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The infralittoral prograding wedge: a new large-scale progradational sedimentary body in shallow marine environments

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Abstract A progradational sedimentary body, the infralittoral prograding wedge (IPW), has been developing from the mean fair-weather wave-base level to the storm wave-base level between the onshore (beach) and the offshore (inner continental shelf) depositional zones along the Spanish coast during the Late Holocene. The main sedimentary body is composed of large inclined master beds which prograde seawards parallel to the shoreline, formed by sediments swept offshore by waves from shallow-water littoral environments. The inclined beds downlap onto finer-grained offshore sediments and, in turn, are overlain by shoreface deposits. The IPW is generated by downwelling storm currents and associated seaward transport of sediment. It represents a new depositional model for clastic wave-dominated coasts, and its identification requires a new subdivision of the nearshore environment.

Introduction

Numerous studies of sedimentological and geomorphological aspects of coastal and continental shelf sedimentary environments have been carried out during the last century (see reviews in Davis 1985; Swift et al. 1991; Carter and Woodroffe 1994; Reading and Collinson 1996). However, research on beach deposits has mostly been carried out from an excessively "terrestrial" point of view, and has been concerned with coastal evolution and coastal defense while studies of continental shelves have been dominated by a "marine" point of view, addressing geological issues such as facies identification and depositional processes. Additionally, marine studies focus mainly on the connection between the continental shelf, slope and basin. Therefore, literature on the sedimentary characteristics of the nearshore to offshore transition on wave-dominated coasts is limited, especially regarding interior seas. The reasons for this include methodological limitations such as the presence of short-period multiples and reverberation of the seismic signal, and the navigational limits of research vessels.

The infralittoral zone extends between the shoreface and the inner continental shelf from the mean storm wave base to the mean fair-weather wave base (Guillen and Diaz 1990; Guillen 1992). It is equivalent to the Offshore Transitional Zone described by Reading and Collinson (1996). Knowledge of the sedimentary processes and stratigraphic architecture of this zone is important because it could explain the origin of both Holocene and some ancient transitional sand facies. It also offers a new vision of various "Vailian" concepts such as accommodation space, depositional profiles, and depositional shoreline breaks (Jervey 1988; Van Wagoner et al. 1988). The present paper provides new insights into Late-Holocene stratigraphic and sedimentary characteristics of the onshore–offshore transition. In particular, a progradational sedimentary body, the infralittoral prograding wedge (IPW), is discussed as a characteristic element of wave-dominated coasts.

These findings are the result of research carried out on Late-Holocene sedimentary deposits from Spanish Mediterranean and Atlantic infralittoral prograding environments over the last 7 years. We have investigated the NW sector of the Alboran Sea between Malaga and the Straits of Gibraltar in great detail, and have also

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conducted site-specific studies in (1) the NE part of the Alboran Sea off Malaga in the Velez and Torrox area, Granada in the Motril area, and Almeria in the Cabo de Gata area; (2) the Mediterranean Sea at Alicante and in the Balearic Islands; and (3) the Atlantic Ocean in the Gulf of Cadiz (Spanish and Portuguese area) and the Bay of Cadiz (Fig. 1). In addition, data from research projects around Spain have also been summarized and taken into account (Medialdea et al. 1982, 1986, 1989, 1990, 1994; González et al. 1994).

The methodology used includes (1) detailed bathymetric and geomorphological analyses; (2) sedimentological analyses of 440 sediment samples (dredges and cores) from northwest of the Alboran Sea; and (3) seismic and sequence stratigraphy analyses involving very high resolution seismic reflection profiles (3.5 kHz, Geopulse-Uniboom, and Sparker systems).

Infralittoral prograding wedge

The Late-Holocene IPW around the Spanish coast is a narrow, shore-parallel depositional body (about 1–2 km wide, 20–30 m thick, and 10–100 km long) which develops seawards from the lower edge of the shoreface (Figs. 2–5). This sedimentary body can be laterally related to coeval deltaic deposits or it can also appear as an isolated body not linked to deltaic deposits. The IPW developed during the last highstand system tract of the last fourth-order cycle which took place during the last 6500 years B.P. (Hernández-Molina et al. 1994; Somoza et al. 1998; Dabrio et al. 2000; Hernández-Molina et al. 2000). The IPW may overlay either (1) a 6–12 m thick, seismically transparent wedge-shaped unit with parallel low-amplitude reflectors (Figs. 3, 4), representing the Holocene deposits during the maximum eustatic event (Hernández-Molina et al. 1994, 2000) in areas close to river mouths or having a high sediment supply and strong littoral currents; (2) a lower transgressive sand or gravel layer; or (3) a succession of small backstepping units (Figs. 3, 4) which represent the last transgressive system tract. The latter two possibilities may occur either far from river mouths or close to river mouths with low rates of sediment supply.

