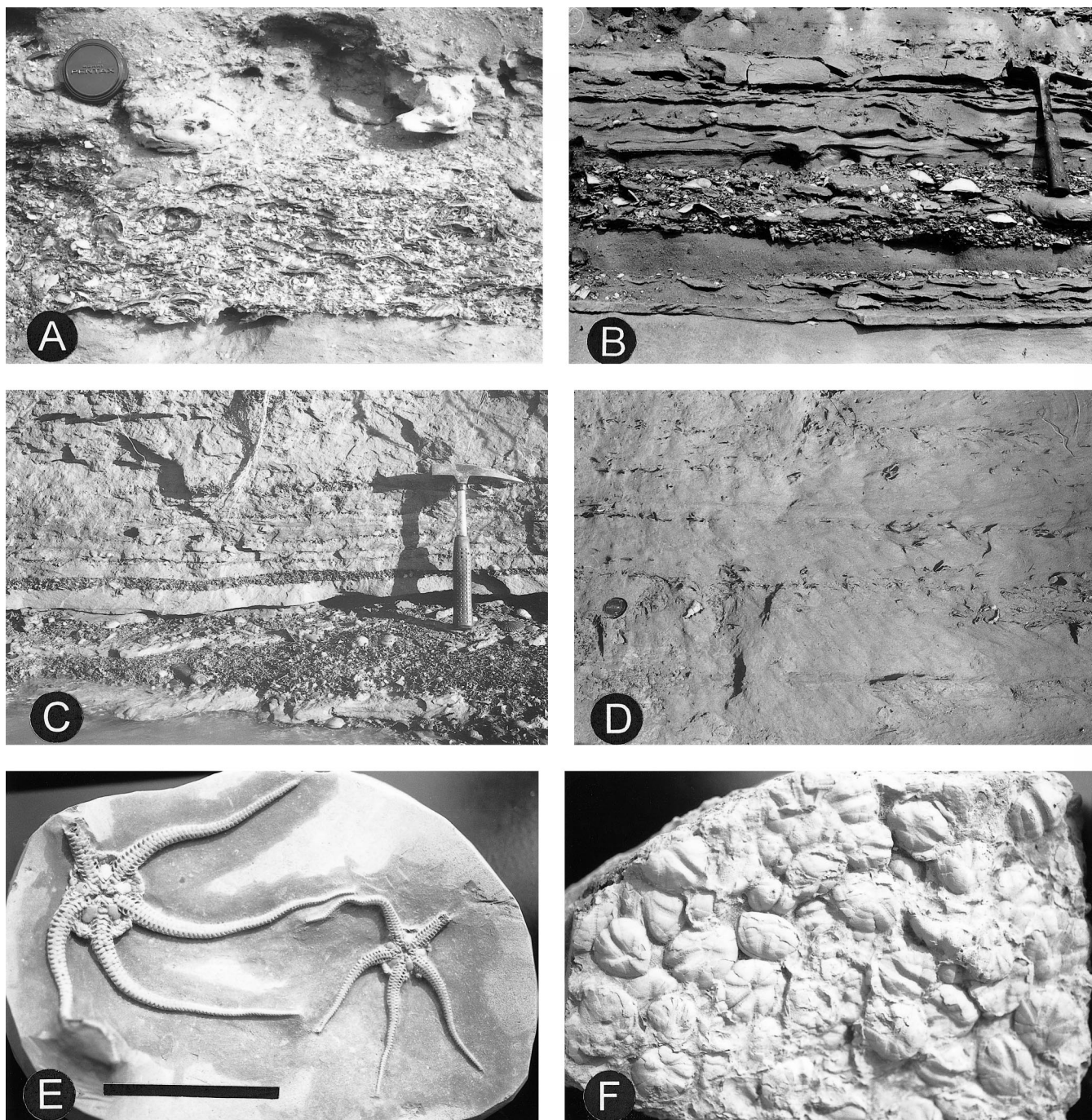
FIGURE 4—Types of sedimentological shell beds and echinoderm obrution deposits. (A–C) Densely packed sedimentological accumulations from the Qm_1 of the Arda section (shell bed Type 3a). (A) Shell bed (sample M5b) characterized by the abundant remains of *Corbula gibba,* forming the base of a graded shelfal lobe sandstone. (B) Shell bed with disarticulated valves of *Arctica islandica* (large white valves). These are scattered within a high-diversity assemblage dominated by *Spisula subtruncata,* transported from well-oxygenated nearshore sandy bottoms, and mixed with the remains of the hypoxic muddy bottom fauna. The shell bed is interspersed with abundant mudstone clasts from a high-density turbidity current, and is abruptly overlain by laminated and rippled fine sandstones deposited during the waning phase of the turbidity current. Hammer handle is 16 cm. (C) Shell beds with valves of *Arctica islandica* and shell debris intercalated through sharp contacts with mudstones, in a thinning-upward succession. Hammer handle is 16 cm. (D) Shell pavements in horizontal-plane laminated fine sandstones (Qm_1, sample M4, Arda section; shell bed Type 3b). (E) *Ophiura texturata* (aboral view) from a museum collection (Qm_1 deposits, Stirone section). The two specimens rest on a fine sandstone with climbing ripple lamination. Bar is 5 cm long. (F) Qm_1 mudstone slab (Stirone section) with densely packed specimens of *Echinocardium cordatum.* The unusual concentration of specimens of this infaunal species could have been caused either by a turbidity current or by mass migration to the surface during a hypoxic event. Ruler on the right is 10 cm long.

TABLE 2—Taphonomic signatures and interpretations of Type 3 shell beds.

	Abrasion	Articulation	Colour	Encrustation and bioerosion	Taxonomic composition and environmental significance
Signature 1	Fine details of ornamentation preserved	*Glycymeris insubrica,* echinoderm plates	light gray, some remains of original colours	none	High-diversity assemblage from nearshore, sandy bottom community (*Spisula subtruncata, Glycymerys insubrica, Ensis ensis, Chamelea gallina, Tellina* spp. etc.)
Signature 2	Moderate to heavy abrasion, rounded fragments	none	black shells	Incrustation by membraniporiform bryozoa and serpulids; trace fossils: *Polydora, Entobia, Gastrochaenolithes*	High-diversity assemblage from various nearshore and inner-shelf communities (*Aequipecten opercularis, Spisula subtruncata, Bittium reticulatum, Turritella tricarinata, Glossus humanus* etc.)
Signature 3	Some light dissolution on outer surface of bivalves, otherwise fresh appearance	*Corbula gibba, Arctica islandica*	black or gray shells	none	Low-diversity assemblage from hypoxic, muddy bottom community (*Arctica islandica, Corbula gibba*), or lower shoreface-inner shelf community (*Aequipecten opercularis*)
Signature 4	Fine details of ornamentation preserved	none	white shells	none	Low-diversity assemblage from inner shelf muddy bottom community (*Venus multilamella, Turritella tricarinata*)

rest on erosive surfaces. The upper boundary can be gradational (i.e., the shell bed grading upward to a fine or medium sandstone; Fig. 4A) or sharp. In the latter case, it is capped by a fine sandstone bed with either planar-lamination, low-angle cross-lamination, or rippled-lamination (Fig. 4B), or directly by a mudstone (Figs. 4C). Structures associated with the sandstone facies include plane lamination, form-discordant ripples (Fig. 4B), and climbing ripples in-drift (Molinari, 1997). Shells are concordant and convex-up, with rare oblique imbrication. Some beds show a complex internal structure, with layers of large shells and rip-up clasts alternating with layers of minute fragments (Fig. 4B). Bimodal size distributions are common (Fig. 4A, B). Type 3b shell beds are horizontal to gently dipping shell pavements associated with plane-laminated and/or low-angle cross-laminated fine sandstones (Fig. 4D), or hummocky-cross stratification (Molinari, 1997). Shells are usually concordant and convex-up.

