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Shelves around the Iberian Peninsula (II): Evolutionary sedimentary patterns

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ABSTRACT

We present a synthetic view of continental-shelf evolutionary patterns around the Iberian Peninsula, focusing on proposed sequence stratigraphy interpretations and attempting a comparison between Atlantic- and Mediterranean-type shelf-margin constructions.

Most of the studied shelves show a dominance of regressive to lowstand deposition through successive progradations, particularly evident in the Pliocene-Quaternary, documenting the influence of glacio-eustasy. Transgressive to highstand development predating the Last Glacial Maximum seems to be favoured off major rivers, but the highest variability is seen during postglacial evolution. Transgressive deposits tend to show a higher spatial variability, ranging from prograded parasequences to extensive sand sheets. Holocene highstand deposits usually show a more homogeneous character, with development of proximal wedge-shaped deposits and a distal sheet-like deposition.

Atlantic continental shelves off Iberia display three different types of shelf growth: depositional shelves, shelves with restricted progradation and erosional shelves. They result from the interplay between depositional and hydrodynamic regimes, with the occurrence of a latitudinal gradation from erosional shelves in the Cantabrian continental shelf to depositional shelves in the northern Gulf of Cadiz shelf. Some shelf sectors do not correspond to this general pattern, as shelf sedimentation is mainly controlled by morpho-structural features (e.g., ria environments and shelves crossed by major tectonic accidents). The Mediterranean continental shelves of Iberia show two basic types, high- versus low-supply shelves, and their growth patterns are mainly a response to the amount of fluvial supply. The low-supply style is clearly the most frequent type, and it may show further complexity according to the occurrence of submarine canyons and/or morpho-structural control.

Key words: continental shelves, Iberian Peninsula, glacio-eustasy, long-term evolution, morpho-structure, sediment supply, sequence stratigraphy.

Las plataformas continentales de la Península Ibérica (II): Patrones sedimentarios evolutivos

RESUMEN

Presentamos una visión sintética de los patrones sedimentarios evolutivos de las plataformas continentales de la Península Ibérica, con un énfasis particular en las interpretaciones de estratigrafía secuencial propuestas y con el objetivo de realizar una comparación entre los estilos de construcción de plataformas continentales en el Atlántico y el Mediterráneo.
La mayor parte de las plataformas estudiadas muestran un claro predominio de los depósitos progradantes desarrollados durante intervalos de descenso relativo y de bajo nivel del mar, lo cual es particularmente evidente en el registro sedimentario Plioceno-Cuaternario, reflejando el control primario de los cambios glacio-eustáticos. Los depósitos transgresivos y de alto nivel del mar previos al Último Máximo Glacial parecen estar mejor representados en plataformas continentales influenciadas por los grandes cursos fluviales. Los depósitos transgresivos postglaciales muestran una gran variabilidad espacial, cambiando lateralmente desde parasecuencias progradantes hasta extensas láminas arenosas. Por el contrario, los depósitos de alto nivel del mar Holocenos muestran un carácter más homogéneo, con desarrollo de cuñas sedimentarias proximales y depocentros fangosos distales.
Los diferentes estilos de crecimiento de las plataformas continentales atlánticas de Iberia resultan básicamente de la interacción entre los regímenes deposicionales e hidrodinámicos, observándose una gradación latitudinal de plataformas desde la plataforma erosiva del Mar Cantábrico a la plataforma deposicional del Golfo de Cádiz. Localmente, se identifican algunos sectores de la plataforma que no responden a este patrón general, sino que su crecimiento está controlado por rasgos morfo-estructurales (por ejemplo, los ambientes de rías y las plataformas atravesadas por accidentes tectónicos mayores). Los patrones de crecimiento de las plataformas mediterráneas de Iberia están estrechamente relacionados con el aporte fluvial, diferenciándose dos estilos básicos: plataformas con alto aporte y plataformas con bajo aporte sedimentario. El estilo de bajo aporte sedimentario es el tipo más frecuente, el cual puede mostrar una mayor complejidad en función de la existencia de cañones submarinos y/o de rasgos morfoestructurales.

Palabras clave: plataformas continentales, Península Ibérica, glacio-eustasia, evolución a largo plazo, morfoestructura, aporte sedimentario, secuencia estratigráfica.

VERSIÓN ABREVIADA EN CASTELLANO

Introducción

La evolución sedimentaria de las plataformas continentales de Iberia está controlada fundamentalmente por fluctuaciones glacio-eustáticas (Fig. 1). Este factor de control ha sido determinado en las plataformas continentales atlánticas de Iberia para gran parte de la era Cenozoica. Por el contrario, la evolución sedimentaria de las plataformas continentales mediterráneas de Iberia durante el Plioceno-Cuaternario ha estado condicionada por la Crisis de Salinidad del Messiniense que favoreció el desarrollo de una superficie de erosión muy marcada a partir de la cual se construyó el perfil deposicional de las plataformas continentales. En este trabajo se presenta una visión sintética de los patrones sedimentarios evolutivos de plataformas continentales de Iberia, con dos objetivos fundamentales: (1) determinar la arquitectura sedimentaria por medio de una aproximación de estratigrafía secuencial; (2) realizar un análisis comparativo de la evolución de las plataformas atlánticas y mediterráneas.

Resultados y discusión

Las plataformas continentales de la Península Ibérica se han dividido en siete sectores de acuerdo con el contexto geo-morfológico y las condiciones regionales de aporte sedimentario y oceanográficas: (1) Cantabria; (2) Galicia; (3) Oeste de Portugal; (4) Golfo de Cádiz; (5) Mar de Alborán; (6) Sudeste de Iberia; y (7) Nordeste de Iberia. A continuación se presenta la arquitectura sedimentaria de las plataformas continentales de Iberia siguiendo el orden de los sectores citados anteriormente.

La plataforma continental cantábrica está compuesta en gran medida por depósitos progradantes deformados, generados durante descensos del nivel del mar del Plioceno-Cuaternario, y únicamente sedimentación marginal durante intervalos de bajo nivel del mar (Fig. 2). La sedimentación postglacial está dominada *por la formación de cuerpos fangosos en zonas del margen con una configuración geomorfológica favorable para la acumulación sedimentaria.*

La plataforma continental de Galicia está caracterizada por el depósito preferente durante condiciones de descenso relativo del nivel de mar, con desarrollo ocasional de patrones de apilamiento indicativos de transgresión-alto nivel del mar en el pre-Cuaternario. Durante el Cuaternario, gran parte del relleno sedimentario ha quedado atrapado en las rías, destacando la formación de depósitos transgresivos por encima de la superficie erosiva del Último Máximo Glacial (Fig. 3). Dichos depósitos transgresivos han sido relacionados con el nivel del mar fluctuante condicionado por eventos climáticos como el Younger Dryas.

La plataforma continental Oeste de Portugal está compuesta por cuñas progradantes y valles encajados frente a los cursos fluviales más significativos durante el Cuaternario (Fig. 4). La arquitectura sedimentaria postglacial está caracterizada por una gran variabilidad de ambientes sedimentarios. Durante la estabilización Holocena, se ha generado un cinturón fangoso en la plataforma septentrional.

La plataforma continental del Golfo de Cádiz está definida por el predominio de cuñas progradantes regionales interpretadas como cortejos sedimentarios regresivos y de bajo nivel del mar durante el Plioceno-Cuaternario. El registro sedimentario del Cuaternario muestra la intercalación de unidades progradantes y unidades de espesor constante, que se interpretan como el resultado de sedimentación durante condiciones de descenso-bajo nivel del mar y ascenso-alto nivel del mar (Fig. 5), y se han asociado al control principal de los ciclos eustáticos de 100 ka de periodicidad. Las secuencias sedimentarias están atribuidas a la superposición de ciclos de 20 ka. Los depósitos transgresivos postglaciales exhiben una gran variabilidad, desde cuñas progradantes costeras a depósitos arenosos de espesor moderado y constante generados por el retrabajamiento durante la retirada erosiva de la línea de costa. Los depósitos de alto nivel Holocenos incluyen depósitos deltaicos de distinta naturaleza, cuñas progradantes infralitorales, cinturones fangosos y cuerpos arenosos de plataforma media-externa.

La plataforma continental septentrional del Mar de Alborán muestra una arquitectura sedimentaria similar a la descrita en el Golfo de Cádiz durante el Plioceno-Cuaternario, con dominancia de facies progradantes atribuidas a Cortejos Sedimentarios Regresivos y de Bajo Nivel del Mar (Fig. 6). No obstante, la compartimentación del margen continental de Alborán posibilita la formación de patrones de apilamiento transgresivos y/o del alto nivel del mar en determinadas zonas del margen. El registro postglacial muestra un Cortejo Sedimentario Transgresivo poco desarrollado y un Cortejo Sedimentario de Alto Nivel del Mar formado por depósitos deltaicos arenosos y de elevada inclinación, producto de flujos sedimentarios de alta energía, que lateralmente evolucionan a cuñas progradantes infralitorales en zonas sin aportes fluviales directos.

La plataforma continental del Sudeste de Iberia está caracterizada por una gran variabilidad de patrones de apilamiento (Fig. 7), donde zonas subsidentes alternan lateralmente con zonas que experimentan levantamiento durante el Plioceno-Cuaternario. La plataforma durante el Cuaternario está definida por el predominio de cuñas progradantes atribuidas a los períodos de descenso-bajo nivel del mar. La arquitectura del registro postglacial no se conoce en detalle, pero se identifican parasecuencias transgresivas, pequeños depósitos deltaicos y cuñas infralitorales.

La plataforma continental del Nordeste de Iberia está definida por un prisma sedimentario Plioceno-Cuaternario acumulado sobre una importante superficie de erosión atribuida al descenso del nivel del mar Messiniense. La arquitectura sedimentaria del Cuaternario muestra la superposición de cuñas progradantes regresivas cuya génesis se atribuye a la influencia de los ciclos eustáticos de 100 ka (Fig. 8). Las facies transgresivas postglaciales muestran el predominio de cuerpos arenosos de espesor moderado, indicativos de unas condiciones de aporte sedimentario limitadas. El Cortejo Sedimentario de Alto Nivel del Mar Holoceno muestra deltas de dimensiones variables y cuñas infralitorales en segmentos específicos de la línea de costa.

A gran escala temporal, los patrones evolutivos de las plataformas continentales alrededor de Iberia muestran secuencias dominadas por depósitos regresivos y de bajo nivel del mar, con un mayor desarrollo de depósitos transgresivos y/o de alto nivel del mar en zonas subsidentes durante el Plioceno-Cuaternario. A escala Cuaternaria, las secuencias se han desarrollado al menos durante el Cuaternario Medio-Superior bajo la influencia directa de ciclos de Milankovitch de 100 ka. Estas secuencias muestran en las zonas de mayor influencia fluvial valles encajados. Los depósitos transgresivos y de alto nivel del mar pre-glaciales muestran en general un desarrollo limitado. Los depósitos postglaciales muestran una variabilidad muy elevada, en repuesta a diferentes condiciones de aporte sedimentario, cambio relativo del nivel del mar e intensidad de procesos hidrodinámicos.

Los patrones sedimentarios evolutivos de las plataformas continentales atlánticas y mediterráneas de Iberia son diferentes. Las plataformas continentales atlánticas reflejan una gradación latitudinal, desde plataformas erosivas en el Mar Cantábrico hasta plataformas deposicionales en el Golfo de Cádiz, producto de la interacción entre el régimen deposicional y las condiciones hidrodinámicas. Localmente, se identifican segmentos de plataforma con un fuerte control morfo-estructural, como las rías-plataformas de Galicia o las plataformas surcadas por accidentes tectónicos mayores (Fig. 9). Los patrones evolutivos de las plataformas continentales mediterráneas son fundamentalmente una respuesta a las condiciones de aporte fluvial, dife-

renciándose las plataformas de alto aporte representada por la plataforma del Ebro y el resto de plataformas continentales mediterráneas, consideradas como de bajo aporte sedimentario. Éstas últimas pueden mostrar una mayor variabilidad, en función de la existencia de cañones submarinos y/o de control morfo-estructural (Fig. 10).

Introduction

The growth and evolutionary patterns of peri-continental shelves are determined to a large extent by allocyclic glacio-eustatic fluctuations. Atlantic-type shelves represent a significant example of this kind of evolutionary pattern, as glacio-eustasy is a major driver of sequence boundary generation during most of the Cenozoic epoch (e.g., Browning *et al.*, 2013; Katz *et al.*, 2013). The growth patterns of Mediterranean shelves are slightly different, as the stratigraphic record of most Mediterranean margins is strongly marked by the occurrence of the Messinian Salinity Crisis that led to a large sea-level fall (Hsü *et al.*, 1973) causing extreme erosion and incision on the margins, with development of a pronounced unconformity (the Messinian erosional surface) and large canyon systems. This surface was overlain by a thick Pliocene-Quaternary progradational prism which re-established typical shelf-slope morphologies (Lofi *et al.*, 2003; García *et al.*, 2011).

During the Quaternary, Milankovitch-type, sea-level cyclicity has governed the main cycles of continental shelf growth at different time scales; particularly, Middle-Upper Pleistocene sequences have formed under the control of 100 and 20 ka cycles (Fig. 1). 100 ka sea-level cycles are the expression of glacial-interglacial cycles during the last ca. 800 ka; these cycles were characterized by long-lived, sea-level falls and abrupt sea-level rises connecting short-lived lowstands and highstands (e.g., Siddall *et al.*, 2007) (Fig. 1A). The most recent 100 ka cycles are modulated by

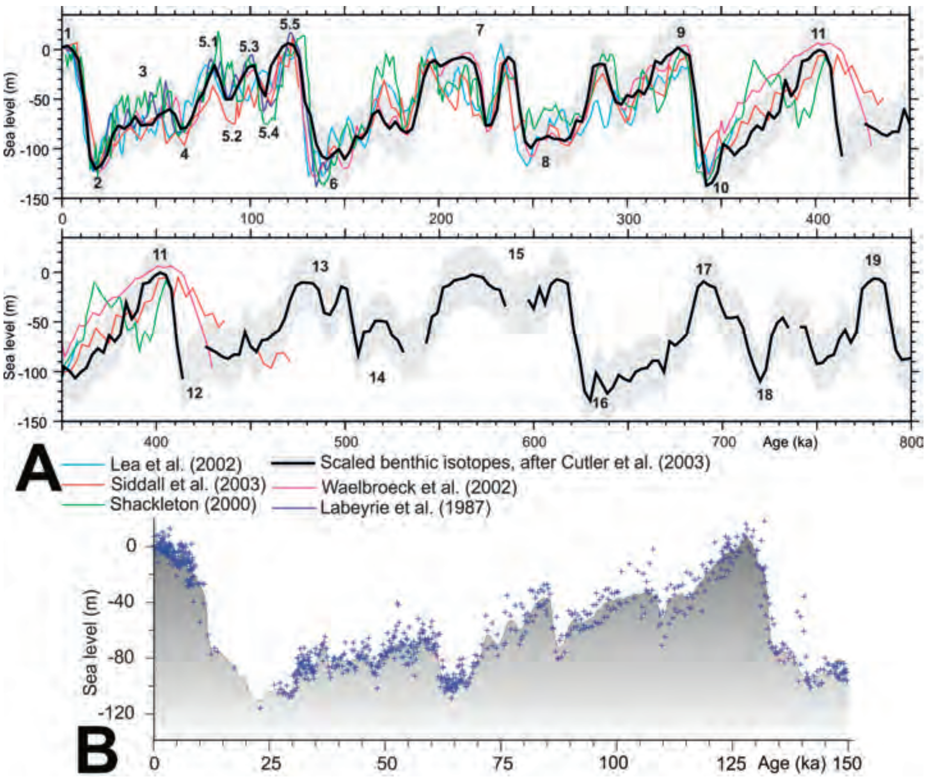

Figure 1. Patterns of Middle to Late Quaternary sea-level change. (A) The pattern of sea-level change during the last 800 ka obtained from different oxygen isotopic sources. Marine isotope stages are numbered. Modified from Siddall *et al.* (2007). (B) Relative sea-level data (blue crosses) and maximum-probability of relative sea-level (grey shading) for the last 150 ka. Modified from Grant *et al.* (2012).