In terms of seafloor morphology, the IPW forms a relatively narrow zone seawards of the shoreface which extends to a water depth of 10 m (Figs. 2, 4). Further seawards, the IPW forms a low-angle slope (0.6° on average) which represents the infralittoral prograding environment, extending to a strong break in slope at

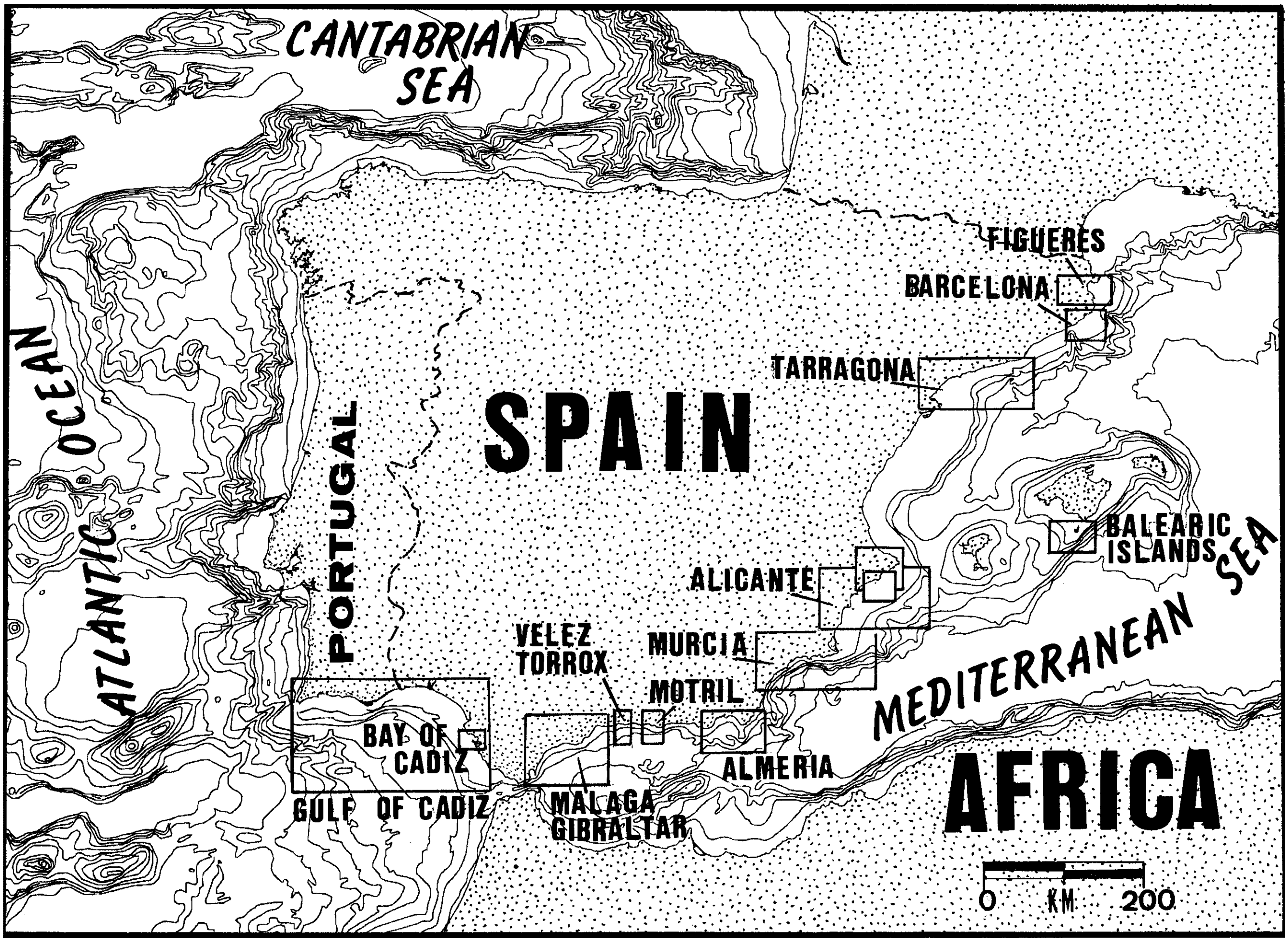
Fig. 1 Location of infralittoral prograding study areas (*boxes*)