Bioclasts in type 3 shell beds show various degrees of alteration (Table 2), including the following taphonomic signatures: (1) fresh, occasionaly still articulated, shells with remains of the original color; (2) heavily encrusted and/or abraded black shells; (3) pristine or little altered black or gray shells; and (4) white shells with well-preserved ornamentation.

Echinoderm *lagerstätten* are found on top of rippled, very fine sandstones sharply overlying Type 3a shell beds. The fauna, composed by specimens of *Astropecten irregulare, Ophiura albida,* and *O. texturata* (Fig. 4E), is considered a sedimentological accumulation. Due to its pristine state, it is included in taphonomic signature 1. The collection contains a mudstone slab with a dense cluster of *Echinocardium cordatum,* that could be either included in Type 1b or Type 3a shell beds (Fig. 4F).

Mode of Shell-bed Formation

The overall preservational state of the bioclasts of Type 1 accumulations reflects rapid burial under high net rates of sedimentation. Assemblages are considered biogenic, autochthonous to parautochthonous, and within-habitat time-averaged. Time involved in shell bed formation is estimated to be 0.01–0.1 kyr.

The highly irregular shapes of Type 2 shell beds likely were produced by the activity of burrowers, suggesting a biogenic origin for these concentrations. The high degree of bioerosion and encrustation indicates long residence time on the sea floor and low-net sedimentation rates. Type 2 shell beds are interpreted as biogenic, parautochthonous assemblages formed on the shelf during times of sediment starvation. They may occur along facies boundaries, separating bioturbated sandstones (Type 1a assemblages) from mudstones or siltstones (Type 1b assemblages), where they represent environmentally condensed assemblages formed during transgression. Otherwise, they are interpreted as within-habitat concentrations. Time spans involved in their formation are estimated in the range of 0.1–10 kyr.

Such features as the concordant and convex-up orientation of valves, the presence of imbricated shells and rip-up clasts, and the association with current ripples (Molinari, 1997) indicate that Type 3 shell beds formed under the action of unidirectional currents. Large mudstone clasts and shells were eroded from the seafloor by the current and concentrated in traction carpets (Type 3b). Pulses during the event led to amalgamation of more shell layers in thicker beds (Type 3a, Fig. 4C). Sand was deposited under a subordinate oscillatory component, producing planar or gently-dipping, hummocky lamination, and wave-ripple

laminae. Mud settled from suspension, sealing the shell bed-sandstone couplet, or the shell bed directly, in which case the lack of intermediate grain sizes indicates sediment bypass. This idealized facies sequence, and the shelfal context, are diagnostic of a waning turbidity current. This hypothesis is supported by the interpretation of the taphonomic signatures, as compared with the results of the paleoecologic analyses (Table 2). In fact, these prove that the turbidity currents gathered shells from at least four different sources: (1) contemporaneous, nearshore communities; (2) time-averaged nearshore and/or inner-shelf death assemblages; (3) muddy bottom, fossil assemblages from older cycles; and (4) contemporaneous, hypoxic, muddy bottom communities. The co-occurrence of bioclasts from possibly contemporaneous, nearshore (signature 1) and inner-shelf communities (signature 4) is indicative of travel distances on the order of a hundred meters to kilometers. Moreover, the occurrence of shell beds abruptly overlain by less fossiliferous sediments associated with exceptionally well-preserved asteroids and ophiuroids matches an echinoderm obrution model (Rosenkrantz, 1971, and references therein; Seilacher et al., 1985). The rapid influx of fine sediments carried in suspension by turbidity currents buried the local fauna ("burial layer": Brett, 1990). Echinoderms could not escape from the burial layer, perhaps because mud clogged the ambulacral system, and quickly died by smothering (cf. Brett and Seilacher, 1991). The deposition of fines during the waning phase was responsible for entombment. Shelfal turbidity currents are conspicuously ineffective in modern settings, and models rely on geologic examples. These include the storm-surge model (Hamblin and Walker, 1979) and the catastrophic river-flood model (Mutti et al., 1996). Storm surges are improbable causes to be invoked, because the Adriatic Sea is out of the latitudinal belt for hurricanes or tropical storms. On the other hand, modern small Apennine rivers are capable of producing hyperpycnal plumes (Mulder and Syvitsky, 1995). Accordingly, Type 3 shell beds are geologically instantaneous accumulations (hours to days), while the complex mixture of contemporaneous shells from the nearshore and the inner shelf, with relict shells, suggests mixing of ages, the latter ranging from zero (animals buried alive) to perhaps 100 kyr or more (shells from eroded older sediments).

Vertical Distribution of Taphonomic Types

Sequence P_2 is characterized by the alternation of Type 1 and Type 2 shell concentrations. Thin and isolated sedimentologic shell concentrations (3b) were recovered only in sandstones in the lower part of the Stirone section. Type 2 shell beds characterize the middle part, and Type 1 shell beds characterize both the middle and the upper part of small-scale cycles. Type 3 shell beds rapidly increase in frequency and thickness in Qm_1 deposits.

Sandstones and mudstones from Qm_1 cycles are dominated by Type 3 shell beds; and Type 1b shell beds, respectively. Type 1b shell beds also occur within some muddy intervals of sandstone members. Type 1a and 2 shell beds are not common, and the latter disappears altogether in the upper part of Qm_1.

The passage from shell beds of biogenic origin to the alternation of biogenic and sedimentologic accumulations is
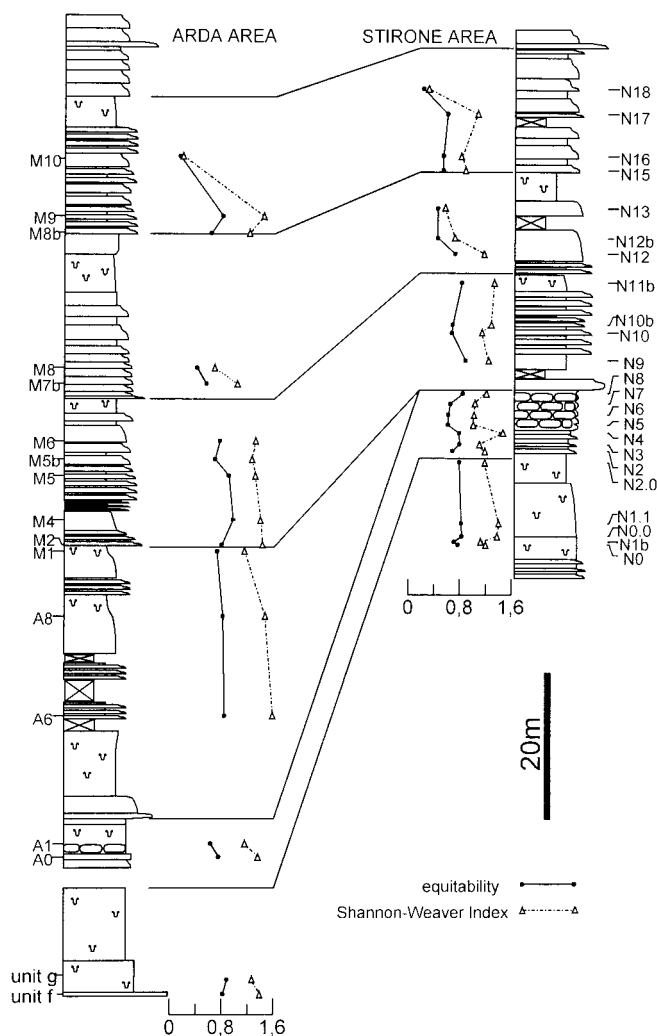

FIGURE 5—Diversity variations measured by the Shannon-Weaver Index (H) and equitability. Sequence- and small-scale cycle boundaries as in Figure 2.

in accordance with the general regressive trend of the Pliocene-Pleistocene succession. Taphonomic patterns suggest that the upper Pliocene was a time of relatively constant sediment input, punctuated by times of sediment starvation. On the other hand, the early Pleistocene was characterized by high energy conditions, and by sudden pulses of high sediment discharge onto the shallow shelf.