Figura 1. *Curva de cambio del nivel del mar durante el Cuaternario Medio y Superior. (A) Curva de cambio de nivel del mar durante los últimos 800 ka obtenido a partir de diferentes fuentes de isótopos de oxígeno. Modificado a partir de Siddall* et al. *(2007). (B) Cambios relativos del nivel del mar (cruces azules) y probabilidad máxima de variación relativa del nivel del mar (sombreado gris) para los últimos 150 ka. Modificado a partir de Grant* et al. *(2012).*

sea-level cycles of shorter duration (i.e., 20 ka) that are related to stadial interstadial climatic variability. In general terms, 20 ka sea-level cycles also display an asymmetric character, with stepped, relatively gentle sea-level falls and abrupt stadial terminations (e.g., Siddall *et al.*, 2010; Grant *et al.*, 2012) (Fig. 1B). The last major sea-level fall led to the LGM at around 19-20 ka, when sea levels fell between 120 m (e.g. Fairbanks, 1989; Bard *et al.*, 1996; Hanebuth *et al,* 2000) and 140 m below the present-day level and the coastline was located near the shelf edge (Dias, 1987; Dias *et al.*, 2000; Rodrigues *et al.*, 2000). The post LGM sea-level rise was not monotonic, intervals of high rates of sea-level rise known as Meltwater Pulses were disrupted by short-lived stillstands (Fairbanks, 1989, Bard *et al.*, 2010; Deschamps *et al.*, 2012).

The 100 ka sequences exhibit a relatively homogeneous character and composition in most margin settings (e.g., Rabineau *et al.*, 2005; Bassetti *et al.*, 2008; Ridente *et al.*, 2009), being mainly composed of stacked progradational wedges involving progradation during periods of relative sea-level fall. However, the expression of 20 ka sequences is more variable as a function of oceanographic regimes and conditions of sediment flux and transport (Lobo and Ridente, 2014). The stacking pattern of the sequences appears to be controlled by the relationship between the rates of subsidence and sediment supply (e.g., Lofi *et al.*, 2003; Maselli *et al.*, 2010; Rabineau *et al.*, 2014).

Continental shelves contouring the Iberian Peninsula constitute an outstanding example for understanding the different factors involved in shelf margin development, and in particular to attempt a comparison between Atlantic- and Mediterranean-style growth patterns. Some recent synthetic studies have summarized several continental-margin, geological features around the peninsula; however, these studies have either been restricted to the description of large-scale seafloor geomorphology (Maestro *et al.*, 2013) or focused on the deep-water sedimentary record, namely along-slope contourite features (Hernández-Molina *et al.*, 2011). In order to fill the gap in knowledge regarding the shelf environment, we summarize the existing knowledge concerning continental shelf evolution around the Iberian Peninsula, with emphasis on: (1) sequence stratigraphic patterns: and (2) the distinction between Atlantic- and Mediterranean-type shelf construction. We have followed the same partition of shelf sectors used in the companion paper dealing with shelf morphology and sediments (Fernández-Salas *et al.*, this issue). Readers are also referred to this study for documenting regional geological and oceanographic conditions prevailing in each of the shelf sectors. For sequence stratigraphy-based interpretations, we adhere to the four-fold subdivision of system tracts developed during a cycle of relative sea-level change: lowstand systems tract (LST), transgressive systems tract (TST), highstand-systems tract (HST) and falling-stage systems tract (FSST) (or equivalent terminology for deposits generated during falling sea-level conditions, such as regressive-system tracts, or falling regressive wedge-system tracts) and the most important bounding surfaces, such as the sub-aerial unconformity, the transgressive surface and the maximum flooding surface (e.g., Zecchin and Catuneanu, 2013).

Continental Shelves around the Iberian Peninsula: Sedimentary Architecture and Evolution

The Cantabrian Continental Shelf

The Cantabrian continental shelf occupies the northern margin of the Iberian Peninsula in the Bay of Biscay (Fig. 2A). Knowledge regarding the construction of this shelf is very limited at present.

Pre-Quaternary

In general, the shelf is poorly developed (Fig. 2A) due to an efficient downslope sediment transfer through canyons and channels (Ercilla *et al.*, 2008). The opening and oceanic spreading of the Bay of Biscay clearly dictated the embrionary geomorphological configuration of the margin during the Mesozoic. Carbonate sedimentation was established on the continental shelf during the Cretaceous, with a maximum thickness greater than 2 km (Pascual *et al.*, 2004). The sedimentary architecture of the Cantabrian continental shelf shows oblique-parallel configurations of inferred Cretaceous to Miocene age (Fig. 2B), frequently disrupted and/or deformed by faults and folds (Vigneaux, 1974). The Cenozoic convergence between the Iberian and European plates caused the overall steep geomorphology of the margin (Maestro *et al.*, 2013).

Quaternary

The sedimentary architecture of the Cantabrian continental shelf reveals periodic shelf erosion during this time, and only residual deposition at the shelf margin during the Late Pleistocene (Ercilla *et al.*, 2008) (Fig. 2C). Repeated sea-level oscillations are recorded on the shelf by incised valleys (Pascual *et al.*, 2004; Galparsoro *et al.*, 2010).

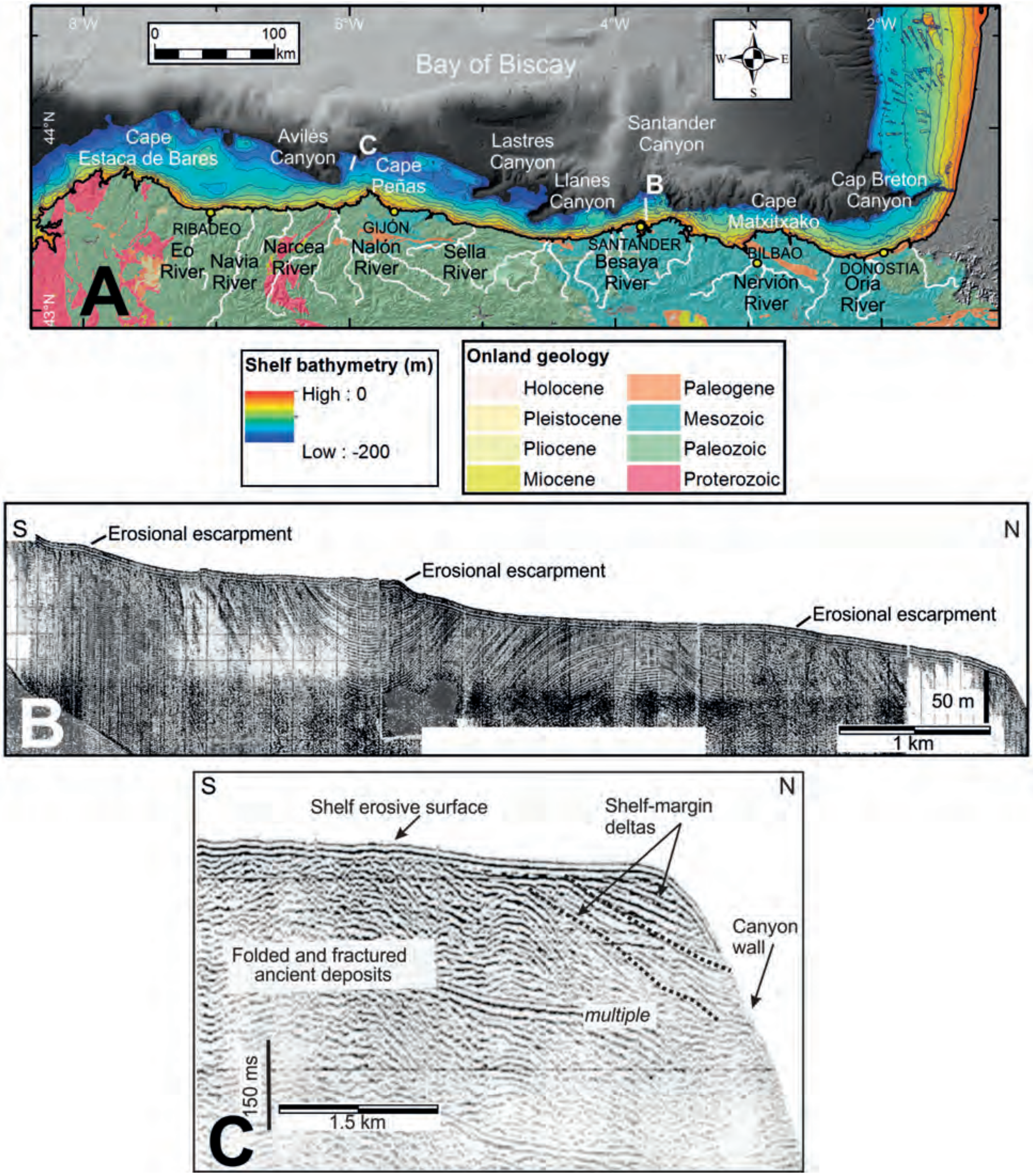

Figure 2. Representative examples of the sedimentary architecture of the Cantabrian continental shelf. (A) Physiographic setting of the Cantabrian margin highlighting the shelf bathymetry, with indication of the onland geology, river systems and location of representative seismic profiles (examples B and C). (B) Geopulse seismic profile showing heavily folded ancient shelf strata and a widespread erosional surface on top, with development of escarpments in relation with intensified erosion processes. Modified from Maestro *et al.* (2013). (C) Airgun seismic profile showing the shelf-margin wedge possibly related to the LGM lowstand. Modified from Ercilla *et al.* (2008).
Figura 2. *Ejemplos representativos de la arquitectura sedimentaria de la plataforma continental cantábrica. (A) Emplazamiento fisiográfico del margen cántabro destacando la batimetría de la plataforma, e incluyendo la geología de tierra, los sistemas fluviales y la localización de perfiles sísmicos representativos (ejemplos B y C). (B) Perfil sísmico de Geopulse mostrando estratos antiguos de plataforma fuertemente plegados y una superficie erosiva a techo, con desarrollo de escarpes morfológicos indicativos de intensificación de procesos erosivos. Modificado a partir de Maestro* et al. *(2013). (C) Perfil sísmico de Airgun mostrando una cuña sedimentaria de borde de plataforma posiblemente relacionada con la posición de bajo nivel del mar durante el Último Máximo Glacial. Modificado a partir de Ercilla* et al. *(2008).*

Postglacial Transgression

After the Last Glacial Maximum (LGM), a thin transgressive layer was formed on the shelf up to 6 ka (Pascual *et al.*, 2004). The landward coastline displacement caused the infilling of estuarine areas, mainly by transgressive and highstand deposits (Uriarte *et al.*, 2004).

Holocene Highstand

During the last 6 ka, recent deposition above the erosional surface of the shelf is mainly composed of a transparent drape interpreted as muddy patches (Ercilla *et al.*, 2008; Jouanneau *et al.*, 2008). These muddy drapes tend to be restricted to water depths shallower than 80 m, and attain maximum thickness greater than 10 m. In places, the surficial drape shows superimposed westward-oriented sediment waves (Ercilla *et al.*, 2008). The best studied depocentre occurs in the middle shelf off the Basque Country, in the easternmost area of the Cantabrian continental shelf. This deposit attains a maximum thickness of 7 m, and extends seaward of the shelf break (Jouanneau *et al.*, 2008).

These muddy patches are attributed to modern shelf sedimentation derived from coastal erosion and/or minor fluvial inputs, which are able to provide high sediment fluxes during short-lived flow events and subsequent sediment transport by shelf hydrodynamics (Uriarte *et al.*, 2004; Ercilla *et al.*, 2008). In the particular case of the depocentre off the Basque Bay, the surface residual circulation is directed towards the southeast for most of the year (from spring to autumn) although shelf circulation is directed towards the west under the influence of north-easterly winds (Uriarte *et al.*, 2004). The geomorphological context also favours sediment trapping in this environment, as the coastline configuration acquires a "cul-de-sac" morphology and the rocky outcrops on the shelf act as a barrier for nepheloid layers (Jouanneau *et al.*, 2008).

The Galician Continental Shelf

The Galician continental shelf occupies the northwestern margin of the Iberian Peninsula, extending from the Eo River mouth to the Miño River mouth (Fig. 3A).

Pre-Quaternary

The sedimentary architecture of the Galician continental shelf displays four 2nd order composite sequences (S1, S2, S3, and S4; Fig. 3B) resting directly above an igneous and metamorphic basement, related to global eustatic cycles with time spans ranging from 10 to 15 Ma and deposited since the Late Cretaceous.

The Late Cretaceous to Middle Miocene sequences (S1, S2, and S3) are progradational (Fig. 3B) and are interpreted as deltaic geometries outcropping in the middle and lower continental slope. They are highly folded and faulted in relationship to the Eocene Pyrenean Orogeny (Boillot *et al.,* 1979, Muñoz *et al.,* 2003). Atop of S3 on the shelf, an unconformity surface (U4, Fig. 3B) represents a time gap from at least the Middle Eocene to the Middle Miocene. Uplifting of the Western Banks High on the Galicia Bank and intense regional erosion is represented by the stratigraphic hiatus characteristic of this period.