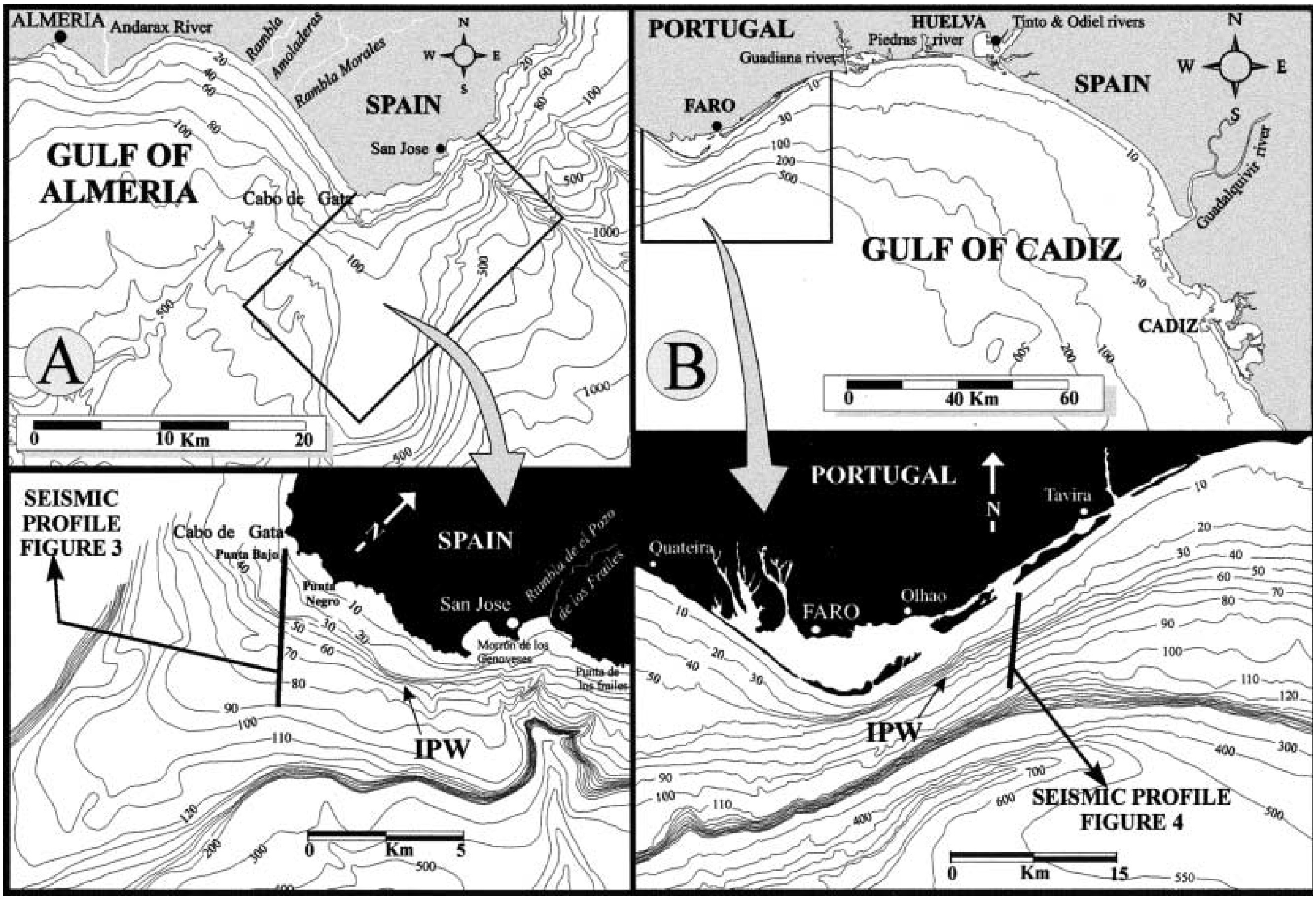

Fig. 2 Sketch of the infralittoral prograding wedge (*IPW*) in front of *A* Cabo de Gata (Almeria, Mediterranean Sea), and *B* Faro (Gulf of Cadiz, Atlantic Ocean), showing the bathymetric and main geographical features of the area as well as the location of the high-resolution reflection seismic lines in Figs. 3 and 4

water depths of 20–25 m in the Mediterranean areas, and 30–35 m in the Atlantic areas (Figs. 2–5). These depths correspond to the mean level of the storm wave base in each case, and could represent the closure depth for engineers. Seawards of this break point, a slope (2.10° on average) extends to water depths of 40–50 m. Even further seawards, a decrease in the angle of the slope characterizes the slope toe, evolving seawards to the inner continental shelf.