DIVERSITY OF FOSSIL ASSEMBLAGES

Evenness Indices, measuring the apportionment of individuals among species, were plotted against stratigraphic position (Fig. 5) and demonstrate remarkably parallel trends along the two sections. In particular it is evident that: (1) small-scale sedimentary cycles are marked by cyclic variations of diversity; and (2) diversity gradually decreases, in a stepwise fashion, from the upper Pliocene to the Pleistocene.

Small-scale changes, in part, can be artifacts of time-averaging or hydraulic mixing, because assemblages characterizing the lower half of cycles are usually high-diver-
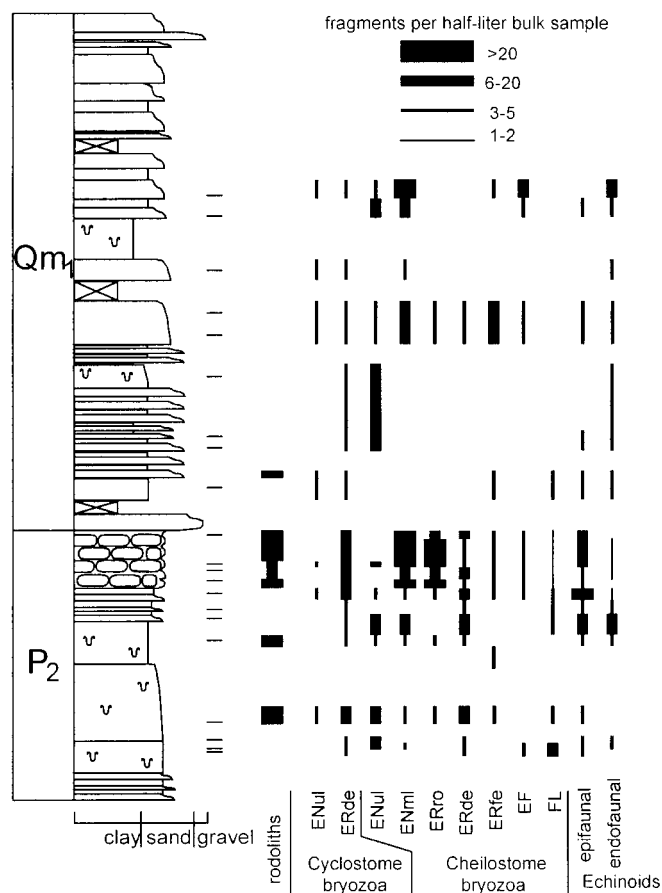
FIGURE 6—Distribution of rodoliths, bryozoans, and echinoid remains across the P₂-Qm₁ boundary (Stirone section). Positions of samples are shown on the right side of the column. Apart from two Qm₁ samples from transported assemblages, diversity shows a sharp decrease across the boundary. P₂ assemblages are characterized by encrusting forms and epifaunal echinoids.

sity Type 2 or Type 3b assemblages. Nevertheless, it is suggested that the measured diversity cycles reflect real paleobiologic phenomena related to cyclic passages from relatively predictable- to unpredictable environmental conditions. In fact, evenness, a major component of diversity of living communities, can be regarded as a proxy of environmental stability (Brenchley and Harper, 1998). The large-scale change from high-diversity P_2 to low-diversity Qm_1 assemblages is tied to the local spreading of two opportunist filter-feeders (*Corbula gibba* and *Ditrupa arietina*).

MACROBENTHIC PALEOCOMMUNITIES

The results of the paleoecologic analyses are illustrated in Figures 6 and 7, and in Table 3. The paleoecological analysis and recognition of fossil macrobenthic communities (*paleocommunity* in the sense of Kauffman and Scott, 1976) took advantage of an uniformitarian approach. In fact, many late Pliocene and early Pleistocene taxa are still living on modern shores and shallow shelves of the Mediterranean and the North Atlantic. The long tradition investigating marine organims and the environmental factors affecting their distribution within modern benthic

communities provided an excellent ecological database. Community features and a selection of relevant ecological literature are given in Table 3.

Cluster Analysis

The Q-mode dendrogram (Fig. 7) is subdivided into seven small clusters, four encompassing only Qm_1 samples (B, D, F, G), the other three formed largely by P_2 samples (A, C, E). The distance of clusters F and G from the others is tied to the local spreading of the opportunist *Ditrupa arietina,* perhaps reflecting an important environmental change at the passage from P_2 to Qm_1. These two clusters also record the lowest values of diversity (H<1.0). The highest diversities occur in clusters A and C (1.1<H<1.6).

Recurring associations were studied through the R-mode dendrogram. This is subdivided into three large clusters, representative of sandy bottom associations (1–3), vegetated, shell-gravel bottom associations (4, 5), and mixed bottom (shell-gravel and fines) associations (6, 7). Large clusters can be subdivided into seven associations, each particularly represented in one or more of the Q-mode clusters. Through the study of these dendrograms, and considering that many of the assemblages were subjected to significant sedimentological mixing, six paleo-communities were recognized.

Nuculana Paleocommunity

This paleocommunity is represented by cluster A in the Q-mode dendrogram, where association 7 and the sandy bottom associations (1–3) are abundant. As this paleocommunity is largely found in biogenic shell concentrations (Fig. 3B), it is suggested that the majority, if not all members, of the association belong to the *Nuculana* paleocommunity.

The bivalve *Nuculana fragilis,* after which the paleocommunity is named, is often abundant within cluster A (mean percentage, X_m = 10%). This species is a deposit-feeder living in muddy interstices of shell-gravel bottoms at different depths on the shelf. Two other characteristic bivalves, *Aequipecten opercularis* (X_m = 3.3%) and *Parvicardium minimum* (X_m = 4.3%), are indicative of firm, sandy shell-gravel bottoms from inner-to-middle shelf depths. Other shell-gravel dwellers are the epibiotic cemented *Serpulorbis* sp. and *Petalochoncus intortus,* the byssate *Arca tetragona,* and *Trivia* aff. *T. europaea.* The lunulitiform bryozoa *Cupuladria* sp. and the Pliocene bivalve *Parvicardium hirsutum* are also typical components. The abundances of *Spisula subtruncata* (X_m = 4.5%) and *Tellina pulchella* (X_m = 1.35%) are indicative of muddy sand bottoms of the shoreface. The overall composition indicates that the *Nuculana* paleocommunity lived in the lower shoreface or the offshore transition zone during times of low terrigenous input. The modern distribution of some characteristic taxa in the Adriatic Sea suggests depths of 20–40 m.