The Middle Miocene to present sequence (S4) consists of five 3rd order depositional sequences, of which four (S4.1 to S4.4) are pre-Quaternary in age. Depositional sequences S4.1 to S4.3 show sheet-like external forms and are highly aggradational (Fig. 3B), and are interpreted as a TST to HST. The depositional sequence S4.4 has a wedge-like external form, is highly progradational (Fig. 3B) and is interpreted as a FSST. Within the rias, the sequence S4.4 was firstly described by Hinz (1970) as a basal unit that fills the basement lows (Fig. 3C). S4.4 is capped by an erosive, highly channelized unconformity surface that has been interpreted as a sequence boundary developed during a prominent sea-level fall at ~2.4 Ma (Shackleton *et al.,* 1984; Raymo *et al.,* 1989).

Quaternary

The sedimentary architecture of the Galician continental shelf is defined by sediment starvation whereas the "rias" have acted as sedimentary traps since the Pleistocene (~2.4 Ma). As a result, the Quaternary record (S4.5) is very thin (10 ms thick) in the continental shelf, and mostly comprises isolated sigmoid sand-bar deposits fed by the Miño River and reworked by littoral drift and storms. This thin sequence is sometimes embedded in and usually capped by a tabular, internally transparent fine-grained sedimentary layer (Ferrín, 2005). It appears laterally extensive throughout the continental shelf with thickening occurring along the so-called Galician mud belts, parallel to the coast in the inner and middle shelf (Dias *et al.*, 2002; Lantzsch *et al.*, 2009a, 2009b).

The rias, which are characterized by a complex

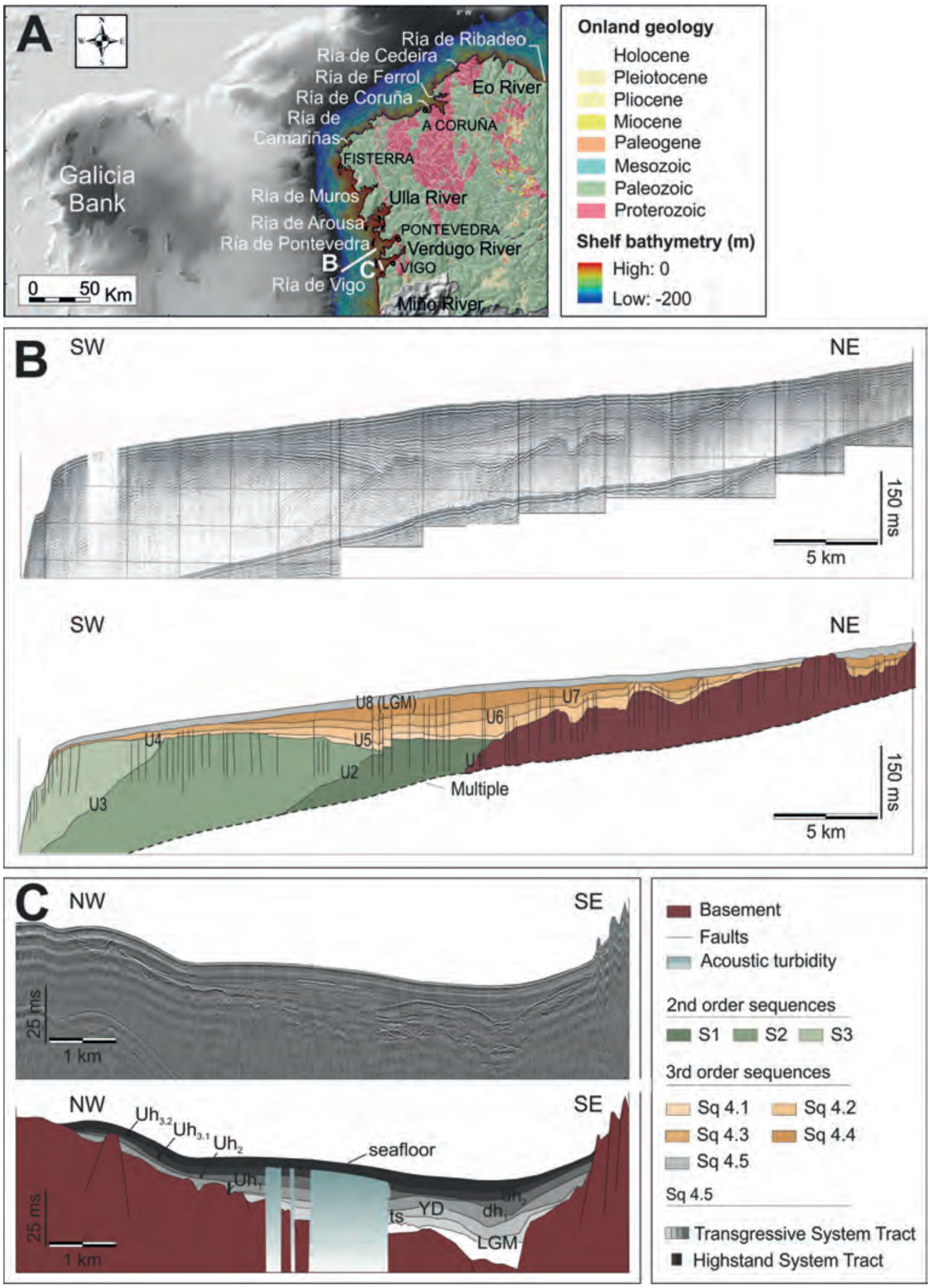

Figure 3. Representative examples of the sedimentary architecture of the Galician continental shelf. (A) Physiographic setting of the Galician margin highlighting the shelf bathymetry, with indication of the onland geology, river systems and location of representative seismic profiles (examples B and C). (B) Sparker seismic profile across the continental shelf off the Ría de Pontevedra, and interpretation of the seismic profile showing the main 2nd and 3rd order sequences. The main discontinuities are named as U1 to U8. Modified from Ferrín (2005). (C) Geopulse seismic profile and interpretation from the Ría de Vigo. The Holocene units identified are represented by Uh1, Uh2 and Uh3. The main discontinuities are named LGM (Last Glacial Maximum), YD (Younger Dryas), dh1 and dh2. Modified from Martínez-Carreño and García-Gil (2013).

***Figura 3**. Ejemplos representativos de la arquitectura sedimentaria de la plataforma continental gallega. (A) Emplazamiento fisiográfico del margen gallego destacando la batimetría de la plataforma, e incluyendo la geología de tierra, los sistemas fluviales y la localización de perfiles sísmicos representativos (ejemplos B y C). (B) Perfil sísmico de Sparker a través de la plataforma continental frente a la Río de Pontevedra, e interpretación del perfil mostrando las principales secuencias de 2º y 3er orden. Las principales discontinuidades fueron designadas U1 a U8. Modificado a partir de Ferrín (2005). (C) Perfil sísmico de Geopulse e interpretación de la Ría de Vigo. Las unidades Holocenas fueron designadas como Uh1, Uh2 y Uh3. Las principales discontinuidades fueron designadas LGM (Último Máximo Glacial), YD (Younger Dryas), dh1 y dh2. Modificado a partir de Martínez-Carreño y García-Gil (2013).*

paleobathymetry and by the presence of islands at their outermost part, have preserved thick deposits, mostly TSTs and HSTs (García-Gil *et al.*, 1999, 2000, 2011; Durán, 2005; García-García *et al.*, 2005; Diez, 2006; Martínez-Carreño and García-Gil, 2013). Within the Quaternary sequence (S4.5), two seismic units (B and C) were initially identified (Hinz, 1970; Acosta, 1984; Rey, 1993). Unit B was interpreted as Pleistocene and is capped by a very erosive an irregular discontinuity associated with sub-aerial exposure and erosion during the LGM sea-level fall. Unit C represents the TST and HST deposited after the LGM. A LST is not present in the rias, appearing only on distal areas of the continental shelf and lower slope (Ferrín, 2005).

Postglacial Transgression

This transgression is represented by a retrogradational TST. Internal surfaces present basal onlap relationships reflecting a progressive landward migration of sedimentary depocentres associated with episodic flooding events. The uppermost parasequence within the TST shows toplap relationships with its upper bounding surface, interpreted as a maximum flooding surface, separating the TST from the upper HST (Fig. 3C).

A detailed chronostratigraphic correlation of the TST parasequences and the successive post-LGM climatic/sea-level events was successfully attempted (García-Gil *et al.*, 2000; García-García et al., 2005; Díez, 2006; Durán et al., 2007; Martínez-Carreño and García-Gil, 2013). The LGM sea-level drop fully exposed the rias and adjacent shelf, leading to associated subaerial erosion, gradient modification, and subsequent fluvial drainage rejuvenation. The postglacial sea-level rise was recorded in the rias by episodic backstepping and flooding surface creation separating TST parasequences (Fig. 3C).

Holocene Highstand

Once the sea level reached its maximum Holocene position, a maximum flooding surface was developed, marking the change from TST retrogradation to HST aggradation. The HST on the coastal areas within the rias is mostly progradational, characterized by wedge-like shape and sigmoidal to oblique internal reflectors. In the deeper areas of the rias the HST becomes more aggradational, with an overall tabular shape and internal parallel reflectors (Fig. 3C).

The Western Portuguese Continental Shelf

The Western Portuguese continental shelf occupies most of the western margin of the Iberian Peninsula, between the Minho River to the north and Cape São Vicente to the south (Fig. 4A).

Pre-Quaternary

Mesozoic sediments constitute the foundations of the margin and correspond to the offshore part of the Lusitanian basin, a rift-basin formed during the opening of the North Atlantic Ocean, from the Late Triassic through the Early Cretaceous (Alves *et al.*, 2003). Pre-rift sediments consist of limestone and marlstone deposited in continental shelf and lagoon environments (Boillot *et al.*, 1987). Post-rift sedimentation began in the Early Cretaceous and was dominated by mixed carbonate-siliciclastic systems (Rasmussen *et al.*, 1998). Such systems were characterized by the deposition of shallow carbonates on topographic highs, shifting laterally to fluvial-deltaic siliciclastic deposits near the shore and to marine shale and limestone towards the deeper parts of the basin (e.g. Wilson, 1988; Rasmussen *et al.*, 1998). The beginning of the Cenozoic was characterized by periods of compression and tectonic inversion related to the Pyrenean and Alpine orogenies, and thus the Paleogene deposits are scarce along the margin and also onshore (Mougenot, 1989). In such a tectonic framework, the sedimentation during the Eocene consisted of shallow limestone, while the Oligocene is mainly represented by shallow marine sands, conglomerates and red marls (Mougenot, 1989).

The present-day sedimentary architecture of the western Portuguese continental shelf developed since the Neogene (Mougenot, 1989). The sedimentation evolved through the Miocene to shallow marine clastic and carbonate deposition (Pena dos Reis and Meyer, 1982). The Pliocene sedimentary record covers unconformably the underlying Miocene deposits and is characterized by siliciclastic deposition driven by transgression and regression cycles (e.g. Mougenot, 1989). This succession of sea-level changes produced several generations of protofluvial deltas and prograding wedges truncated by ravinement surfaces on the continental shelf (Mougenot, 1989).

Quaternary

Knowledge regarding the Quaternary sedimentary

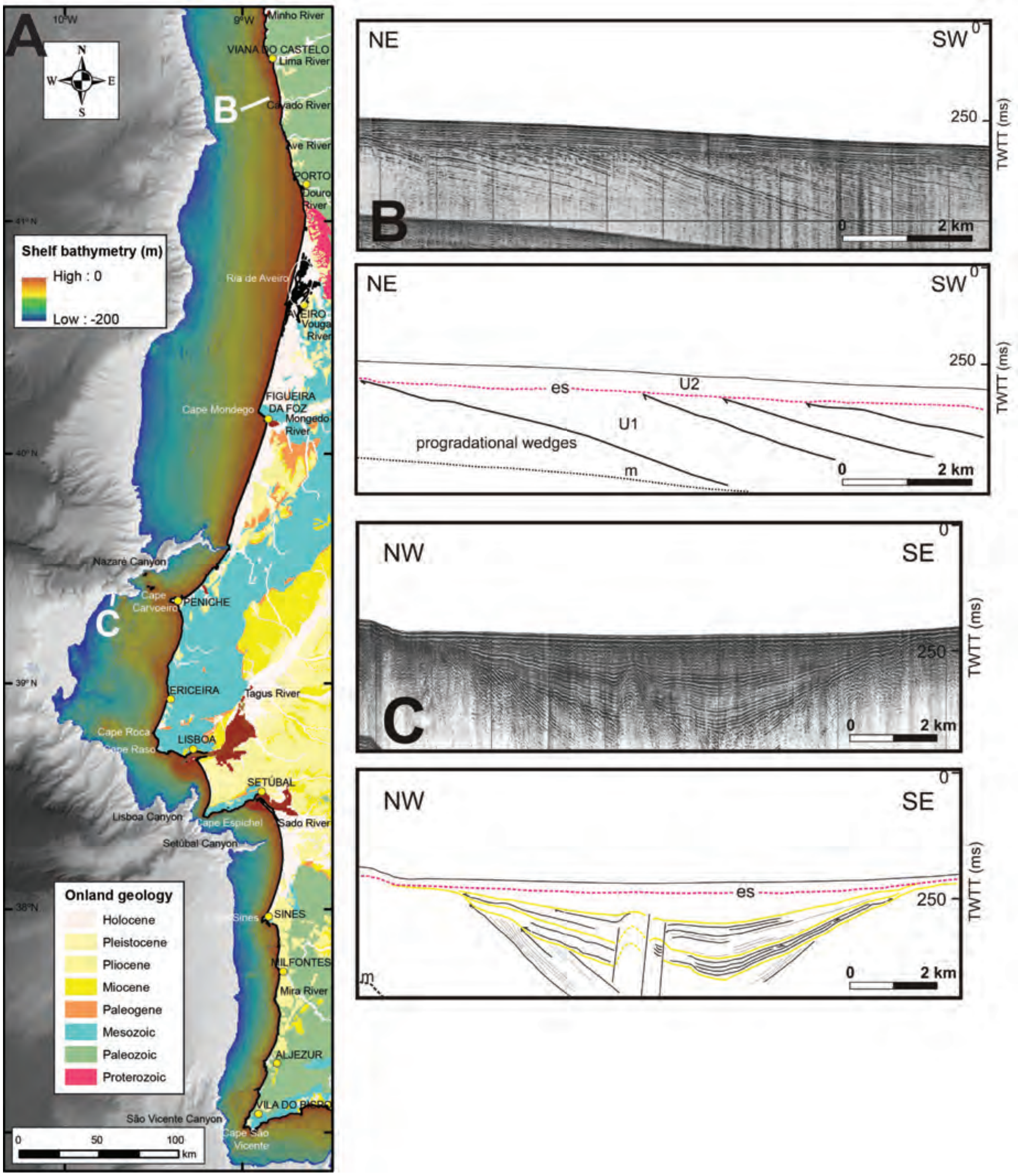

Figure 4. Representative examples of the Quaternary sedimentary architecture of the eastern Portuguese continental shelf. (A) Physiographic setting of the western Portuguese margin highlighting the shelf bathymetry, with indication of the onland geology, river systems and location of representative seismic profiles (examples B and C). (B) Uniboom seismic profile and interpretation. Seismic unit U1 corresponds to a succession of several progradational wedges deposited during a lowstand stage. These wedges are truncated by an erosional surface (es) formed during the transgressive stage. Seimic unit U2 is aggradational and probably deposited during the highstand stage. (C) Sparker seismic profile and interpretation. A paleo-valley was formed during a lowstand stage and filled up by sediments when the sea level started to rise.