Two main types of sediment have been differentiated in the IPW (Fig. 5).

1. Infralittoral sands: these are composed of well-sorted, very fine and fine sands. They are texturally homogeneous, very continuous laterally, and present in the infralittoral prograding domain to water depths of 20–25 m. This facies is characterized by a gradual seaward decrease in sand content and increase in mud content.
2. Infralittoral slope sands: these are silty sands present at water depths of 25–50 m on the slope and occasionally extending onto the inner shelf. Seawards of the IPW, the inner continental shelf may be composed of either relict muddy sands or modern and palimpsest clayey silts derived from adjacent deltaic systems (Fig. 5).

Internally, the IPW is characterized by an upward and outward-prograding sedimentary wedge (Figs. 3–5). Topsets are usually thin (only a few meters, and consequently recognized only by seismic profiles of 3.5 kHz), and have an aggradational configuration characterized by high acoustic reflectivity, subhorizontal reflectors with common amalgamations, erosion surfaces and, locally, infilled erosion troughs (Fig. 3). Foresets are composed of seaward-dipping progradational clinoforms characterized by high to very high acoustic reflectivity and sharp to weak sub-bottom reflectors. The lower boundary is a downlap surface, the upper boundary is a toplap surface, and internal downlap surfaces are common (Figs. 3–5). Bottomsets are composed of low-angled, seaward-dipping layers which converge towards the basin, and generally display a transparent to weak acoustic response (Fig. 3). Layers with very high reflectivity may be present locally between the foreset and bottomset layers, probably representing coarse sand or gravel at the base of the foresets. The origin of coarser sediments at the base of the IPW is important because it has previously been considered to represent a reworked transgressive facies (Swift et al. 1991), usually expected to form between the

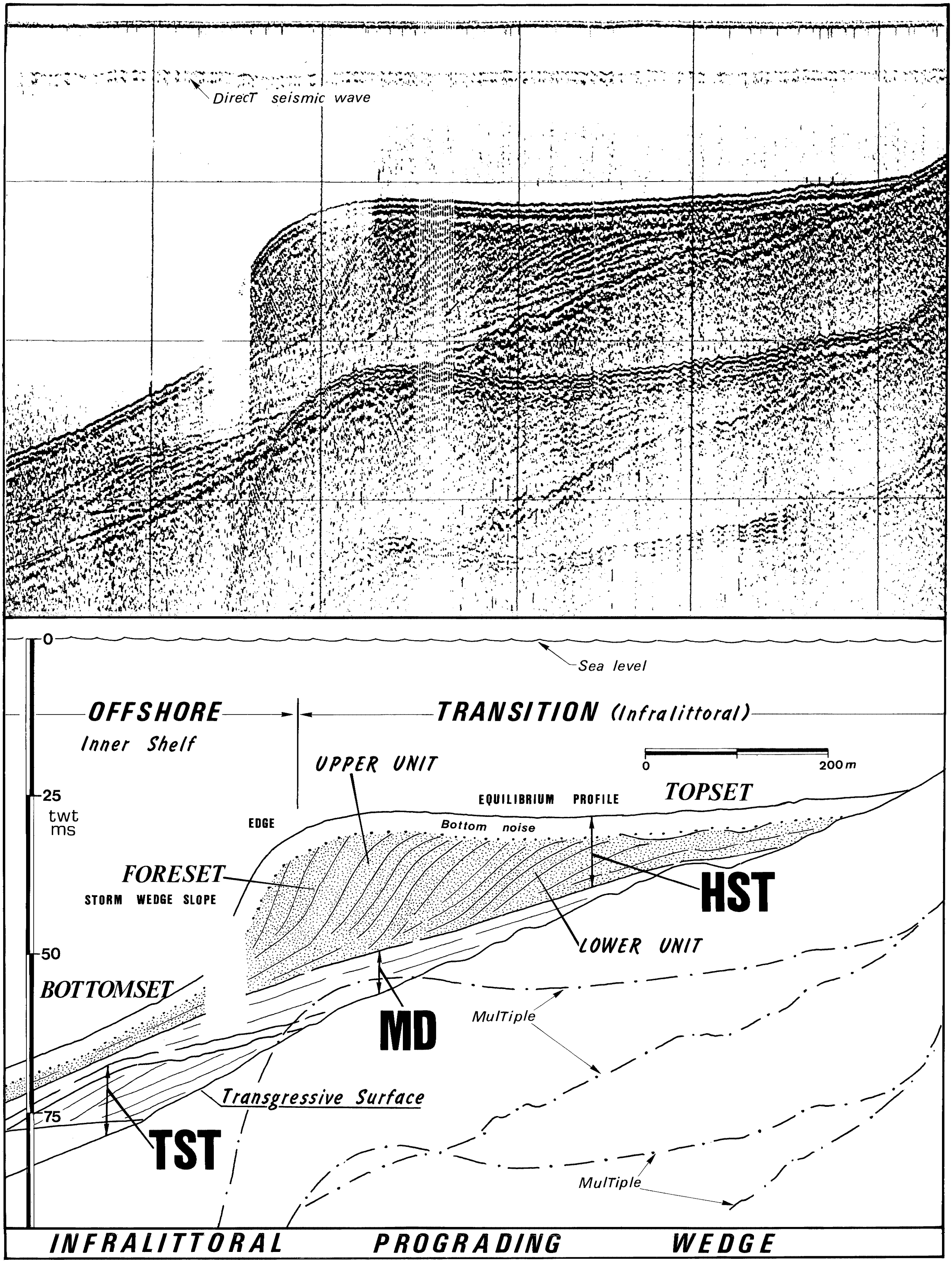
DirecT seismic wave
0
Sea level
OFFSHORE
Inner Shelf
TRANSITION (Infralittoral)
0
200m
UPPER UNIT
25
twt
ms
EQUILIBRIUM PROFILE
TOPSET
EDGE
Bottom noise
FORESET
STORM WEDGE SLOPE
HST
LOWER UNIT
50
BOTTOMSET
MD
MulTiple
Transgressive Surface
75
TST
MulTiple
INFRALITTORAL PROGRADING WEDGE