Timoclea Paleocommunity

This paleocommunity is cluster C in the Q-mode dendrogram. In the R-mode dendrogram, it is largely represented by taxa of association 4, to a lesser extent by asso-
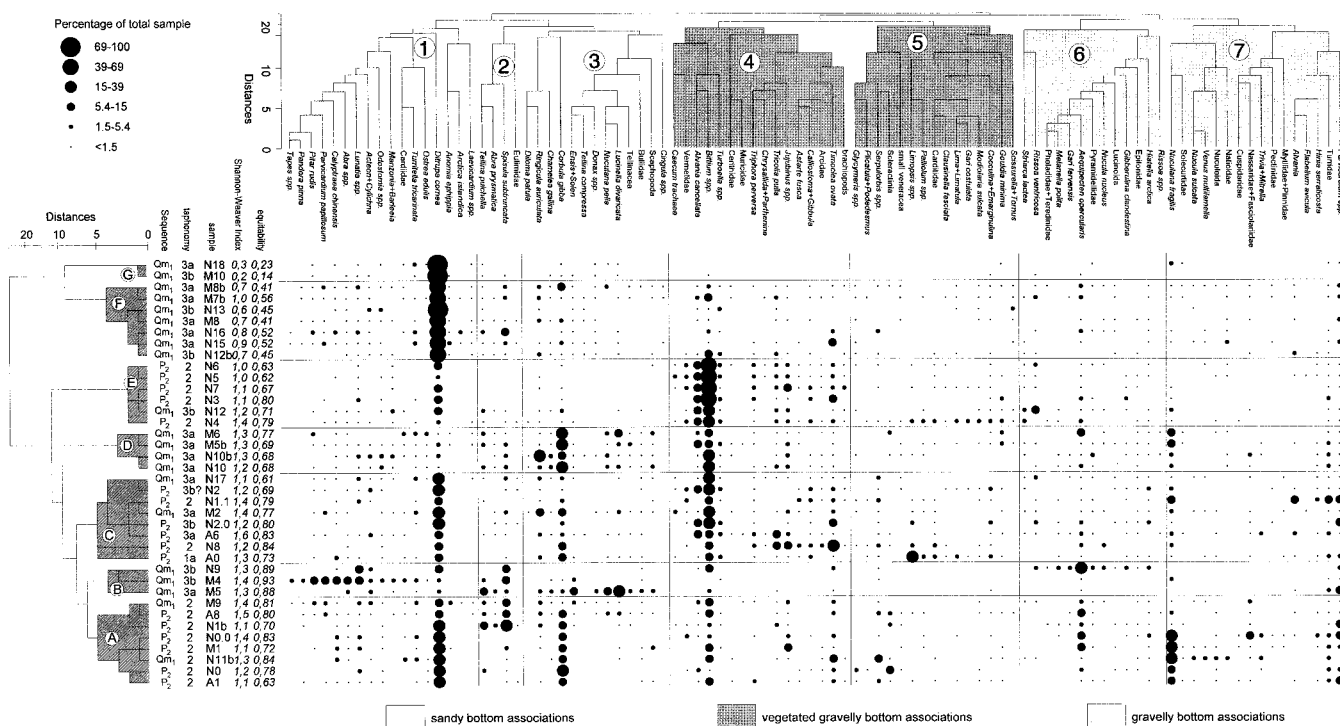
FIGURE 7—Q-mode and R-mode cluster analyses from the Arda and the Stirone sections (Ward's method of Minimum Variance, distance metric Euclidian distance, and Average Linkage, distance metric 1-Pearson correlation coefficient, respectively).

ciation 6, and is accompanied by a decrease of sandy bottom taxa (associations 1–3). Cluster C was collected from three biogenic and five sedimentological accumulations. Most species are interpreted as members of the *Timoclea* paleocommunity.

The paleocommunity is named after the sandy shell-gravel bivalve *Timoclea ovata* (X_m = 5%). Herbivores diagnostic of algal covered sites are the most important guild after suspension-feeders, as is shown by the abundance of *Bittium reticulatum* (X_m = 19%) and *Alvania cancellata* (X_m = 4.5%). The paleocommunity is characterized by the abundant epibiotic cemented forms, such as the polychete *Serpulorbis* sp., rodoliths, a diverse association of bryozoans, and *Petalochoncus intortus.* An important group of species is indicative of shell-gravel bottoms: *Parvicardium minimum* (X_m = 3.5%), *Limopsis* spp. (X_m = 4%), *Astarte fusca* (X_m = 0.7%), *Hiatella arctica* (X_m = 0.7%), and *Gouldia minima* (X_m = 0.3%). Shell-gravel dwellers are more abundant than in the *Nuculana* paleocommunity, whereas the opposite is true for sandy bottom species (e.g., *Spisula subtruncata,* X_m = 1.4%). The above characteristics support the hypothesis of a community living in the inner shelf at times of low net-rate of sedimentation. The modern distribution in the Adriatic Sea of the characteristic taxa is suggestive of 30–60 m depths.

Corbula Paleocommunity

The *Corbula* association (association 3 in Fig. 7) has been recovered in the transported and mixed shell beds of cluster D. Several species are unique to these collections, and are characterized by a pristine taphonomic signature (signatures 1 or 3).

Species characterizing this association are the opportunist suspension-feeding bivalve *Corbula gibba* (X_m = 23.5%, compared to X_m = 3.7% elsewhere in the sections), the deposit-feeder *Nuculana pella* (X_m = 2%), the parasitic opistobranch *Ringicula auriculata* (X_m = 6%), and the small suspension-feeding bivalve *Lucinella divaricata* (X_m = 4.5%). Another common species, although not limited to this association, is the small opportunist grazer *Bittium reticulatum* (X_m = m = 19%). Another important, although not exclusive, species group within these collections is the sandy nearshore bivalves *Chamelea gallina* (X_m = 1.6%), *Spisula subtruncata* (X_m = 2.1%), *Tellina pulchella* (X_m = 2.1%), *Acanthocardia tuberculata* (X_m = 0.1%), and *Aequipecten opercularis* (X_m = 3.7%).

Corbula gibba is a well-known living species, sometimes occurring in great abundance within both Recent and fossil communities. Modern literature on the ecological effects of marine benthic hypoxia (oxygen concentrations of 2–0 ml l-1), the condition that immediately precedes anoxia, suggests an explanation for the local abundance of this species. In fact, *Corbula gibba* is common in, but not exclusive to hypoxia-stressed areas and is considered one of the most tolerant forms to oxygen depletion (Diaz and Rosenberg, 1995). Another hypothesis, based on the assumption that it can handle large quantities of suspended material (Yonge, 1946), indicates that *Corbula gibba* takes advantage of turbid water conditions, unbearable to other suspension-feeders (Di Geronimo et al., 1987). In the present study, the high abundance of *C. gibba* is considered diagnostic of a *Corbula* paleocommunity living in muddy bottoms of the inner shelf experiencing periodic hypoxia. If Lough Ine, a modern enclosed basin of the Irish coast, is considered as a modern counterpart, the abundance of *Bit-*

TABLE 3—Upper Pliocene and lower Pleistocene shallow shelf benthic paleocommunities of western Emilia. Abbreviations of trophic categories: inf: infaunal; epi: epifaunal; vag; vagrant; susp: suspension feeder; det: detritus feeder; herb: herbivore; pred: predator; phot: photosynthetic. References: (1) Vatova (1943); (2) Thorson (1957); (3) Van Straaten (1965); (4) Pérès and Picard (1964); (5) Picard (1965); (6) Ledoyer (1968); (7) Guille (1970); (8) Glémarec (1973); (9) Gamulin-Brida (1974); (10) Kitching et al. (1976); (11) Fretter and Manly (1980); (12) Stachowitsch (1984); (13) Pearson et al. (1985); (14) Carthew and Bosence (1986); (15) Baden et al. (1990); (16) Rosenberg et al. (1992); (17) Sanfilippo (1993); (18) Diaz and Rosenberg (1995, and references therein); (19) Zuschin et al. (1999, and references therein).