Figura 4. *Ejemplos representativos de la arquitectura sedimentaria de la plataforma continental portuguesa occidental. (A) Emplazamiento fisiográfico del margen portugués occidental destacando la batimetría de la plataforma, e incluyendo la geología de tierra, los sistemas fluviales y la localización de perfiles sísmicos representativos (ejemplos B y C). (B) Perfil sísmico de Uniboom e interpretación. La unidad sísmica U1 se corresponde con una sucesión de varias cuñas progradantes atribuidas a periodos de bajo nivel del mar. Las cuñas son erosionadas a techo por una superficie relacionada con un evento transgresivo. La unidad sísmica U2 es agradante, posiblemente relacionada con la estabilización reciente del nivel del mar. (C) Perfil sísmico de Sparker e interpretación. Se identifica un paleovalle formado durante un intervalo de bajo nivel del mar, relleno durante la subida posterior del nivel del mar.*

architecture of the Portuguese continental shelf is scarce. In fact, only a few studies have been carried out during the last four decades on the Late Quaternary depositional evolution of the western Portuguese shelf (e.g Musellec, 1974; Dias, 1987; Mougenot, 1989; Baas *et al.* 1997; Rodrigues, 2001; Oliveira *et al.*, 2002; Badagola, 2008; Lantzsch *et al.*, 2009b). Thus, the understanding of the sedimentary dynamics of the shelf during the Quaternary and the role of the forcing factors and controlling processes still remain insufficient and further work is needed.

The most significant stratigraphic features include progradational wedges, which are truncated at the top by an erosional surface (Fig. 4B), and paleo-valleys in the continental shelf (Fig. 4C). These wedges can be interpreted as the record of the lowstand stages (Fig. 4B), the most recent of them linked to the LGM. Paleo-valleys mostly occur in the mid-continental shelf linked with important rivers (Fig. 4C), such as the Tagus and Sado. A deeper paleo-valley, located at a depth of approximately 160 m, is recognised in the Estremadura Spur, a structural high bounded by the Lisboa and Nazaré canyons (Mougenot, 1989; Badagola, 2008).

Postglacial Transgression

The majority of studies carried out on the Late Quaternary sedimentary evolution of the western Portuguese shelf have concentrated on the northernmost part of the shelf, between Porto and the Galician shelf (e.g. Dias, 1987; Rodrigues, 2001; Oliveira *et al.*, 2002; Lantzsch *et al.*, 2009b).

During postglacial times, the location of the coastline migrated eastwards and the continental shelf exposed during the previous LGM became submerged. The continuous sea-level rise led to: (1) the erosion of previous estuarine deposits and progradational wedges with a subsequent generation of an erosional surface; (2) the filling up of ancient valleys and canyons incised during the LGM (Fig. 4C); (3) the formation of thick, coarse-grained coastal bodies in response to an increase in terrigenous sediment input, mainly sand and silt (Baas *et al.*, 1997), during the Younger Dryas around 10.5 ka; (4) the formation of several terraces laterally from the coastal prisms (Rodrigues, 2001); (5) the westward transport of fine sediments, deposited on the outer shelf and upper slope (Rodrigues, 2001).

Holocene Highstand

The highstand stage was reached between 5 and 3 ka (Rodrigues, 2001). This high sea-level condition favoured the development of progradational coastal sand bodies (Rodrigues, 2001). In the northern sector of the shelf, during the Late Holocene highstand, the deposition of muddy sediments was restricted to the middle shelf, forming a muddy belt (Lantzsch *et al.*, 2009b).

The Northern Continental Shelf of the Gulf of Cadiz

The northern continental shelf of the Gulf of Cadiz occupies the south-western margin of the Iberian Peninsula, between Cape São Vicente and the Strait of Gibraltar (Fig. 5A).

Pre-Quaternary

The onset of Mesozoic passive margins favoured the development of carbonate platforms, which became mixed (i.e., calcareous–terrigenous) during the Late Cretaceous–Early Tertiary (Riaza and Martínez del Olmo, 1996). A progressive change to terrigenous sedimentation was established over transcurrent margins and culminated in the Early Miocene (Maldonado and Nelson, 1999).

The Pliocene was recorded by two major sequences, mainly composed by FSSTs and LSTs. The Lower Pliocene sequence is aggradational and is capped by a discontinuity with a well-defined shelf-to-slope profile. The Upper Pliocene sequence is progradational and is eroded by a Late Pliocene (~2.4 Ma) regional discontinuity (Hernández-Molina *et al.*, 2002).

Quaternary

The Quaternary architecture of the Gulf of Cádiz shelf is defined by two major sequences separated by a prominent discontinuity at about 1-0.9 Ma interpreted as the result of the Middle Pleistocene Revolution (Hernández-Molina *et al.*, 2002). After the Middle Pleistocene Revolution, this continental margin is dominated by wedge-shaped progradational units (major progradational complexes) and intercalated sheeted units (widespread sheeted units) (Lobo and Ridente, 2014) (Fig. 5B).

Widespread sheeted units occur over the shelf and upper slope domains, although in places they may pinch out. Thickness values tend to be laterally constant and low (up to 10-12 m). Internally, they show sub-parallel, aggrading configurations (Fig. 5C).

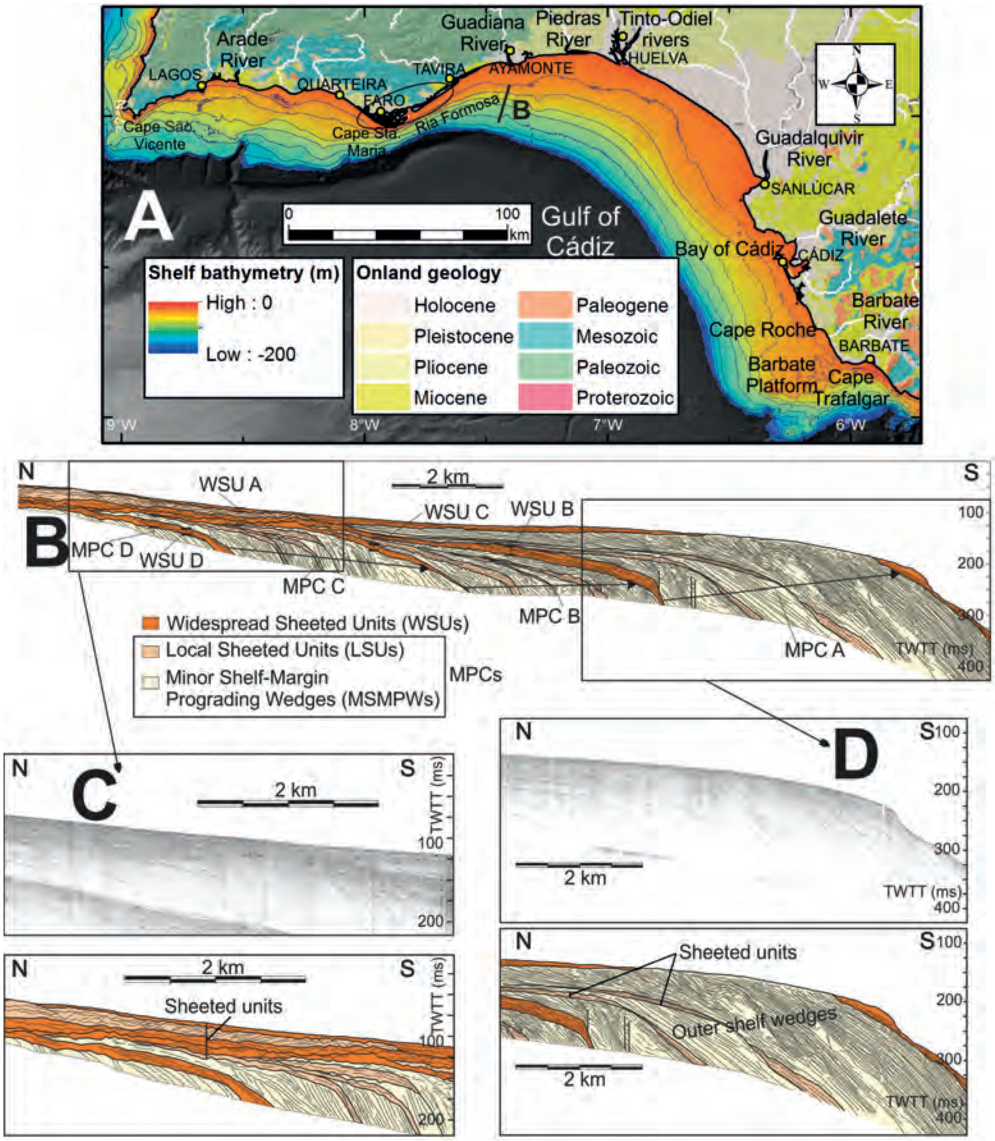

Figure 5. Representative examples of the sedimentary architecture of the northern continental shelf of the Gulf of Cádiz. (A) Physiographic setting of the northern continental shelf of the Gulf of Cádiz highlighting the shelf bathymetry, with indications of the onland geology, river systems and location of representative seismic profile (example B). (B) Interpretation of a cross-shelf Geopulse seismic profile collected in the shelf influenced by the Guadiana River. (C) Zoomed seismic section and interpretation of the inner shelf, characterized by the vertical stacking of sheeted units and landward pinch out of wedge-shaped units. (D) Zoomed seismic section and interpretation of the outer shelf, dominated by progradational shelf-margin wedges and distal terminations of sheeted units. Modified from Lobo and Ridente (2014).

Figura 5. *Ejemplos representativos de la arquitectura sedimentaria de la plataforma continental septentrional del Golfo de Cádiz. (A) Emplazamiento fisiográfico de la plataforma continental destacando la batimetría de la plataforma, e incluyendo la geología de tierra, los sistemas fluviales y la localización de un perfil sísmico representativo (ejemplo B). (B) Interpretación de un perfil sísmico de Geopulse normal a la plataforma frente al río Guadiana. (C) Ampliación del perfil sísmico en la plataforma interna e interpretación, donde se distingue el apilamiento vertical de unidades laminares y la terminación de unidades con forma de cuña. (D) Ampliación del perfil sísmico en la plataforma externa e interpretación, mostrando la geometría de las unidades con forma de cuña y la terminación distal de las unidades laminares. Modificado a partir de Lobo y Ridente (2014).*

Major progradational complexes pinch out landward on the inner to middle shelf and their overall thickness increases seaward (Fig. 5D).

The major progradational complex-widespread sheeted-unit couplets are interpreted as asymmetric shelf sequences led by 100 ka Milankovitch-scale eccentricity cycles. These 100 ka sequences are mainly composed of regressive shelf-margin deltas attributed to FSSTs and LSTs (Somoza *et al.*, 1997; Rodero *et al.*, 1999; Hernández-Molina *et al.*, 2000a, 2002).

Major progradational complexes are composed of minor shelf-margin prograding wedges which stack laterally to control the margin outbuild and are separated by local sheeted units (Figs. 5B, 5C and 5D). Minor shelf-margin prograding wedges generally pinch out landward on the paleo-outer shelves, and they show variable thicknesses but with low values over the paleo-shelves and increasing abruptly over the paleo-upper slopes. Alternating local sheeted units tend to occur over the paleo-shelves. Most of these local sheeted units exhibit sub-parallel configurations both on the shelf and on the upper slope. Their thickness tends to be laterally constant and moderate (Figs. 5B, 5C and 5D).

The minor shelf-margin prograding wedge-local sheeted unit couplets are regarded as higher-frequency (or 5th order) sequences related to 20 ka cycles (Somoza *et al.*, 1997). These high-frequency sequences are mainly composed of low-angle oblique shelf-margin wedges interpreted as the distal portions of coastal to pro-deltaic deposits mainly generated during stepped sea-level falls and thus composing FSSTs (Lobo *et al.*, 1999; Hernández-Molina *et al.*, 2000a; Lobo *et al.*, 2005a). The dominance of these deposits led to strong margin progradation with much reduced aggradation. TSTs and HSTs were poorly preserved within high-frequency sequences. However, in confined shelf sectors transgressive to highstand deposition forming sandy barrier islands and coastal lagoons occurred (Lobo *et al.*, 1999).

Postglacial transgression

The postglacial transgression is recorded by a TST developed during 14-6.5 ka (Hernández-Molina *et al.*, 1994; Gutiérrez-Mas *et al.*, 1996). Initial interpretations considered the postglacial TST as basically composed of a sandy layer overlying a ravinement surface and outcropping over extensive outer shelf areas (Nelson *et al.*, 1999) and off Cape Trafalgar (Gutiérrez-Mas *et al.*, 1996; López-Galindo *et al.*, 1999). Later interpretations registered up to four seismic units on the Huelva Shelf regarded as postglacial TSTs (Lobo *et al.*, 2001). The initial shelf flooding was recorded by a low-angle progradational, continuous outer shelf deposit (Lobo *et al.*, 2001), linked to the activity of overflow channels during large-scale flood events (González *et al.*, 2004). The shelf off the Guadiana River, with irregular sea-floor topography and sandy composition, shows three lenticular-shaped deposits interpreted to have been deposited in a high-energy environment (Lobo *et al.*, 2001). Various depositional mechanisms have been proposed, with the influence of both flood events in the river basins and storm-induced seaward sediment transport (González *et al.*, 2004).

The generation of these postglacial transgressive deposits was linked with the stepped and fluctuating pattern of the sea-level rise, and by extension to climatic fluctuations that also triggered significant modifications of the sediment flux to the shelf. The Younger Dryas event probably caused the most dramatic consequences (Hernández-Molina *et al.*, 1994; Lobo *et al.*, 2001), as this event was terminated by increased marine sediment supply during the subsequent sea-level rise (Burdloff *et al.*, 2008).