Fig. 3 High-resolution seismic profile (Geopulse, 175 J) in the Mediterranean infralittoral prograding environment off Cabo de Gata, Almeria (see Fig. 2 for location; adapted after Hernández-Molina et al. 1995). Note the transgressive system tracts (*TST*), maximum eustatic deposits (*MD*), and highstand system tracts (*HST*) of the Late-Holocene infralittoral prograding wedge (IPW)

zone of downwelling transport and the beach. In ancient rocks of western Canada, this facies has been reported to be sharp-based sandstones (Plint 1988).

Very high resolution seismic and sequence stratigraphy analyses enable us to differentiate two internal seismic units (Figs. 3, 4) within the IPW, determined by Hernández-Molina et al. (1994, 1995, 2000), Fernández-Salas et al. (1996), and Somoza et al. (1998). These are (1) a lower wedge-shaped progradational unit (6500–5200 years B.P.) with a sigmoid-oblique configuration, becoming transparent in a seaward direction; and (2) an upper wedge-shaped progradational unit (3700 years b.p. to Present) with an oblique-tangential configuration. Both units are generally present in the Holocene deposits, and are considered separate deposits related to two minor-order, asymmetrical, relative sea-level fluctuations (sixth-order cycles) which modulated the Late-Holocene sea-level highstand. These allocyclic processes controlled the sedimentary stacking and evolution of the IPW.

The Late-Holocene IPW is considered to have originated in storm-generated currents (downwelling currents) which produce a seaward sediment transport and deposition of distal infralittoral silty sands, and sometimes coarse sand or gravel, at the base of the foresets (Fig. 5). During storms, sediments are shed downslope to below the storm wave base. Accommodation has been defined as the space available below base level, which on the continental margin is equivalent to sea level (Jervey 1988). However, it is the level of the storm wave base which actually controls the available accommodation space (and, therefore, the depositional equilibrium profile and depositional shoreline break; Fig. 5) because storm waves act like a “carpenter’s broom”, sweeping the sediment eroded from the beach seawards. Sediments avalanched onto the infralittoral slope during the Late-Holocene sea-level highstand are preserved as stable deposits.