Paleo community	Taxa	Trophic category	Community characteristics	Environment and depth range	References
Nuculana	*Nuculana fragilis*	in det	Dominated by suspension feeders; predators and deposit feeders common. Moderate diversity supported by a fairly stable environment	Offshore transition or inner shelf. Periodic lowering of terrigenous input leads to the formation of a mixed muddy sand-shelly gravel substrate (20–40 m)	4, 5, 7, 14
	Aequipecten opercularis	epi susp			
	Parvicardium minimum	inf susp			
	Parvicardium hirsutum	inf susp			
	Trivia aff. *europea*	vag pred			
Timoclea	*Timoclea ovata*	inf susp	Equally dominated by suspension feeders, herbivores, and predators. Cemented epibionthic forms are common (e.g., serpulids, *Petaloconchus,* rodoliths, bryozoa). High diversity supported by a stable environment	Starved inner shelf. Non-deposition leads to the periodic formation of a shell-ground substrate (30–60 m)	4, 5, 6, 7, 8, 9, 14
	encrusting serpulids	epi susp			
	Hiatella arctica	inf susp			
	Emarginula fissura	vag herb			
	Petalochoncus intortus	epi susp			
	Turboella incospicua	vag herb			
	Rissoa ventricosa	vag herb			
	Hinia serraticosta	vag pred			
	rodoliths	epi phot			
	erect delicate cheilostomes	epi susp			
Corbula	*Corbula gibba*	in susp	Low diversity community dominated by suspension feeders and deposit feeders adapted to unpredictable environment	Muddy bottoms of the inner shelf. Water stratification induces periods of hypoxia (20–40 m)	10, 15, 16, 18
	Nuculana pella	inf det			
	Lucinella divaricata	inf susp			
	opisthobranchs	vag paras			
Bittium	*Bittium reticulatum*	epi herb	Dominated by herbivores and suspension feeders. Many forms are cemented epibionts. Moderate diversity sponsored by a stable environment. Wide range of niches available in a shelly substrate	Starved inner-to-middle shelf swept by moderate currents. Non-deposition leads to the formation of a shellground substrate (30–60 m)	1, 4, 5, 6, 7, 8, 9, 12, 14
	Pteromeris corbis	inf susp			
	Astarte fusca	inf susp			
	Gari costulata	inf det			
	Gouldia minima	inf susp			
	Clausinella fasciata	inf susp			
	Jujubinus striatus	vag herb			
	Tricolia pulla	vag herb			
	Alvania cancellata	vag herb			
	Caecum trachea	vag herb			
	Triphora perversa	vag herb			
	encrust. multil. cheilostomes	epi susp			
	erect rigid robust cheilost.	epi susp			
Spisula	*Spisula subtruncata*	inf susp	Dominated by shallow infaunal suspension feeders (e.g., *Glycymeris, Spisula, Pitar*). Moderate to high diversity promoted by a predictable environment	Sandy bottoms in the shoreface (5–30 m)	2, 3, 4, 5, 7, 8
	Ditrupa arietina	epi susp			
	Glycymeris insubrica	inf susp			
	Anomia ephippium	epi susp			
	Parvicardium papillosum	inf susp			
	Donax venustus	inf susp			
	Tellina pulchella	inf susp			
	Pitar rudis	inf susp			
Ditrupa	*Ditrupa arietina*	epi susp	Monospecific populations of opportunists in sandy bottoms	(?) Sandy bottoms of the delta front, with turbid water condition (5–30 m)	17
Arctica	*Arctica islandica*	inf susp	Low diversity community with deposit feeders and suspension feeders adapted to unpredictable environments	Muddy bottoms of the inner shelf subject to periodic oxygen stress (20–40 m)	11, 13, 15, 16, 18
	Ophiura albida	vag dep			
	Astropecten irregularis	vag pred			
	Aporrhais pespelecani	inf dep			
Venus	*Nucula sulcata*	inf dep	Soupy bottom community dominated by shallow suspension feeders and deposit feeders	Muddy bottoms of the inner shelf (20–40 m)	1, 3, 4, 5, 7, 8, 18
	Abra alba	inf dep			
	Venus multilamella	inf susp			
	Turritella tricarinata	inf susp			
Pinna	*Pinna* spp.	semi-inf susp	A soupy bottom community of suspension feeders	Muddy bottoms of the inner shelf (18 m–?)	19
	Atrina pectinata	semi-inf susp			
Thalassinoides	*Thalassinoides* isp.	—	Firm bottom community	(?) Muddy bottoms of the inner shelf (20–40 m)	—

tium reticulatum is also in accordance with this interpretation. Here a blanket of filamentous algae populated by large numbers of *B. reticulatum* covers the bottom from −3 to −17 m, while *Corbula gibba* thrives in oxygen-depleted muds at depths of 25–40 m (Kitching et al., 1976). As the sampled shell beds are the result of sedimentological mixing, this hypothesis needs to be tested by analyzing of autochthonous or parautochthonous associations of the *Corbula* paleocommunity that have not been recovered yet. It is supported nevertheless by the occurrence of the *Arctica* paleocommunity in a similar stratigraphic position along Qm_1 cycles, yielding an analogous paleoecologic interpretation (see later discussion). The paleocommunity could have lived at depths of 20–40 m.

Bittium Paleocommunity

The *Bittium* paleocommunity is present in cluster E. Association 4 in the R-mode dendrogram is representative of this paleocommunity. It is important to note that in cluster E the sandy bottom associations (1–3) are at their minimum values. Most collections containing the *Bittium* paleocommunity are from biogenic concentrations, with the exclusion of the mixed and transported N12, and occur within the biocalcirudite at the top of P_2 (Stirone section). All taxa of the association are considered members of the *Bittium* paleocommunity.

Bittium reticulatum ($X_m = 42\%$) and the majority of common and characteristic species of the paleocommunity (e.g., *Solariella peregrina, Jujubinus striatus, Tricolia pulla, Alvania cancellata, Triphora perversa*) are small grazing gastropods that feed on diatoms and dinoflagellates growing on hard bottoms of the inner shelf. Other herbivores common to the association are the regular echinoids. Characteristic species among the bivalves are indicative of gravel bottoms of the inner shelf (e.g., *Gouldia minima,* $X_m = 0.8\%$, and *Astarte fusca,* $X_m = 0.3\%$) swept by currents (e.g., *Clausinella fasciata,* $X_m = 0.2\%$, and *Gari costulata,* $X_m = 0.5\%$). Cemented epibenthos are abundant and are characteristic (Fig. 6: rodoliths, erect rigid robust and encrusting multilaminar bryozoans, vermetid gastropods); sand-dwellers are absent. The *Bittium* paleocommunity can be regarded as diagnostic of an inner-to-middle shelf environment under low terrigenous input, periodically swept by currents. A depth range of 30–60 m is hypothesized.

Spisula Paleocommunity

Two clusters, B and F, record remarkably large proportions of sandy bottom taxa (associations 1 and 2) and the disappearance of many shell-gravel taxa. They are highly divergent in the Q-mode dendrogram, due to the very high abundance of the polychaete *Ditrupa arietina* in cluster F. All of the collections in these clusters are from sedimentological shell accumulations. Both clusters are interpreted as representatives of a *Spisula* paleocommunity, the varying proportions of *Ditrupa arietina* perhaps accounting for variations of water turbidity (see later discussion). The many sandy bottom dwellers well represented in cluster B and in collection N17 of cluster C also are interpreted as members of the *Spisula* paleocommunity, mixed by currents with other taxa.

The *Spisula* paleocommunity is characterized by the occurrence of the suspension-feeding bivalves *Spisula subtruncata* ($X_m = 3.3\%$) and *Tellina pulchella* ($X_m = 1.8\%$), species today living in silty and fine sand shorefaces and restricted to shallow depths. Molluscs, such as *Glycymeris insubrica, Parvicardium papillosum, Mactra corallina, Ensis ensis, Donax venustus, Pitar rudis, Neverita josephinia,* and *Acteon tornatilis,* are all diagnostic of sandy bottoms within the shoreface. The modern analogues of the *Spisula* paleocommunity live in the shoreface of the boreal seas and the Mediterranean, and are restricted to depths of 5–30 m.