Holocene Highstand

The Holocene sedimentation is recorded by a HST composed of diverse depositional systems, such as infra-littoral prograding wedges (IPWs), pro-deltas and muddy belts (Gutiérrez-Mas *et al.*, 1996; Nelson *et al.*, 1999).

The Faro-Tavira IPW was linked to enhanced littoral drift and sediment transport by storm-driven downwelling currents on the western shelf of the gulf (i.e., the Portuguese margin) (Hernández-Molina *et al.*, 2000b). Seaward, the export of fine-grained sediments and the influence of the large-scale anticyclonic circulation led to eastward sediment dispersal and to the construction of outer shelf muddy belts (Lobo *et al.*, 2004).

A proximal pro-delta and a distal muddy belt are connected to the Guadiana River (Lobo *et al.*, 2004). The proximal pro-delta is composed of a mixture of fine and coarse sediments, although the upper part is dominated by muds (from 1 500 to 200 cal yr BP). This recent change is associated to distributary infilling and enhanced seaward sediment transport from the present-day estuary (Mendes *et al.*, 2010). The distal muddy belt has been constructed through the export of fine sediments toward the middle shelf during the last 5 ka. The formation of the muddy belt was favoured by flooding events in the river basin (Rosa *et al.*, 2011; Mendes *et al.*, 2012), and has been enhanced during the last ca. 1 500-1 000 cal yr BP, subsequent to the pro-delta formation (Mendes *et al.,* 2012).

The fluvially-dominated Guadalquivir River pro-delta covers the entire shelf and shows the highest Holocene sedimentation rates in the continental shelf of the Gulf of Cádiz (Nelson *et al.*, 1999). The Guadalquivir-connected deposit extends to the south-east over the middle shelf due to the strengthening of the Surface Atlantic Water toward the Strait of Gibraltar (Gutiérrez-Mas *et al.*, 1994, 1996; Nelson *et al.*, 1999). Another inner-shelf depocentre reflects the influence of the surface Atlantic water during easterlies dominance (Lobo *et al.*, 2004).

Off the Bay of Cádiz a prodeltaic deposit has formed by the supply of the Guadalete River and by fine-grained sediment re-suspension by ebb-tide currents and energetic storm events (López-Galindo *et al.*, 1999). To the southeast of the bay, the fluvially-derived muds are replaced by sandy facies locally moulded into bed-forms by oceanographic agents, such as the lower energy surface Atlantic water and more intense storm events (Nelson *et al.*, 1999). Over the Barbate Platform, the occurrence of sand banks and ridges with superimposed dunes indicate long-term sediment transport patterns toward the southwest and south. These seafloor features have been linked to the combined activity of the surface Atlantic water and the influence of current reversal linked to the tidal cycle in the Strait of Gibraltar (Lobo *et al.*, 2000, 2010).

Two cycles of progradation-aggradation internally composed of minor-scale motifs are recognized in several Holocene shelf depositional systems, such as IPWs and pro-deltas (Lobo *et al.*, 2005b). The major-scale architecture was related to the effect of high-frequency, small-amplitude sea-level changes (Fernández-Salas *et al.*, 2003; Lobo *et al.*, 2004). The smaller-scale architectures were related to the influence of changes in the direction and/or the magnitude of storms, as well as minor changes of sediment supply triggered by climate changes (Lobo *et al.*, 2005b).

The Northern Shelf of the Alborán Sea

The northern shelf of the Alborán Sea is located in the southern Iberian Peninsula, in the southwest Mediterranean Sea between the Strait of Gibraltar to the west and Cape Gata to the east (Fig. 6A).

Pre-Quaternary

The sedimentary architecture of the northern shelf of the Alborán Sea exhibits a major sequence generated during the Early Pliocene, during which sandy sediments were trapped along the coast. This interval was interrupted by a significant sea-level fall at about 4.2 Ma, when a well-marked shelf-to-slope profile was established in the margin. This initial profile influenced subsequent physiographic profiles during successive sea-level lowstands (Fig. 6B) (Hernández-Molina *et al.*, 2002). The Late Pliocene was dominated by falling sea-level conditions (Alonso and Maldonado, 1992) that led to the formation of another major sequence boundary at about 2.4 Ma (Hernández-Molina *et al.*, 2002).

Quaternary

The Quaternary sedimentary architecture is composed of progradational packages only interrupted by isolated carbonate platforms (Alonso and Maldonado, 1992). Two major sequences are separated by a major unconformity related to the Middle Pleistocene Revolution at approximately 900 ka (Hernández-Molina *et al.*, 2002).

The complex architecture of the post- Middle Pleistocene Revolution shelf sedimentary record reflects the onset of 100 ka high-amplitude asymmetric sea-level cycles (Hernández-Molina *et al.*, 2002). The 100 ka shelf sequences are mainly composed of shelf-margin wedges (Fig. 6C), generated during relative sea-level falls and lowstands, and separated by polygenetic erosional surfaces related to transgressive intervals; as a consequence, most Upper Quaternary sequences are mainly composed of FSSTs and LSTs (Ercilla *et al.*, 1994a).

The stacking pattern of post-Middle Pleistocene Revolution sequences is laterally variable according to the uplift/subsidence regime of the continental margin. Forestepping patterns are found in several sectors, such as the shelf off Málaga (Hernández-Molina *et al.*, 2002). In areas subjected to strong tectonic tilting, shelf sequences are poorly preserved due to lack of accommodation space and/or erosion (Ercilla *et al.*, 1994a). However, in areas with high subsidence rates such as shelf sectors off the Guadalfeo and Fuengirola rivers, Upper Quaternary progradational deposits exhibit aggradational to backstepping patterns and are better preserved (Fig. 6C) (Ercilla and Alonso, 1996; Lobo *et al.*, 2008).

Postglacial Transgression

The sedimentary architecture exhibits different types of deposits generated during the rapid postglacial sea-level rise. The most complete record shows several backstepping deposits laterally associated with submarine terraces, and interpreted as beach deposits generated during sea-level stillstands. In places of low sediment supply, the transgressive record is represented by a sand sheet exposed over the outer shelf (Ercilla *et al.*, 1994a).

Holocene Highstand

Two different types of deposits were developed during the Holocene sea-level stabilization: pro-deltaic wedges and IPWs.

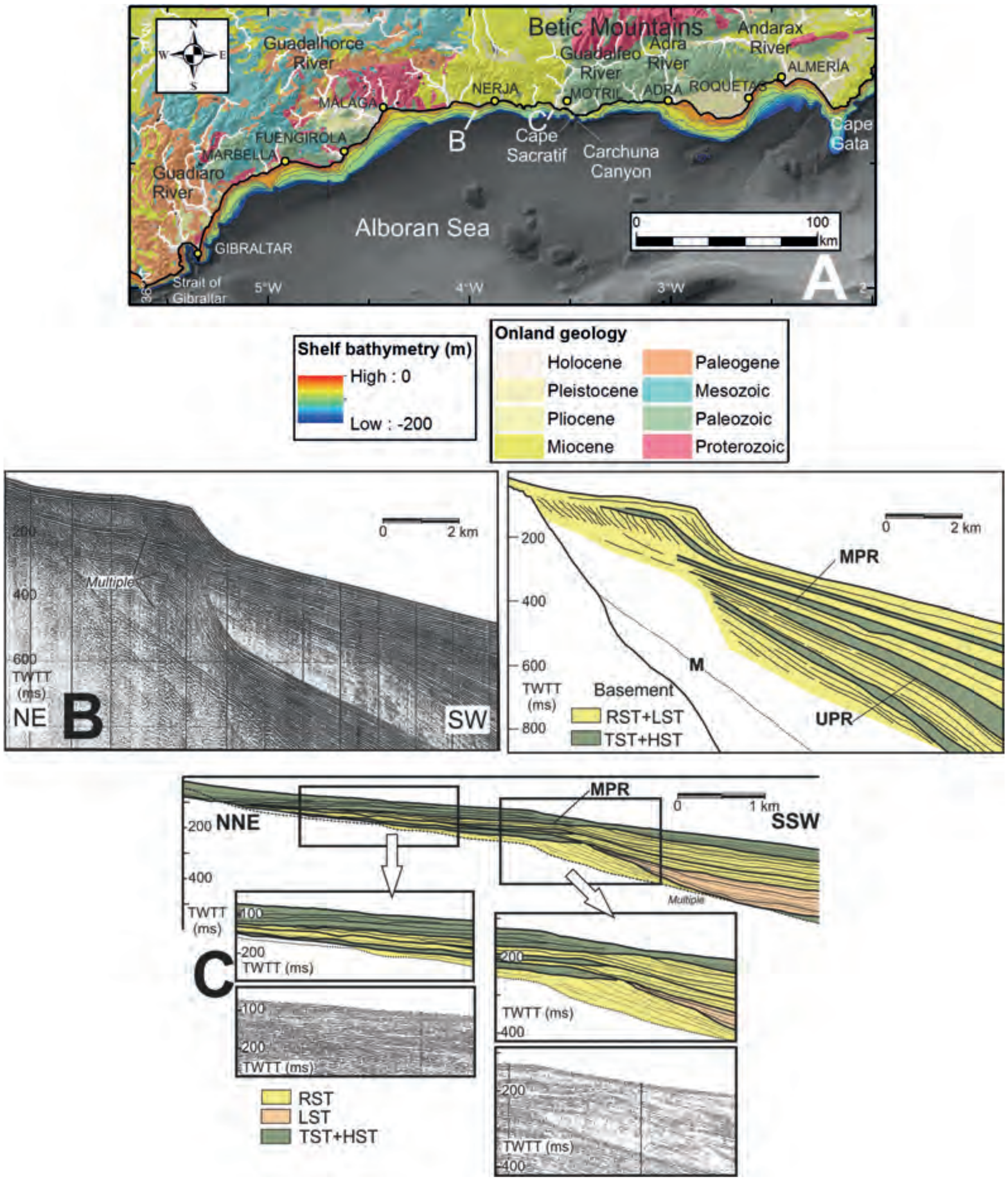

Figure 6. Representative examples of the Pliocene-Quaternary sedimentary architecture of the northern Alborán Sea shelf. (A) Physiographic setting of the northern shelf of the Alborán Sea highlighting the shelf bathymetry, with indication of the onland geology, river systems and location of representative seismic profile (examples B and C). (B) Sparker seismic profile and interpretation of the general architecture of the northern margin of the Alborán Sea, with dominance of progradational stacking pattern. Modified from Hernández-Molina *et al.* (2002). (C) Pliocene-Quaternary shelf stratigraphic architecture off the Guadalfeo River highlighting the aggradational stacking pattern after the Middle Pleistocene Revolution (MPR). Modified from Lobo *et al.* (2008).

Figura 6. *Ejemplos representativos de la arquitectura sedimentaria del Plioceno-Cuaternario de la plataforma continental septentrional del Mar de Alborán. (A) Emplazamiento fisiográfico de la plataforma continental destacando la batimetría de la plataforma, e incluyendo la geología de tierra, los sistemas fluviales y la localización de perfiles sísmicos representativos (ejemplos B y C). (B) Perfil sísmico de Sparker e interpretación de la arquitectura general del margen septentrional del Mar de Alborán, caracterizado por un patrón de apilamiento progradante. Modificado a partir de Hernández-Molina* et al. *(2002). (C) Arquitectura sedimentaria del Plioceno-Cuaternario frente al río Guadalfeo, destacando el patrón agradante tras la Revolución del Pleistoceno medio (MPR). Modificado a partir de Lobo et al. (2008).*

Pro-deltaic wedges occur off major entry points, such as the Guadiaro, Guadalhorce, Guadalfeo, Adra and Andarax rivers. Pro-deltaic wedges exhibit steep clinoform geometry with the offlap break very close to the coastline and coarse sediment composition (Ercilla *et al.*, 1994a; Hernández-Molina *et al.*, 1994; Bárcenas *et al.*, 2015). Their internal architecture is mainly composed of a HST thickening landwards. In addition, the occurrence of a crenulated sea floor is a common phenomenon in many pro-deltaic deposits (Bárcenas *et al.*, 2009; Bárcenas, 2013).

The generation of these pro-deltaic wedges has been related to rapid deposition after high-energy sediment flows and limited lateral redistribution (Lobo *et al.*, 2006). The recent dynamics and growth patterns of pro-deltaic systems have been affected by marked seasonal climate conditions, prone to the generation of episodic torrential discharges, which also seem to exert a major influence on the genesis and development of shallow-water undulations (Fernández-Salas *et al.*, 2007; Bárcenas *et al.*, 2009; Bárcenas, 2013). In addition, human intervention in the river basins has caused significant reorganization of deltaic growth patterns. Human influence on deltaic environments is particularly noticeable on the Adra Delta, whereas the sedimentary response of the Guadalfeo Delta to river channel deviation has been modulated by more efficient longshore sediment redistribution (Jabaloy-Sánchez *et al.*, 2010, 2014).

In places of minor direct fluvial input such as coastal stretches off the Malaga, Granada and Almeria provinces, the Holocene HST is thought to be composed of sigmoid-to-oblique progradational wedges interpreted as IPWs, and their origin linked to offshore sediment transport below storm-wave base level led by downwelling currents (Hernández-Molina *et al.*, 2000b). More recent work has revealed a strong parallelism between the internal architecture of these shallow-water sediment wedges and the stratigraphic architecture of adjacent coastal plains in coastal segments with enhanced littoral drift, suggesting a genetic relationship. For example, in the Carchuna Beach the influence of erosional events on the coastline seems to have been amplified by the occurrence of the shelf-indenting Carchuna Canyon. This geomorphological pattern has provided sufficient sediment subsequently transported eastward, enabling the formation of an IPW prograding oblique to parallel in relation to the main shoreline (Fernández-Salas *et al.*, 2009; Ortega-Sánchez *et al.*, 2014).

The South eastern Iberian Shelf

We refer to the south-eastern Iberian shelf of as the sector between the La Nao and Gata capes in the Iberian Peninsula, comprising two arc-shaped segments (northern and southern) bounded by Cape Palos (Fig. 7A). It also includes the shelf of the Balearic Promontory, which is attached to the Iberian Margin. The knowledge of evolutionary patterns and build-up at different time scales is quite limited for the case of the south-eastern Iberian shelf.