Discussion

Several studies have described Holocene stratigraphic features and sedimentary bodies similar to the IPW, like the prograding prodeltaic wedges on shelves off the mouths of major rivers such as the Amazon, Yangtze and

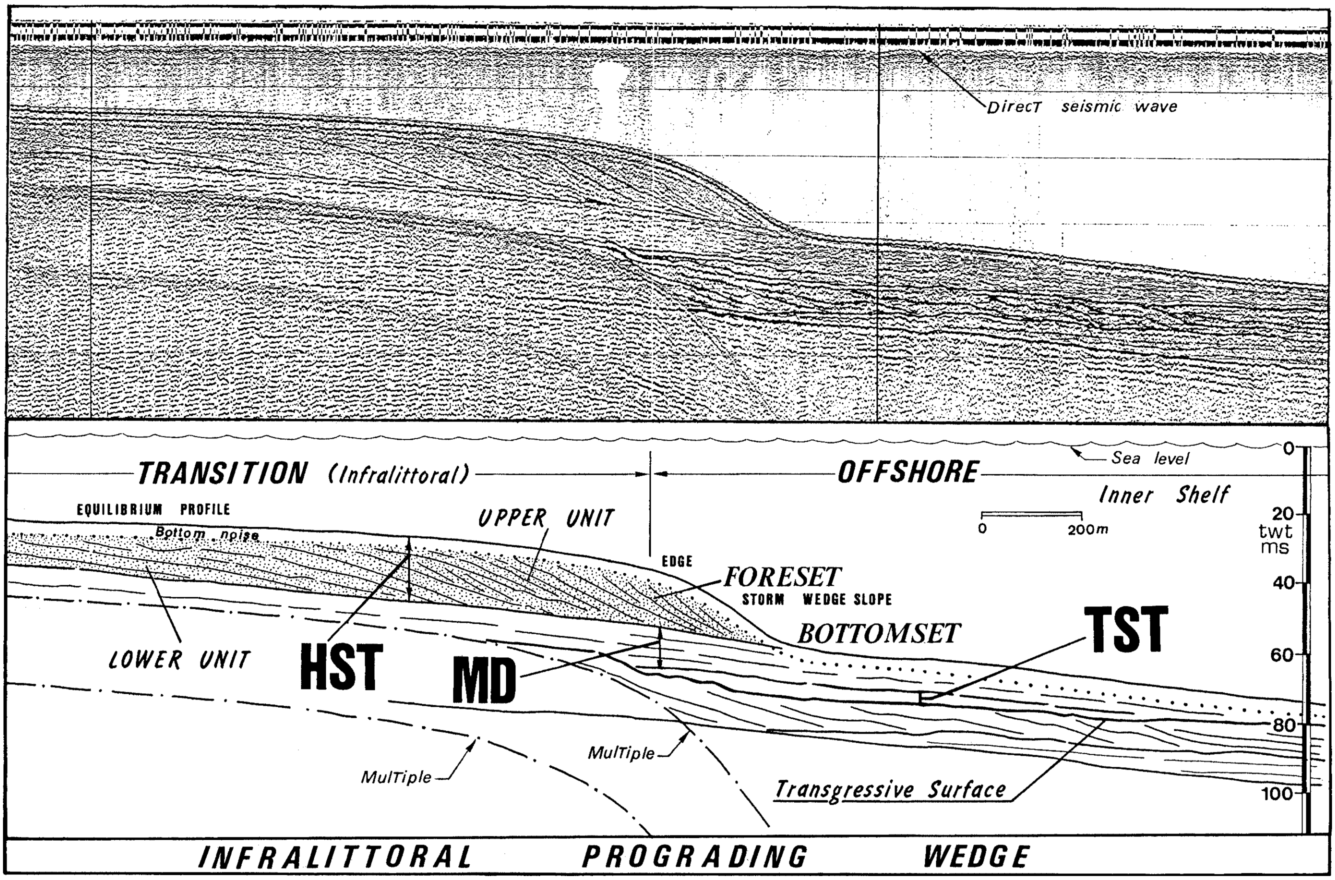

Fig. 4 High-resolution seismic profile (Geopulse, 175 J) in the Atlantic infralittoral prograding domain off Faro, Gulf of Cadiz (see Fig. 2 for location). Note the transgressive system tracts (*TST*), maximum eustatic deposits (*MD*), and highstand system tracts (*HST*) of the Late-Holocene infralittoral prograding wedge (*IPW*)