Ditrupa Paleocommunity

The small polychaete *Ditrupa arietina* is very abundant in the two collections of cluster G and in N13 of cluster F, encompassing values of 73–94%. These collections are all from mixed and transported shell beds; the few associated species come from the *Spisula* paleocommunity.

Ditrupa arietina is considered as an *instability indicator* (Picard, 1965), tolerant of high quantities of suspended inorganic matter and thriving in conditions of turbid waters (Di Geronimo et al., 1987). Literature on the biology and the modern distribution of *Ditrupa* is poor (see Sanfilippo, 1993); in the Mediterranean this species thrives at particular sites close to river mouths (Sanfilippo, pers. commun. 1993), while in the North Gascony shelf it is reported at depths of 130–160 m (Glémarec, 1973). Available data, although scanty, and overall low assemblage diversity ($0.2 < H < 0.3$) suggest that the community lived in turbid waters of a delta-front setting, under stressed environmental conditions. Due to the constant association with species from the *Spisula* community, a paleobathymetric range of 5–30 m is suggested.

Other Paleocommunties

Four paleocommunities that characterize mudstones with biogenic Type 1b shell beds not sampled for cluster analysis were recognized on semi-quantitative grounds based on personal field observations and on published literature.

Venus Paleocommunity

The association dominated by the bivalve *Venus multilamella* occurs in dispersed, autochthonous to parautochthonous assemblages in mudstones and siltstones (Papani and Pelosio, 1963; Bertolani Marchetti et al., 1979; Dominici et al., 1996; Taviani et al., 1997). Characteristic species are *Nucula placentina, N. sulcata, Acanthocardia paucicostata, Abra alba, Turritella tricarinata, Aporrhais pespelecani,* and *Amyclina semistriata. Mytilus* aff. *galloprovincialis, Ostrea edulis,* and *Glossus humanus* are sometimes abundant. Bivalves occur in life position.

Venus multilamella lives in muddy, soupy bottoms of the inner shelf, indicating high rates of terrigenous input. Local fluvial influences are shown by the abundance of *T. tricarinata. Nucula sulcata* is also characteristic of the muddy inner shelf (Thorson, 1957; Pearson et al., 1985) and points to the presence of a soupy bottom. The occurrence of species resistant to hypoxia, such as *Abra alba* (moderate

hypoxia), *Aporrhais pespelecani,* and *Mytilus* aff. *gallo-provincialis* (severe hypoxia; Diaz and Rosenberg, 1995), suggests that this paleocommunity is transitional to the *Arctica* paleocommunity.

The *Venus* paleocommunity is interpreted to reflect a moderately well-oxygenated muddy shallow shelf, at depths comparable to those inhabited by the *Arctica* community during times of longer and more frequent hypoxia. Taviani et al. (1997) suggest that the *Venus* paleocommunity lived at water depths of 20–40 m.

Pinna Paleocommunity

The Pinnidae (e.g., *Atrina pectinata*: Dominici et al., 1996) are found commonly in life position with associations of the *Timoclea* paleocommunity. A *Pinna* association is cited in the upper Pliocene of the Arda area (*Pinna nobilis*: Monegatti et al., 1997). A similar fauna is recorded in the Stirone area, either as monospecific associations in siltstones, or with the bivalves *Pelecyora brocchii* and *Penicillus bacillus,* the gastropod *Turritella tricarinata,* and the echinoid *Schizaster canaliferus,* in silty fine sandstones. The *Pinna* paleocommunity shows a gradual transition to the *Timoclea* association.

Atrina pectinata is reported in deeper stations of the northern Adriatic Sea, in muddy bottoms (Zuschin et al., 1999). Based on the little evidence available, the paleocommunity probably lived in soft bottoms of the inner shelf, at a minimum depth of about 20 m, during times of higher clastic input relative to the *Timoclea* paleocommunity.

Arctica Paleocommunity

Assemblages with adult specimens of *Arctica islandica* in life position (e.g., Fig. 3A), sometimes associated with *Venerupis senescens cuneiformis* and *Aporrhais pespelecani* (G. Pelosio, pers. commun. 1996), are recovered in mudstones intercalated between shell beds of the *Spisula* association (Pelosio and Raffi, 1974). These species, together with *Ophiura albida* found on the tops of shell beds, are interpreted as members of the *Arctica* paleocommunity.

Arctica islandica thrives on the eastern Atlantic coasts north of the English Channel and in the western Atlantic north of Long Island, New York, in the mild- to cool-temperate climatic zone (Raffi, 1986). The ecological success of *Arctica islandica* is tied to its ability, as indicated by field and laboratory experiments, to resist bottom hypoxia for longer intervals as compared to other benthic species (Diaz and Rosenberg, 1995). By adopting special strategies, *Ophiura albida* can resist severe hypoxia (Baden et al., 1990; Diaz and Rosenberg, 1995); *Aporrhais pespelecani* is tolerant of brief periods of oxygen depletion (Stachowitsch, 1984; Diaz and Rosenberg, 1995); and *Echinocardium cordatum, Ophiura texturata,* and *Astropecten irregulare,* although sensitive to low oxygen concentrations, nevertheless are members of offshore muddy bottom communities thriving between hypoxia events (Stachowitsch, 1984; Baden et al., 1990; Nilsson and Rosenberg, 1994). Mass migration to the surface of *Echinocardium cordatum,* reported during such events (Baden et al., 1990; Nilsson and Rosenberg, 1994), could account for the occur-
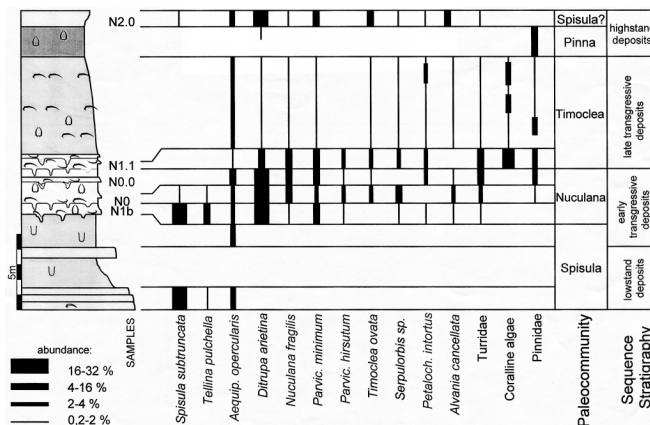
FIGURE 8—Distribution of selected taxa and community replacement sequence in P_2 small-scale sequences (basal sequence of the Stirone section). Species indicative of sandy bottoms to the left (*Spisula* to *Ditrupa*); moving towards the right side, selected species are indicative of shell-gravel bottoms (*Nuculana* to coralline algae); the species on the far right (Pinnidae) are indicative of muddy bottoms.

rence of densely-packed *Echinocardium* accumulations (Fig. 4F). It is hypothesized that the *Arctica* community lived in muddy bottoms in areas of the inner shelf that experienced low oxygen levels. The bathymetric range of *Arctica islandica* is indicative of depths of 15–75 m.

### Thalassinoides-bearing Paleocommunity

Mudstones with fossils from the *Venus* paleocommunity are sometimes overlain by a bioturbated interval with *Thalassinoides* burrows extending up to 50 cm into the underlying mudstones, and filled with sand and fine shell debris from the overlying, unbioturbated sandstones. Sand-filled burrows are absent in other parts of the mudstones.

This fossil community is included in Table 2 and its interpretation is based on the analysis of the trace fossils. The *Thalassinoides* association points to the presence of a muddy firm bottom, opposed to the soupy bottoms of the *Venus* paleocommunity. The formation of the burrows was preceded by the submarine erosion and exhumation of compacted muds, and was followed by the filling of the galleries with shelly sand.