Pre-Quaternary

The sedimentary thickness and distribution of the Miocene series are very variable, as major depocentres are controlled by graben location (Fig. 7D). Pliocene sediments show a more widespread distribution, covering most of the shelf and outcropping above basement highs (Fig. 7C). Miocene and Pliocene sediments are affected by reactivated faults and folding in many places (Catafau *et al.*, 1994). In the abrupt margin of the southern arc the sedimentary cover is even thinner, although small sedimentary basins have been identified (Serra *et al.*, 1979).

Quaternary

A general trend of laterally constant, seaward increasing thicknesses of the Quaternary sedimentary cover is observed, although the thickness is also controlled by underlying horsts and grabens (Catafau *et al.*, 1990, 1994). Thus, the Quaternary sedimentary cover is very thin (tens of metres) over basement highs such as those located off and to the south of Alicante. Quaternary deposits may reach thicknesses of several hundreds of metres, with maximum values of > 400 m in the main depositional areas of the northern arc (Fig. 7B). In the southern arc, Quaternary deposits reach a moderate development, due to the narrowness of the shelf, and maybe locally eroded at the shelf break by submarine canyons.

The Quaternary shelf record is composed of several wedge-shaped offlapping wedges separated by erosional surfaces interpreted as shelf-margin deltas linked to different regressive phases culminating in Late Quaternary glacial, sea-level lowstands, related to Marine Isotopic Stages 2, 6, 8.2, 10 and 12. These shelf-margin wedges are affected by faults and folds that seem to have been active during the last 135 ka, and even in some cases there is evidence of post-LGM tectonic activity (Perea *et al.*, 2012).

Postglacial transgression

During the postglacial transgression, a process of quasi-continuous retreat of a barrier-lagoon system was recorded by sediment ridges and bedforms on several areas of the shelf, with the most extensive field located off the Mar Menor Lagoon. In addition,

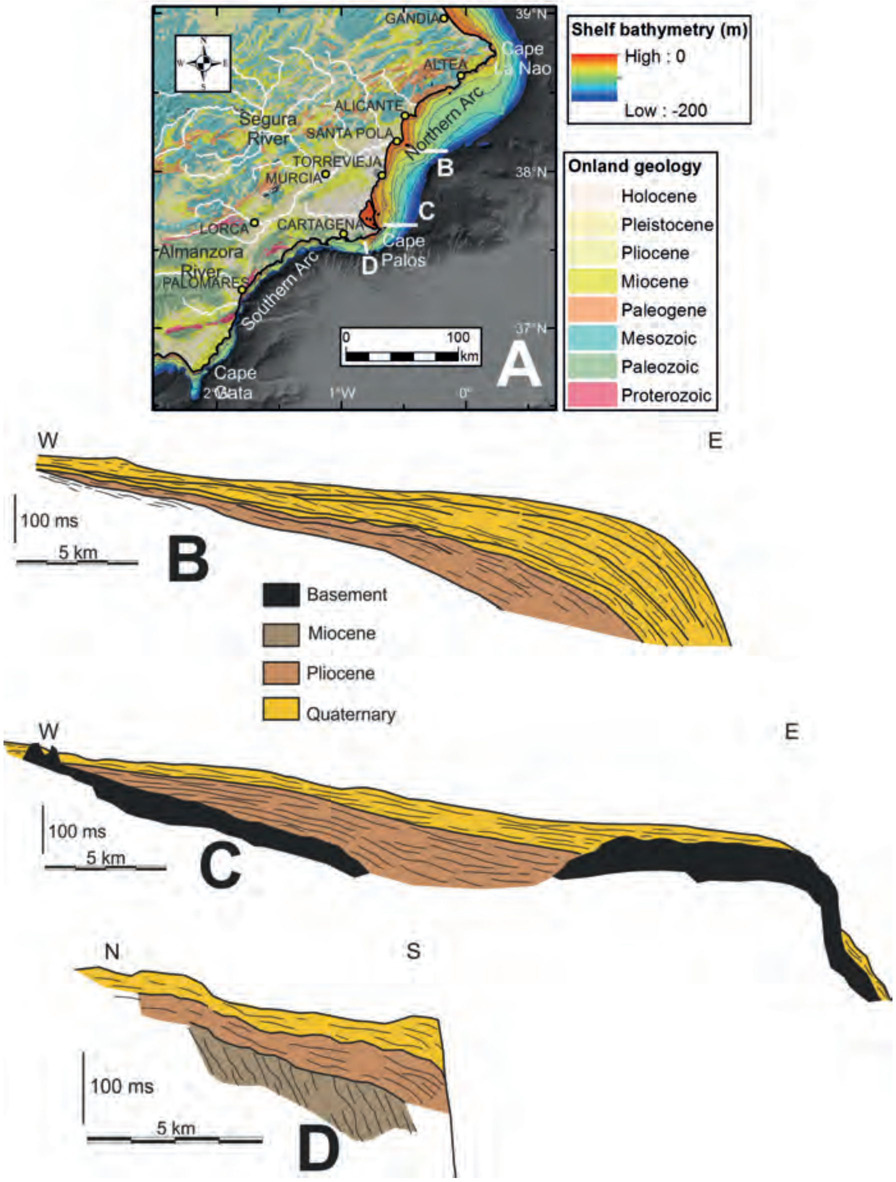

Figure 7. Representative examples of the Pliocene-Quaternary sedimentary architecture of the south-eastern Iberian continental shelf. (A) Physiographic setting of the south-eastern Iberian continental shelf of highlighting the shelf bathymetry, with indication of the onland geology, river systems and location of representative seismic interpretations (examples B, C and D). (B) Interpretation showing numerous offlapping sequences in the northern arc. (C) Interpretation showing restricted progradation controlled by basement outcropping in the outer shelf. (D) Interpretation showing Pliocene-Quaternary progradations overlying a prograding Miocene. Interpretative stratigraphic schemes modified from Catafau *et al*. (1990).

Figura 7*. Ejemplos representativos de la arquitectura sedimentaria del Plioceno-Cuaternario de la plataforma continental sudeste de Iberia. (A) Emplazamiento fisiográfico de la plataforma continental destacando la batimetría de la plataforma, e incluyendo la geología de tierra, los sistemas fluviales y la localización de un perfil sísmico representativo (ejemplos B, C y D). (B) Interpretación que muestra varias secuencias con dispositivo progradante en el Arco Septentrional. (C) Interpretación mostrando progradaciones restringidas por afloramientos del basamento en la pataforma externa. (D) Interpretación mostrando progradaciones del Plioceno-Cuaternario sobre depósitos Miocenos progradantes. Esquemas interpretativos modificados a partir de Catafau* et al*. (1990).*

several wedge-shaped deposits identified at water depths of 20-60 m have been related with cold climatic events such as the Younger Dryas and the 8.2 ka cooling event (Tent-Manclús *et al.*, 2009; De la Vara *et al.*, 2011).

Holocene Highstand

The Holocene highstand deposits comprise proximal sediment wedges and distal muddy belts. Small, coarse-grained prodeltaic deposits laterally connected through elongate IPWs occur off coastal bays and off the Segura River in the northern arc (Díaz del Río and Fernández-Salas, 2005). A continuous muddy belt occurs from the Gulf of Valencia to the shelf off Alicante (Maldonado and Zamarreño, 1983), in relation with the southward transport of suspended fine sediments (Maldonado *et al.*, 1983).

The most recent accumulations are restricted to small pro-deltaic deposits off the main fluvial inputs, such as the Segura and Almanzora rivers (Rey and Díaz del Río, 1983; Catafau *et al.*, 1990, 1994). Fine-sediment transport towards the south coupled with the abrupt shelf configuration led to fine sediment capture by submarine canyons and its export towards deeper domains. In addition, scarce terrigenous supplies and high biogenic production favour the development of extensive sea-grass meadows in the southernmost part of the southeastern shelf (Zamarreño *et al.*, 1983).

The North-eastern Iberian Shelf

We refer to the north-eastern Iberian shelf as the sector comprising the Catalan and Gulf of Valencia shelves, from the Cap de Creus to the Cap La Nao (Fig. 8A).

Pre-Quaternary

The sedimentary record of the north-eastern Iberian shelf comprises: (1) Lower to Upper Oligocene sediments deposited in piggyback basins; (2) Lower Miocene syn-rift sediments deposited in graben troughs; (3) Late Langhian to Messinian sequences (Roca *et al.*, 1999).

A network of paleo-valleys and wide flat platforms that occupied most of the continental shelf and slope, particularly in the La Planassa and Barcelona shelves, and the deposition of detrital wedges on the slope and basin were triggered by the sub-aerial erosion of the margin during the Messinian (Maillard and Mauffret, 2006; García *et al.*, 2011; Urgeles *et al.*, 2011a). The main paleo-drainage systems include the Cap de Creus , the La Fonera and Blanes large submarine canyons, as well as the downslope-trending valleys on the Barcelona shelf (Tassone *et al.*, 1994; Maillard and Mauffret, 2006; García *et al.*, 2011), and the Messinian fluvial system of the Ebro River (Frey-Martínez *et al.*, 2004; Urgeles *et al.*, 2011a). On the Valencian shelf, pre- Messinian erosional surface units are poorly deformed, but clearly eroded by the Messinian erosional surface, which is only slightly flexured (Maillard and Mauffret, 2013).

Above the Messinian erosional surface, Miocene strata are overlain by the Pliocene-Quaternary deposits filling the Messinian valleys and depressions and forming canyon-head deltas that partially fill the canyons (e.g. Serra, 1976; Soler *et al.*, 1983; Alonso *et al.*, 1990; Farrán and Maldonado, 1990; Tassone *et al.*, 1994; García *et al.*, 2011; Lastras *et al.*, 2011; Urgeles *et al.*, 2011a; Cameselle *et al.*, 2014). The top of the Pliocene deposits is marked by a regional erosional surface formed during a sea-level still-stand below the present shelf-edge (Serra, 1976; Alonso *et al.*, 1990; Ercilla *et al.*, 1994b; Tassone *et al.*, 1994).

Quaternary

The Quaternary sedimentary architecture of the north-eastern shelf of Iberia is represented by a vertical stacking of pro-gradational sequences separated by major discontinuities (e.g. Serra, 1976; Medialdea *et al.*, 1986, 1989; Checa *et al.*, 1988; Alonso *et al.*, 1990; Farrán and Maldonado, 1990; Díaz and Ercilla, 1993; Ercilla *et al.*, 1994b; Liquete *et al.*, 2008; Gámez *et al.*, 2009). This shelf has been divided into three segments for the description of the sedimentary architecture: Catalan Margin, Ebro Margin and Valencia Margin (Fig. 8A).

The continental shelf of the Catalan Margin comprises the Roses, La Planassa and Barcelona shelves and is characterized by thin Quaternary deposits at the coast with the thickness increasing abruptly towards the shelf-edge (García *et al.*, 2011; Lastras *et al.*, 2011). The Quaternary stratigraphic architecture is composed of several prograding seismic units bounded by major erosional unconformities (Figs. 8B and 8C) (Medialdea *et al.*, 1986, 1989; Ercilla *et al.,* 1994b; Liquete *et al.*, 2008). Within these sequences, FSSTs are the predominant element comprising the outer shelf sequences (Fig. 8C) (Farrán and Maldonado, 1990; Ercilla *et al.*, 1994b; Liquete *et al.*, 2008). The vertical stacking of these regressive deposits built a pro-gradational growth pattern that has been related to the fourth-order (100–120 ka) asymmetric glacio-eustatic cycles that prevailed during the Late Quaternary (Medialdea *et al.*, 1986, 1989; Checa *et al.*, 1988; Alonso *et al.*, 1990; Farrán and Maldonado, 1990; Díaz and Ercilla, 1993; Ercilla *et al.*, 1994b; Liquete *et al.*, 2008; Gámez *et al.*, 2009).

The main Quaternary depocentre in the NE Iberian continental shelf occurs on the Ebro shelf (Soler *et al.*, 1983; Medialdea *et al.*, 1986; Alonso *et al.*, 1990). Farrán and Maldonado (1990) described a stacking of thirteen progradational and aggradational seismic units developed in the inner (named as inner units) and middle to outer shelf (referred as outer units).

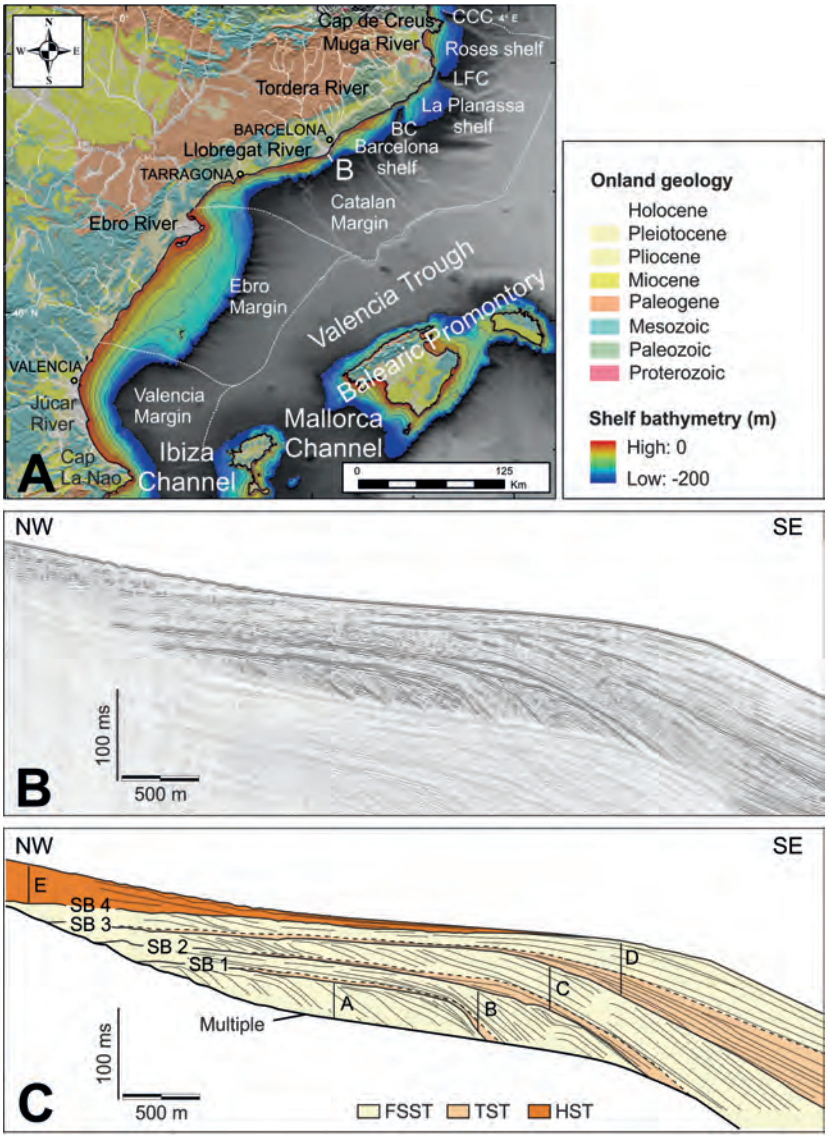

Figure 8. Representative example of the Quaternary sedimentary architecture of the north-eastern Iberian continental shelf. (A) Physiographic setting of the continental shelf highlighting the shelf bathymetry, with indications of the onland geology, river systems and location of representative seismic profile (example B). (B) High-resolution single channel seismic reflection profile from the Barcelona continental shelf. (C) Interpretation of the seismic profile showing the Quaternary record of the continental margin. Note that the Quaternary stratigraphic architecture is composed of a vertical stacking of sequences (A to E) separated by major discontinuities (SB 1 to SB 4). Within these sequences, FSST are the predominant element. The uppermost sequence (E) corresponds to the TST and HST deposited after the LGM. Legend: FSST: Forced-regressive System Tract. TST: Transgressive System Tract. HST: Highstand System Tract. Modified from Liquete *et al.* (2008).