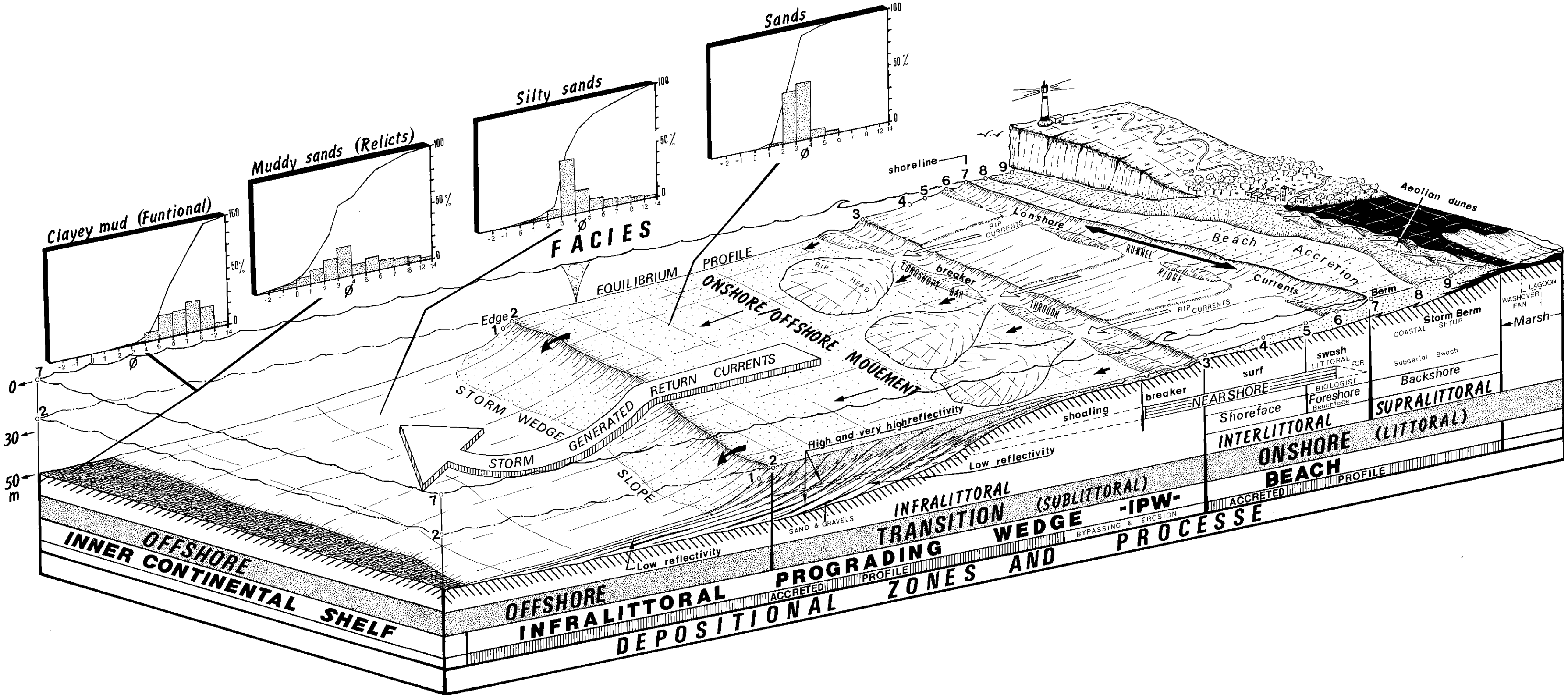

Fig. 5 Depositional model for the infralittoral prograding wedge (*IPW*), indicating morphological characteristics, depositional zone and processes, internal sedimentary stacking pattern, and sedimentary facies. *Reference points 1–8* along offshore, transitional and onshore sections of the profile are: *1* Exceptional storm wave base; *2* mean storm wave base (closure depth for engineers); *3* mean fair-weather wave base; *4* maximum spring low-tide level; *5* mean low-tide level (*MLW*); *6* mean tide level (mean sea level); *7* mean high-tide level (*MHW*); *8* maximum spring high-tide level; *9* maximum storm-action level (storm cut). Also shown are depth-related sediment facies

Ganges-Brahmaputra. These features are typified as subaqueous deltas, prodelta shelf scarps or constructional shelf scarps (Swift et al. 1991), although these bodies may be considered as shelf terraces from a geomorphological viewpoint (Swift, personal communication). We think that IPWs can not be considered as deltas because they develop in littoral areas without significant fluvial supply. Also, the IPW is not necessarily laterally related with coeval deltaic deposits. Nevertheless, the upper surface of subaqueous deltas or prodeltaic shelf scarps could be controlled by the same processes as those active at the upper surface of the IPW.