STACKING PATTERN OF FOSSIL COMMUNITIES

The vertical distribution of paleocommunities in one of the studied P_2 small-scale cycles is shown in Figure 8. The basal sandstones bear an impoverished, transported shoreface assemblages with bivalves of the *Spisula* (paleo) community (*Spisula subtruncata, Aequipecten opercularis,* cardiids). The overlying bioturbated sandstones are marked by the emplacement of the *Nuculana* community. The bottom was comprised of a mixture of sand and shell gravel, reflecting a lowered terrigenous input with respect to underlying sandy bottoms. A gradual transition to shelly bottoms is marked by the onset of the *Timoclea* community. This vertical succession ("community sequence" of Miller, 1986) indicates benthic community replacement triggered by a further deepening and interruption of terrigenous input. The subsequent increase in terrigenous in-
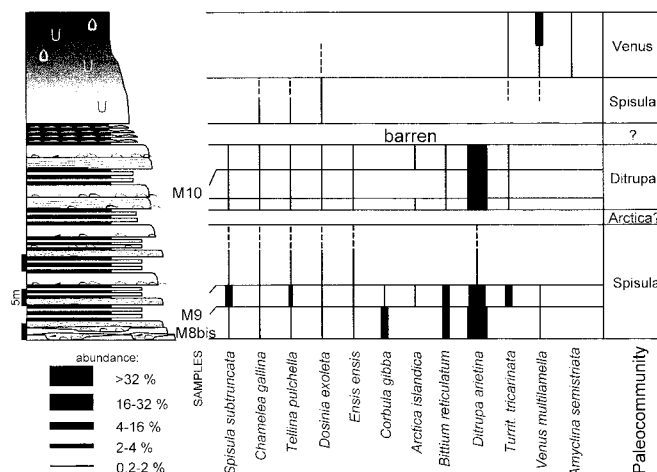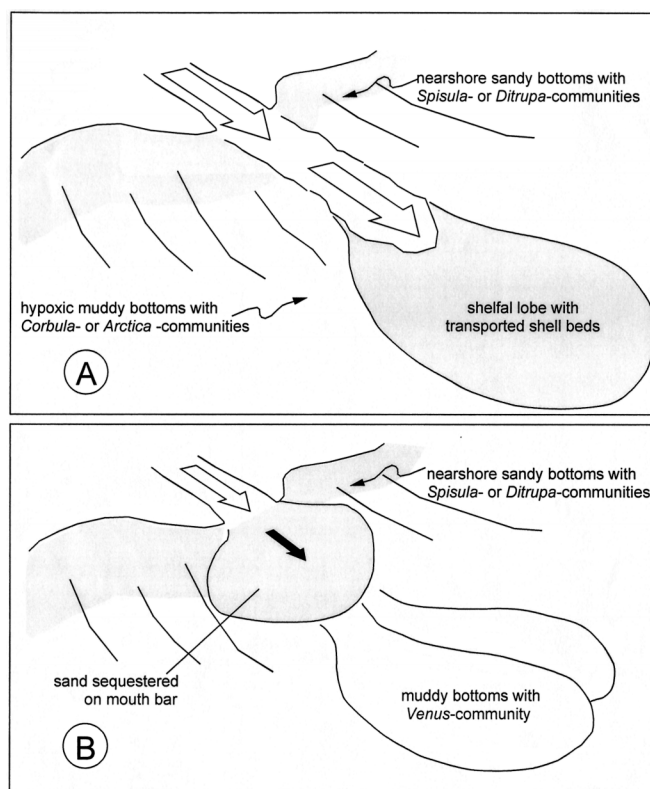
FIGURE 9—Distribution of selected taxa and interpreted community replacement sequence in one of the Qm₁ sedimentary cycles (uppermost cycle of the Arda section). Species indicative of sandy bottoms to the left (*Spisula* to *Ensis*); species indicative of muddy hypoxic conditions (*Corbula* to *Bittium*) or turbid waters (*Ditrupa*) in the middle part; the three species on the far right are indicative of oxygenated muddy bottoms. Shell beds show a passage from *Spisula* to *Arctica* (here only reworked elements), to *Ditrupa,* and to *Venus* associations. The paleoecological analysis suggests that this biofacies succession reflects a change from hypoxic to normally oxygenated inner shelf environments.

FIGURE 10—Model of benthic community distribution on the shallow shelf during the formation of a Qm₁ cycle (adapted from the depositional model of Martinsen, 1990). (A) During times of high sediment discharge, shallow water turbidity currents triggered by catastrophic flooding events displace shells from delta front and nearshore sandy bottoms to a deeper shelfal lobe setting. Between events of sandy deposition, a low diversity benthic community inhabited the muddy bottoms of the hypoxic inner shelf environment. Remains of the muddy bottom fauna are eventually mixed with nearshore faunas by the next turbidity current (e.g., Fig. 4). (B) The upper part of the cycle is characterized by stable climatic conditions and low sediment discharge. Sand is trapped on the delta mouth and only fines reach the inner shelf. A stable muddy bottom community lived on the inner shelf under conditions of normal oxygenation.

put is reflected in the replacement by the *Pinna* community in the upper part of the cycle.

The *Spisula-Nuculana-Timoclea-Pinna* community sequence is consistent with an environmental control on the composition of benthic communities driven by water depth and clastic input. In particular, it is diagnostic of a cycle of depth increase-decrease paralleled by the lowering and increase of terrigenous input. The paleodepths of the above mentioned communities would indicate a change most probably within the 10–40 m range. On this basis, and by comparison with similar replacement sequences from the literature (e.g., Abbott and Carter, 1997), it is hypothesized that high-frequency eustatic variations are the main controlling factor in the deposition of P₂ cycles, and that these represent small-scale depositional sequences. Accordingly, stratigraphically lower sandstones represent the lowstand deposits, bioturbated sandstones are transgressive deposits, shelly intervals represent the condensed section, and the upper mudstones represent highstand deposits. The shell-gravel bottom *Bittium* community of the Stirone biocalcirudite (Fig. 2) is interpreted as a transgressive deposit, formed in a mid-shelf setting.

Qm₁ small-scale cycles, from sandy shelfal lobes to muddy shelf, also are marked by a vertical succession interpreted as a community replacement sequence (Fig. 9). This is marked by the passage from beds with mixed remains of *Spisula* and *Arctica* (or *Corbula*) communities, through beds with mixed elements of *Ditrupa, Spisula* and *Arctica* communities, to beds with the *Venus* community (locally preceded by the *Nuculana* or the *Timoclea* community). Cycle-bounding surfaces sometimes are marked by the *Thalassinoides* association. This sequence records colonization by the *Spisula* community in a well-oxygenated sandy bottom of the shallow delta front and

the nearshore during the lower part of the cycle. The association with pristine shells from the *Arctica* community, and the intercalation of mudstones with *in situ* elements of the *Arctica* community, indicate that shells were transported (perhaps for hundred of meters to several kilometers) from the sandy shoreface to deeper muddy bottoms of an inner shelf charcterized by more or less permanent hypoxia, and were mixed with elements of the *Arctica* (or the *Corbula-*) community (Fig. 10A). The occurrence of *Arctica islandica* specimens up to 80 mm long (Pelosio and Raffi, 1973) within the 10-to-20-cm-thick mudstones interbedded with shell lags (e.g., Figs. 3A, 4D) represents at least a hundred years separation between two consecutive turbidity current events (*A. islandica* can live up to 125 years, reaching a maximum dimension of about 110 mm). The passage to the *Ditrupa* community possibly marks the gradual return to times of normal bottom oxygenation and turbid waters. The *Nuculana* or *Timoclea* community indicates eventual interruption of sediment flux and a deepening with respect to the shelfal lobe depositional environment. Muddy deposition took over, characterizing the up-

per part of Qm_1 cycles, indicating a well-oxygenated sea floor (Fig. 10B). The occurrence of the *Thalassinoides* association suggests that submarine erosion preceded the return to sandy deposition. On the whole, Qm_1 cycles seem to record sea-level variations of lesser amplitude with respect to those of the underlying P_2 cycles. Given the above data, a sequence stratigraphic interpretation of Qm1 cycles is not a straightforward task and will not be discussed here.