***Figura 8.** Ejemplo representativo de la arquitectura sedimentaria del Cuaternario de la plataforma continental nordeste de Iberia. (A) Emplazamiento fisiográfico de la plataforma continental destacando la batimetría de la plataforma, e incluyendo la geología de tierra, los sistemas fluviales y la localización de un perfil sísmico representativo (ejemplo B). (B) Perfil sísmico de alta resolución de la plataforma continental de Barcelona. (C) Interpretación del perfil sísmico. La arquitectura estratigráfica Cuaternaria está determinada por el apilamiento vertical de secuencias (A-E) separadas por discontinuidades mayores (SB 1-SB 4). Las secuencias están constituidas preferentemente por cortejos sedimentarios regresivos (FSST). La secuencia superior está formada por cortejos sedimentarios transgresivos (TST) y de alto nivel del mar (HST) depositados tras el Último Máximo Glaciar. Modificado a partir de Liquete* et al. *(2008).*

The inner units have been interpreted as a stacking of TSTs at the bottom, overlain by highstand deposits, and bounded by a maximum flooding surface. Outer units are located in the middle to outer shelf and correspond to deltas and shelf-margin deltas formed in relatively stable water depths when the sea-level drop was compensated by subsidence (Farrán and Maldonado, 1990).

The sedimentary infill on the Valencia continental shelf corresponds to a thick series of Quaternary deposits, which become progressively thinner southward in the direction of the Betic system (Rey and Diaz del Rio, 1983). The deposition of this sequence is the result of a series of epeirogenic flexure movements, producing a subsidence of the shelf at a relatively low differential rate, which is well-developed in the areas of recent faulting (Diaz del Rio *et al.*, 1986). The most recent sedimentary cover is characterized by the occurrence of several barrier-lagoon systems whose formation has been related to Late Quaternary stillstand periods (e.g., during Marine Isotope Stage 5); therefore, their preservation implies very high subsidence rates (Albarracín *et al.*, 2013; Alcántara-Carrió *et al.*, 2013).

Postglacial Transgression

During the transgressive stage, erosion prevailed over sedimentation leading to the development of palimpsest and relict facies that are exposed on the outer shelf as extensive sand sheets (e.g. Serra, 1976; Medialdea *et al.*, 1989, 1994; Ercilla *et al.*, 1994b; Rey *et al.*, 1999; Liquete *et al.*, 2007; Durán *et al.*, 2013). At the northernmost point of the Roses shelf, near the Cap de Creus canyon head, as well as in the La Planassa shelf, the TST is almost absent and large rocky outcrops dominate the middle shelf (Serra, 1976; Medialdea *et al.*, 1989; García *et al.*, 2011; Durán *et al.*, 2013, 2014). In the Barcelona shelf, several transgressive features, such as elongated ridges, marine terraces and large sand bodies, can be observed at present in the middle to outer shelf (Medialdea *et al.*, 1986, 1989; Díaz and Maldonado, 1990; Serra and Sorribas, 1993; Liquete *et al.*, 2007; Ercilla *et al.*, 2010). In the Ebro shelf, transgressive deposits cover the shelf and are exposed on the outer shelf where a sandy shoal, sand ridges and hardground carbonate mounds have been described (Díaz *et al.*, 1990). Finally, in the Valencia continental shelf, the Holocene transgression razed the littoral forms built on the Valencia margin during the last Pleistocene regressive stadium. The new Holocene erosive surface of gravel and coarse sand determines the baseline level of the present-day sedimentation on the Gulf of Valencia shelf (Rey *et al.*, 1999). At the southern end of the Gulf of Valencia, characteristic elements of beach-barrier and lagoonal sedimentary units formed during transgression are observed in the inner and middle shelf. This area generally shows a subsidence lasting from the Pleistocene to the present, suggesting structural control both in the depositional behaviour and in the coastal morphology (Rey and Fumanal, 1996).

Holocene Highstand

The transgressive sand sheet is overlain by an HST on the inner shelf, forming the modern pro-deltas and IPWs. During the highstand stage, accumulation occurred mostly in areas with a steady supply of sediment, favouring the development of large pro-deltas. These include, from north to south, the Fluvià-Muga, Ter, Tordera, Besós-Llobregat and Ebro pro-deltas, and smaller pro-delta-like wedges (0.7 km wide along-shelf) at Tossa de Mar and Lloret de Mar and the Júcar River mouth (see Fernández-Salas *et al.*, this issue). Overall, the stratal architecture of the pro-deltas displays sigmoid-to-oblique clinoforms with seaward and south to south-west directed pro-gradations resulting from the prevalent southward geostrophic current flow and the physiographic configuration of the area (Medialdea *et al.*, 1986, 1989; Checa *et al.*, 1988; Díaz *et al.*, 1990; Farrán and Maldonado, 1990; Díaz and Ercilla, 1993; Ercilla *et al.*, 1994b, 1995; Liquete *et al.*, 2007, 2008; Serra *et al.*, 2007; Gámez *et al.*, 2009). Most of these pro-deltas, such as the Ter and Besós-Llobregat, show undulated sediment features on the foresets, between 20 and 100 m water depth (Urgeles *et al.*, 2007, 2011b). The sediment undulations are rooted at the maximum flooding surface or a secondary flooding surface within the Late-Holocene HST mud wedge. Their formation has been related to sediment re-suspension by internal waves and hyperpycnal flows (Urgeles *et al.*, 2011b).

The IPW develop from the lower edge of the shore face to a strong break in slope at 30–35 m water depth. From the Cap de Creus to the Tordera river mouth, the IPW appears in the form of isolated bodies that are best developed in bays and pocket beaches (Medialdea *et al.*, 1994; Durán *et al.*, 2014). In contrast, south of the Tordera River mouth the IPW appears as a continuous, coast-parallel to coast-oblique sediment body that extends along the Maresme coastline (Medialdea *et al.*, 1989; Liquete *et al.*, 2007; Ercilla *et al.*, 2010). Internally, the IPW that extends along the Maresme coast is formed by progradation of coastal lithosomes formed at different sea-level positions, representing the coastal response to fourth-order transgressive and highstand conditions, modulated by small-scale sea-level oscillations of 5th to 6th order (Ercilla *et al.*, 2010).

Discussion

Sequence stratigraphy considerations

Knowledge relating to the stratigraphic framework of the continental shelves of the Iberian Peninsula is uneven. Regarding the Atlantic continental shelves, most of the schemes have been provided for the northern shelf of the Gulf of Cádiz, and secondarily for the Galician shelf. As far as the Mediterranean continental shelves are concerned, most recent interpretations are focused on the north-eastern continental shelf (the Catalan sector), and secondarily in the northern Alborán Sea shelf; in contrast, they are almost absent for the south-eastern shelf. Consequently, our generic considerations are biased toward the most studied areas. In addition, direct age control is only available in specific shelf areas, and limited to postglacial deposition. As such, the proposed interpretations are based on: (1) the comparison of shelf sedimentary architectures with dated examples; (2) the somewhat speculative link with well-known glacio-eustatic fluctuations.

Long-term stacking patterns

The dominant long-term sedimentary architecture of Iberian shelves is formed by forestepping sequences characteristic of regressive to lowstand sequence sets (i.e., composite sequences). This trend is particularly marked in steep continental margins subjected to strong tectonic tilting such as the Cantabrian shelf and several Mediterranean shelf sectors (Ercilla *et al.*, 1994a; Ercilla *et al.*, 2008), or those affected by regional uplift and high sediment input rates such as the Galician shelf (Ferrín, 2005), although it is the dominant pattern in most of the Iberian shelves (Alonso and Maldonado, 1992; Hernández-Molina *et al.*, 2002). This indicates the combination of low subsidence rates and the asymmetric character of glacio-eustatic cycles, particularly marked during the Pliocene-Quaternary overlying the Messinian erosional surface in the Mediterranean area (e.g., García *et al.*, 2011; Lastras *et al.*, 2011; Urgeles *et al.*, 2011a).

There are some departures from this general pattern in areas with high subsidence rates, with the occurrence of transgressive to highstand sequence sets. For example, for the Galician shelf, transgressive to highstand sequence sets have been documented from the Middle Miocene to the present; their formation is related to the regional paleobathymetry (tectonically-driven gradient changes) that controls the location of depocentres on the continental shelf (Ferrín, 2005). In addition, most of the Mediterranean continental shelves along the Betic Cordillera (i.e., northern Alborán Sea shelf and south-eastern shelf) exhibit frequent uplifting-subsidence lateral changes due to the influence of the cordillera (Ercilla and Alonso, 1996; Lobo *et al.*, 2008).

Sequence development and systems tract composition

The reported sedimentary architecture has been related to the generation of pro-gradational wedges and corresponding sequences over most Iberian shelves by the leading influence of Quaternary 100 ka sea-level cycles (e.g., Farrán and Maldonado, 1990; Ercilla *et al.*, 1994b; Somoza *et al.*, 1997; Rodero *et al.*, 1999; Hernández-Molina *et al.*, 2000a, 2002; Liquete *et al.*, 2008; Gámez *et al.*, 2009; Galparsoro *et al.*, 2010; Perea *et al.*, 2012). In the Gulf of Cádiz, the detection of a higher architectural level was connected to the imprint of higher-frequency (i.e., 20 ka) sea-level cycles (Somoza *et al.*, 1997; Hernández-Molina *et al.*, 2000a, 2002; Lobo *et al.*, 2005a).

In terms of composition of (simple) individual shelf sequences, most examples document a clear dominance of regressive-to-lowstand progradational wedges (Farrán and Maldonado, 1990; Ercilla *et al.*, 1994a, 1994b; Hernández-Molina *et al.*, 2000a; Lobo *et al.*, 1999, 2005a; Liquete *et al.*, 2008). The most significant regressive wedge in terms of thickness distribution is usually related to the LGM (e.g., Dias, 1987; Ercilla *et al.*, 2008). These wedges may show distinct distribution patterns according to the margin sediment flux and hydrodynamic conditions. Thus, regressive progradational wedges with restricted shelf-margin distribution is related to the occurrence of a single, multi-phased erosional surface due to lack of accommodation space and/or erosion (Ercilla *et al.*, 1994a, 2008; Maestro *et al.*, 2013). In contrast, the wedges show a widespread distribution over the shelf with multiple bounding surfaces in high-supply settings, such as the Guadiana-Guadalquivir shelf or the Ebro Shelf (e.g., Farrán and Maldonado, 1990; Hernández-Molina *et al.*, 2000a; Lobo *et al.*, 2005a).

A common feature observed in many continental shelves is the occurrence of incised submarine valleys overlying progradational wedges, connected with major fluvial extensions (e.g., Tagus, Sado, Guadiana, Guadalquivir). In spite of the significance of shelf valley incision, no detailed studies have been undertaken on any of the incised-valley systems around Iberia.

TST to HST deposits seem to be scarce and/or unidentified in most pre-LGM sequences (Farrán and Maldonado, 1990; Ercilla *et al.*, 1994b; Liquete *et al.*, 2008). However, in sectors of the Gulf of Cádiz and the north-eastern shelves, transgressive intervals appear to be represented either by sub-parallel sediment drapes off river sources and/or by adjacent barrier island-lagoon systems (Lobo *et al.*, 1999; Liquete *et al.*, 2008; Gámez *et al.*, 2009; Lobo and Ridente, 2014). Some inner slightly aggradational wedges have been regarded as HSTs in the central sector of the north-eastern shelf off the Llobregat River (Liquete *et al.*, 2008; Gámez *et al.*, 2009). Moreover, the highest development of pre-LGM TST-HST is documented in the Ebro continental shelf, suggesting a sediment supply control (Farrán and Maldonado, 1990). In contrast, post-LGM TST-HST deposits attain their maximum preservation in estuarine environments and rias (e.g., García-Gil *et al.*, 2000; Uriarte *et al.*, 2004; García-García *et al.*, 2005).

Post-LGM TSTs show a high spatial variability, whereas the Holocene HST shows a more lateral uniform distribution and composition. This distinctive pattern maybe related to the combined influence of both allogenic and autogenic processes during stages of relative sea-level rise that may cause variations of sediment supply (Catuneanu and Zecchin, 2013). This contrasts with relatively stable sea-level highstand conditions, when the amount of sediment supply can be stabilized and hydrodynamic activity is enhanced.

A lateral gradation of postglacial transgressive environments is recognized in several continental shelves, most notably on the Gulf of Cádiz and the north-eastern shelves. Far away from significant fluvial inputs, the TST is almost absent and large rocky outcrops dominate the shelf (e.g., Ercilla *et al.*, 1994a; Durán *et al.*, 2013, 2014). Laterally there is a transition to: (1) the most common transgressive pattern that includes thin, transgressive, sandy layers covering widespread shelf areas (e.g., Ercilla *et al.*, 1994a; Gutiérrez-Mas *et al.*, 1996; López-Galindo *et al.*, 1999; Nelson *et al.*, 1999; Liquete *et al.*, 2007; Durán *et al.*, 2013); (2) intermediate areas exhibit retreating barrier systems, sandy ridges and/or submarine terraces in accordance with declining fluvial input (e.g., Díaz and Maldonado, 1990; Ercilla *et al.*, 1994a, 2010; Liquete *et al.*, 2007); and (3) areas with maximum TST development (e.g., Galizian rias, fluvially-influenced shelves) show a number (3-4) of backstepping para-sequences, whose generation has been attributed to the pulsating nature of the postglacial sea-level rise combined with climatically-driven sediment supply fluctuations. Particularly, the imprint of the Younger Dryas event has been suggested in most of the Iberian shelves (García-Gil *et al.*, 2000; Lobo *et al.*, 2001; González *et al.*, 2004; Durán, 2005; García-García *et al.*, 2005; Martínez-Carreño and García-Gil, 2013).