Sedimentary bodies similar to the IPW

Modern and ancient examples of sedimentary prisms have been explained in the same way as the IPW. For example, Chiocci and Orlando (1996) have reported similar sedimentary bodies in the outer shelf of the Tyrrhenian Sea (western Mediterranean) but considered them as lowstand depositional terraces from a morphological point of view. Also, ancient counterparts of Holocene IPWs have recently been documented in outcrops of the Upper Pliocene–Lower Pleistocene Calcarenite di Gravina around Matera in southern Italy (Pomar and Tropeano 2000). These outcrops contain continuous exposures of coarse-grained tabular sand bodies which are laterally extensive and parallel to the paleoshoreline, prograding seawards with large-scale cross beds. In this example, progradation is interpreted (likewise to the IPW) as the result of sediment being swept from the shoreface by waves and wind-driven currents, and avalanching seawards onto a depositional slope below wave-base level during storms.

Sedimentary bodies similar to the IPW but interpreted differently

Other authors have described sedimentary bodies similar to the IPW, interpreting them as shoreface or deltaic (prodeltaic) deposits. Thus, Field and Roy (1984) described large prograding Holocene sand bodies in a steep high-energy environment between the coast and the inner shelf south of Sydney (Australia) with characteristics similar to those of the IPW. These have been interpreted as lower shoreface deposits, formed by offshore sand transport as a result of downwelling currents originating during storms. Subsequently, Roy et al. (1992, 1994) interpreted the same features as sandy drowned barriers prograding seawards on the inner shelf. In our opinion, these sand bodies are not shoreface deposits. They probably represent IPWs as defined in this paper because (1) they occur between the beach and the inner continental shelf, and (2) their geometry, surface morphology, seismic expression, and sedimentary facies do not correspond to standard sedimentary facies of a shoreface. In other studies such deposits have been interpreted as Late-Holocene IPWs formed by storm fan-delta deposits (García-Gil et al. 1998, 1999).

Furthermore, Late Pleistocene–Holocene lowstand (outer shelf) and transgressive (mid shelf) deposits with seismic expressions similar to the IPW have been described in many recent articles (Aloïsi 1986; Dias and Maldonado 1990; Field and Trincardi 1991; Trincardi and Field 1991; Gensous et al. 1993; Tesson et al. 1993; Browne 1994; Hernández-Molina et al. 1994, 1995; Gensous and Tesson 1996; Lobo et al. 1999; Hernández-Molina et al. 2000). Moreover, Late-Quaternary sedimentary outcrops along the southern coast of Spain have been interpreted as beach deposits related to Tyrrhenian sea-level highstands (Dabrio et al. 1984, 1985; Goy et al. 1989; Zazo et al. 1993, 1998). Although most of these Late Pleistocene–Holocene deposits are considered to be beach and shoreface deposits, we suggest that they are genetically equivalent to the Late-Holocene IPW. Similarly, older examples of large-scale cross-bedded sand bodies deposited in shallow clastic seas and with a similar facies architecture may also be reinterpreted as IPWs. Examples are the Pliocene prograding sedimentary bodies of Vitale (1988), later defined as an inclined shoreface by Colella and Vitale (1998), and the sandstone depositional wedge in the Cretaceous of the Western Interior Seaway (North America) which was interpreted as a shoreface by MacEachern and Pemberton (1992).

Conclusions

The Late-Holocene IPW along the Spanish coast has been prograding during the last 6500 years. It corresponds to the highstand system tract of the last fourth-order cycle (Hernández-Molina et al. 1998, 2000). The IPW developed during a relative stillstand of sea level over a relatively steep infralittoral domain, with medium to high wave energy and significant sediment supply by longshore and downwelling currents.

The Late-Holocene IPW represents a new depositional model for wave-dominated clastic coasts without deltaic sedimentation. It has specific sedimentological and stratigraphic characteristics, and occupies a particular position in the depositional equilibrium profile between the onshore and offshore depositional environments. Late-Holocene IPWs are considered to have been formed by storm-generated currents (downwelling currents) which produce a seaward sediment transport. Their identification requires a new subdivision of the inner shelf which should be taken into account when interpreting the facies and stratigraphic architecture of both modern and ancient counterparts.

The existence of IPWs between the shoreface and the inner shelf needs to be taken into consideration when interpreting Quaternary relict coastal deposits as indicators of ancient sea-level positions. If the relict deposits are really IPWs then, depending on the hydraulic energy conditions (waves and wind-induced currents), the associated sea-level positions would be located 20–30 m above such deposits, and not at the level of their upper boundary as has been reported by some authors who considered the foresets of these bodies to represent beach and foreshore or shoreface deposits. In this sense, some Pleistocene and Holocene coastal deposits, dated by U-series, ^{14}C, Th/U, amino-acid racemization or paleomagnetism and considered beaches or fan deltas, are false indicators of Quaternary sea-level positions.

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