DISCUSSION

Available data permit recognition of large-scale paleoenvironmental change at the P_2-Qm_1 boundary. The frequency of shell-ground fossil communities in the western Emilia P_2 succession is indicative of low sediment supply, as is expected during phases of tectonic quiescience, in the later part of an uplift/denudation cycle (Davisian-type cycle of Mutti et al., 1996). Fossil communities from western Emilia are characterized by herbivores and epifaunal suspension feeders. Diversity is high, because shell-gravel bottoms offer a variety of ecological niches. The diverse bryozoan fauna is characterized by ramose forms, and coralline algae are widespread. Denudation complexes formed during the early Pleistocene following the late Pliocene uplift of the southwestern margin of the basin and the ensuing denudation phase. An increase in sediment supply and a steepening of relief marks the P_2-Qm_1 boundary. Qm_1 can be regarded as a new cycle of uplift/denudation. Sediments were supplied mainly from small rivers of the Apenninic mountain front to fan-deltas and shelfal lobes (the high sediment yield of modern Apennine rivers, as reported by Millimann and Syvitsky, 1992, should have been even higher following phases of uplift). The analysis of early Pleistocene macrofossil assemblages suggests that soft sandy and muddy bottoms were generally more widespread with respect to the upper Pliocene, at the expense of shell-gravel bottoms. The latter developed rarely, for short time spans, possibly during high-frequency sea-level rise. Sandy-bottom communities were dominated by infaunal suspension feeders and herbivores. Cemented epifauna were correspondingly less diverse with respect to the upper Pliocene. The bryozoan fauna was dominated by shell-encrusting membraniporiform bryozoans, typical of stressed shallow bottoms.

Upper Pliocene communities record cyclical variation of terrigenous supply and depth, pointing to high-frequency eustatic control on clastic deposition. Benthic communities from the early Pleistocene indicate cyclic changes in bottom oxygenation, turbidity, and depth. Cycles in bottom oxygenation are recorded by foraminiferal faunas from nearby sections (preliminary data in Iaccarino and Monegatti, 1996). As a working hypothesis, these cycles can be interpreted as the shelfal counterparts of the sapropel-nonsapropel cycles recorded in deeper parts of the eastern Mediterranean during the early Pleistocene. Sandstones could indicate phases of deglaciation following glacial maxima, with high input of freshwater and riverborne nutrients, and high summer pelagic productivity at times of high seasonality; mudstones could represent return to full interglacial conditions and to humid, low-seasonality climates. Increase of forest cover in the bordering land masses would have lowered fluvial sediment input to

the basin by stabilizing soils. Renewal of bottom oxygenation could have been caused by a change in the general pattern of circulation in the Adriatic Sea (see Myers et al., 1998). The cyclic stacking pattern of fan-delta forestepping/backstepping episodes described by Mutti (1996) may have been produced primarily by the onset and disappearance of local climatic conditions favoring the development of catastrophic flooding through time (see other geologic examples in Martinsen, 1990; Weltje and de Boer, 1993; and Mutti et al., 1996). In the framework of the high-frequency climatic cycles of the late Pliocene and early Pleistocene, large volumes of water could have been made available by heavy rainfall and/or by snow and ice melt during deglaciation immediately following glacial maxima (see Fairbridge, 1972). During this phase, hyperconcentrated flows and turbidity currents would have carried large amounts of sediment, sequestered in fluvial basins during arid glacial times, from the high-gradient drainage basin onto the shallow shelf. The thinning- and fining-up nature of sandstones marks the passage to interglacial times. Forested and humid interglacials were times when normal fluvial and wave refractory processes allowed only fines to reach the shallow shelf.

The Qm_1 type of sedimentary cycle outlined above can be built only where sediment is made available by tectonic uplift, during early phases of denudation. The same causes are responsible for a steepening of the shelf gradient, supporting turbidity currents for longer periods of time as compared to normal conditions. Thus, Qm_1 cycles have a strong tectonic (long term and possibly short term) and climatic (short term) imprint that partly or completely masks eventual eustatic signals.

When comparing Qm_1 and P_2 cycles, the lack of evidence of a climatic signal in P_2 cycles is notable. Raffi (1986), in synthesizing paleoclimatic evidence for the early Pleistocene, suggested that the first flood of boreal immigrants was a consequence of the onset of a high-seasonality climatic regime associated with a significant drop in winter temperatures, at the Mediterranean latitudes. On the other hand, the detailed analysis of Lourens et al. (1992, 1996) carried out in southern Italy does not indicate a climatic change at the Pliocene-Pleistocene boundary. Palynological studies also indicate that vegetation remained unchanged from 2.6 to 1.0 Ma (Suc et al., 1995). Several explanations are possible: (1) the multiproxy record reviewed by Raffi, and confirmed by the absence of a oxygen-depletion record in the upper part of P_2, highlights the crossing of a climatic threshold in an otherwise gradual and cyclic shift from Pliocene to Pleistocene climates; (2) the uppermost Pliocene record is missing in western Emilia due to the erosion under subaerial conditions of the uppermost part of sequence P_2; (3) upper Pliocene events of sapropel deposition were not accompanied by oxygen depletion on the shelf.

CONCLUSIONS

This study shows that, in active tectonic margins, episodic uplifts of basin margins may trigger uplift-denudation cycles, with consequences for the distribution of marine organims and their remains. This effect is particularly intense during times of climatic deterioration, when large volumes of water are made available by precipitation

and ice melt, triggering turbidity currents on the shelf as a result of catastrophic terrestrial flooding. During early phases of long-term uplift/denudation cycles, the shallow shelf is characterized either by (1) sandy deposition and stressed environmental conditions that favor the development of benthic communities dominated by opportunistic shallow endobiotic filter-feeders, or by (2) muddy soupy bottoms, with a mixed filter- and deposit-feeder infauna. In either case, the formation of shell-gravel bottoms is inhibited. On the other hand, shell-gravels are favored at the end of the uplift/denudation cycle. During phases of high-frequency sea-level rise, time averaging becomes common and high-diversity shell-gravel communities dominated by epibionthic herbivores and filter-feeders spread on the shelf at the expense of sandy and muddy bottom communities. Climatic factors in semi-enclosed basins can result in oxygen depletion at the bottom that may eventually lead to the formation of low-diversity, hypoxia tolerant benthic communities. High-frequency eustatic control is evident only when both tectonics and climate are ineffective in the distribution of sediments onto the shelf. Otherwise, the vertical distribution of biofacies within sedimentary cycles does not easily fit within current sequence stratigraphic models. Provided that local climatic conditions remain relatively stable during cycles of sea-level variation, and during phases of low tectonism, the study confirms that fossil communities can be used as paleodepth indicators, as suggested by previous studies (Abbott and Carter, 1997; Brett, 1998). On the other hand, these results show that active tectonics and climatic factors affect several important parameters, such as the quantity of sediment delivered by rivers to the shallow sea, the type of sedimentary processes involved, water turbidity at delta fronts, and the degree of bottom oxygenation. These factors do alter the taphonomic and paleoecologic expressions expected from current sequence stratigraphic models.

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