The following Holocene HST types can be defined according to the balance between fluvial flux and hydrodynamic energy: coastal attached (submarine deltaic wedges, IPWs) and coastal detached (muddy belts and large-scale sand banks-ridges) sediment bodies. There are several styles of Holocene deltaic growth in response to the combined influence of sediment flux and hydrodynamic regime: (1) large progradational sigmoid deltaic systems with widespread continental shelf coverage (e.g., Guadalquivir, Ebro) (Díaz *et al.*, 1990; Lobo *et al.*, 2004); (2) deltaic systems confined to inner settings, evolving seaward to muddy belts (e.g., Guadiana) (Lobo *et al.*, 2004); (3) steep, thick deltaic systems with ubiquitous undulations formed as the product of episodic sediment flows along most of the Mediterranean shelves (Rey and Díaz del Río, 1983; Urgeles *et al.*, 2007, 2011b; Jabaloy-Sánchez *et al.*, 2010, 2014; Bárcenas *et al.*, 2015); (4) small deltaic systems in coastal embayments (e.g., Bay of Cádiz) (López-Galindo *et al.*, 1999).

IPW development is favoured in areas with minor fluvial input and enhanced littoral drift activity. These settings exhibit specific geomorphological constraints such as straight, coastal sections and shelf-indenting canyons that favour coastal erosion by storm events (e.g., Cape Santa Maria, Carchuna system) (Hernández-Molina *et al.*, 2000b; Fernández-Salas *et al.*, 2009; Ercilla *et al.*, 2010; Durán *et al.*, 2014; Ortega-Sánchez *et al.*, 2014).

The distribution of main muddy belts/patches (Bay of Biscay, the northern Portuguese continental shelf, the Gulf of Cadiz, Gulf of Valencia and Catalan shelves) generally involves some degree of geomorphological control, conditioned either by coastal configuration or by basement outcrop occurrence (Jouanneau *et al.*, 2008; Lantzsch *et al.*, 2009b). In the Gulf of Cadiz, the existence of a current shear system has also controlled the location of shelf muddy belts (Lobo *et al.*, 2004). In all these cases, however, a very active oceanographic regime is responsible for their prevalent elongation formation. The most significant field of sandy bodies occurs over the Barbate Platform, in response to a very energetic hydrodynamic regime involving geostrofic and tidal current activity (Lobo *et al.*, 2010).

Atlantic versus Mediterranean shelves: a comparison

Atlantic-type shelves: depositional regimes versus oceanographic energy

The development of continental shelves on the Atlantic side of the Iberian Peninsula seems to be a function of the interplay between depositional regimes, conditioned to a large extent by fluvial supplies, and oceanographic conditions, which are of moderate to high energy and that are conducive for the generation of erosional regimes. As a consequence, the Iberian Atlantic continental margin can be characterized as a latitudinal gradation of shelves settings, ranging from the essentially erosional Cantabrian shelf to the progradational Gulf of Cadiz shelf. In between the Portuguese shelf can be regarded as a transitional shelf, with a very active oceanographic regime but with some very significant sources of sediments. Regretfully, our knowledge of built-up patterns on the Portuguese shelf is quite limited at present, preventing us from making more in-depth considerations.

Based on this scheme, we consider the occurrence of three basic modes of continental shelf construction in Atlantic Iberia (Fig. 9): depositional shelves, shelves with restricted progradation, and erosional shelves. In addition, we have considered the occurrence of shelf settings strongly conditioned by the

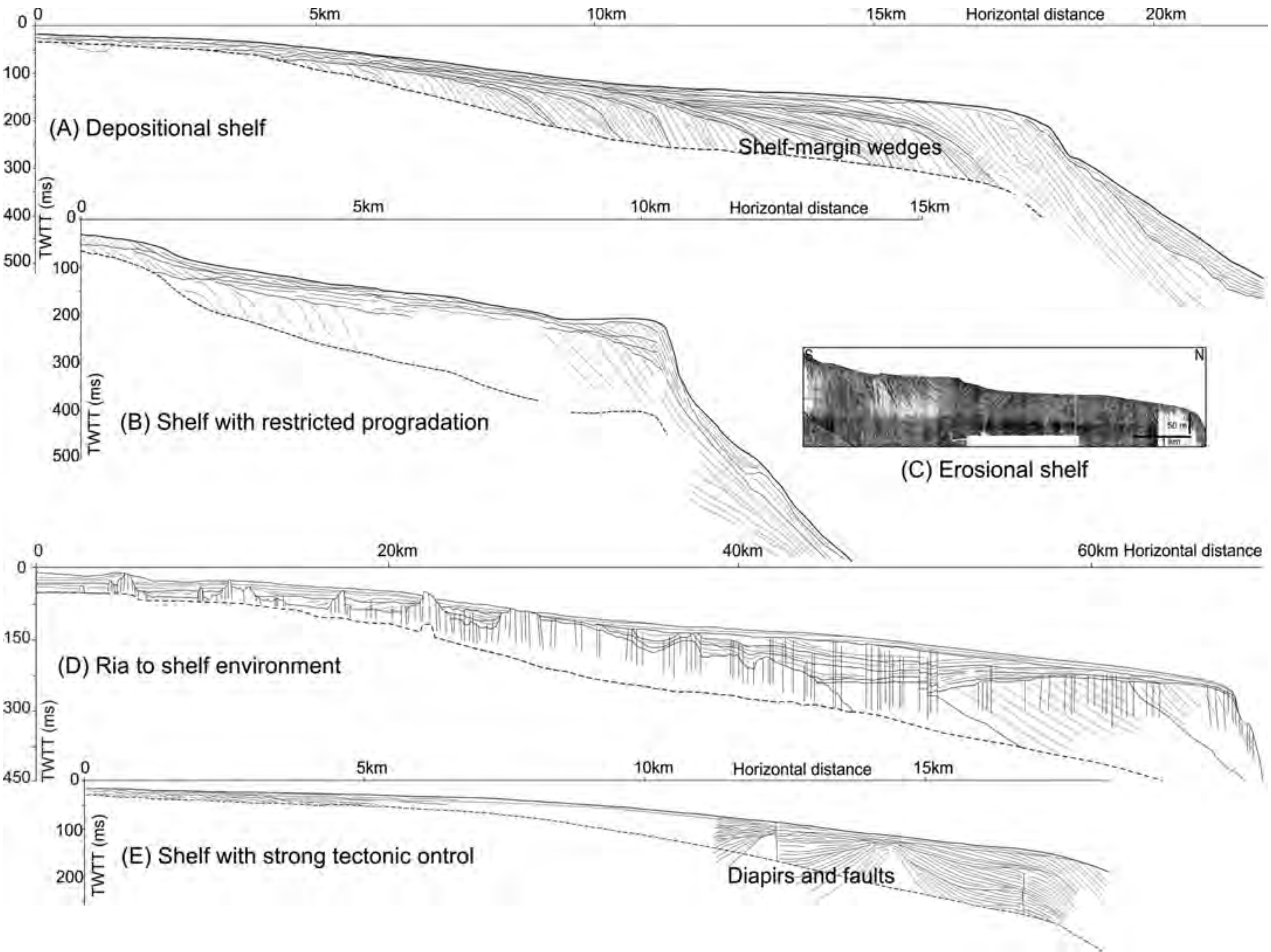

Figure 9. Atlantic-type shelves of the Iberian Peninsula. (A) Depositional shelf. (B) Shelf with restricted progradation. (C) Erosional shelf. (D) Ria to shelf environment. (E) Shelf with strong tectonic control. There is a latitudinal gradation in response to the interaction between depositional and hydrodynamic regimes (A to C). There are, however, specific shelf sectors controlled by background morpho-structural features (D and E). Synthetized from Lobo (2000), Ferrín (2005) and Maestro *et al.* (2013).

***Figura 9**. Plataformas de tipo Atlántico de la Península Ibérica. (A) Plataforma deposicional. (B) Plataforma con progradación restringida. (C) Plataforma erosional. (D) Ambiente de ría-plataforma. (E) Plataforma con control tectónico. Se identifica una gradación latitudinal en respuesta a la interacción entre los regímenes deposicionales e hidrodinámicos (A-C). Existen, sin embargo, sectores específicos controlados por rasgos morfo-estructurales (D-E). Figura sintetizada a partir de los perfiles sísmicos y/o interpretaciones contenidas en Lobo (2000), Ferrín (2005) y Maestro* et al. *(2013).*

morpho-structural settings, such as ria to shelf environment and shelves with strong tectonic control.

(1) Depositional shelves exhibit outstanding progradational patterns led by successive generation of shelf margin-wedges, and with appreciable transgressive to highstand sedimentation in innermost shelf settings (Fig. 9A). The typical example is provided by the composite depocentre formed by the Guadiana-Guadalquivir shelf (e.g., Lobo *et al.*, 2004), receiving sediments through the two most important rivers of the southern half of the Peninsula, and with an oceanographic regime less energetic than the more exposed Portuguese continental shelf, due to the sheltering effect provided by the "cul-de-sac" morphology of the gulf.

(2) Shelves with restricted progradation (Fig. 9B) have low width values and minor development of shelf-margin wedges (e.g., Lobo, 2000) due to the inexistence of significant fluvial sources. Another outstanding feature of this type of shelf is the occurrence of signs of shelf margin-upper slope erosion (Fig. 9B), either by submarine canyon occurrence (e.g., the canyons of the Cantabric margin, Nazaré Canyon, canyons of the western Gulf of Cadiz margin) or by erosional activity of contour currents, such as the upper branch of the Mediterranean outflow water.

(3) Erosional shelves display steep, highly deformed clinoforms spanning very long geological intervals, and marked by the occurrence of a composite, highly erosional surface (Fig. 9C), locally moulded by submarine escarpments due to the occurrence of resistant materials or by prolonged sea-level exposure (e.g., Ercilla *et al.*, 2008). The typical example of this type of shelf is the Cantabrian continental shelf, clearly dominated by a very energetic wave and storm regime and with very limited fluvial contributions from short, mountainous rivers. Extensive sectors of the Portuguese shelf would also fall in this category.

(4) Ria to shelf environment, typical of the Galician Margin, where the occurrence of tectonically-controlled basins has enabled the formation of significant sediment depocentres in inner settings (Fig. 9D), mostly composed by transgressive to highstand sediments (e.g., García-García *et al.*, 2005).

(5) Shelves with strong tectonic control, localized in areas crossed by major tectonic accidents (Fig. 9E), such as the northern boundary of the Allochtonous Body in the Gulf of Cadiz (e.g., Lobo, 2000). There, tectonic deformation such as faults, antiforms and/or salt diapirs related to deep structures may significantly modify sedimentary growth patterns.

Mediterranean-type shelves: a question of sediment supply

The Mediterranean Iberian continental shelves show less morpho-stratigraphic variability than the Atlantic Iberian continental shelves (Fig. 10), as they are affected by a lower energy hydrodynamic regime; the main distinctive pattern is the amount of fluvial supply received in the shelf. Taking this into account, two

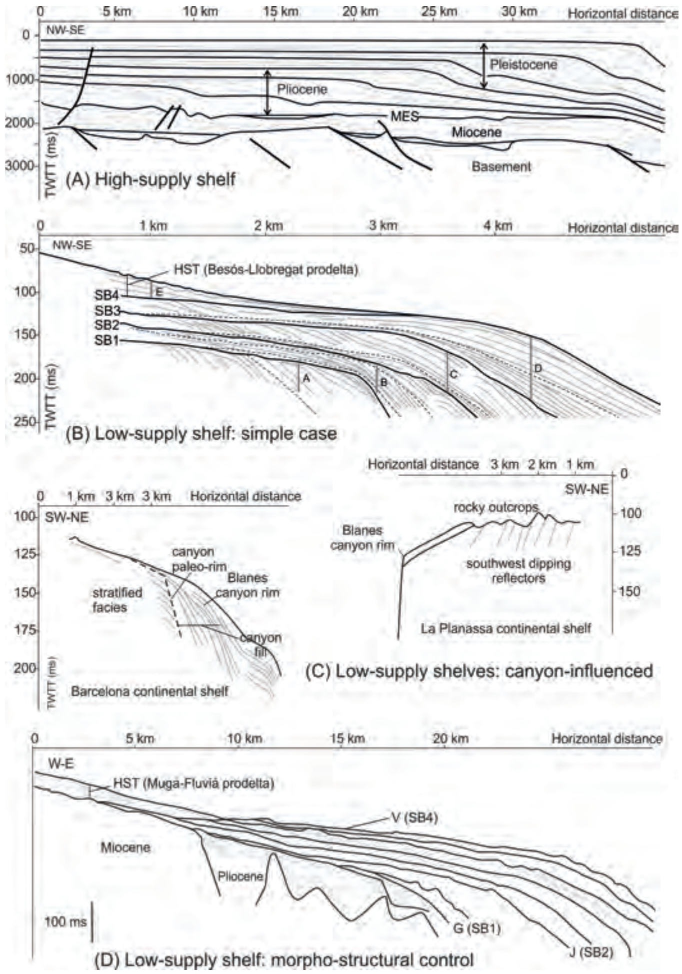

Figure 10. Mediterranean-type shelves of the Iberian Peninsula. (A) High-supply shelf, showing a considerable amount of progradation. (B) Simple case of a low-supply shelf, showing moderate to low progradation. (C) Low-supply shelves influenced by canyons. (D) Low-supply shelf with morpho-structural control. Synthetized from Urgeles *et al.* (2011a), Liquete *et al.* (2008) and Lastras *et al.* (2011).

Figura 10*. Plataformas de tipo Mediterráneo de la Península Ibérica. (A) Plataforma con alto aporte, mostrando una progradación significativa. (B) Caso simple de una plataforma con bajo aporte, mostrando una progradación moderada-baja. (C) Plataforma con bajo aporte influenciada por cañones submarinos. (D) Plataforma con bajo aporte y control morfo-estructural. Figura sintetizada a partir de las interpretaciones contenidas en Urgeles* et al. *(2011a), Liquete* et al. *(2008) and Lastras* et al. *(2011).*

styles are defined: (1) high-supply and (2) low-supply shelves.

(1) The high-supply shelf (Fig. 10A) is essentially represented by the Ebro continental shelf, receiving sediments from the fluvial system with the highest discharges in the Iberian Peninsula. As a consequence, the continental shelf is composed of the stacking of thick muddy sequences, which build up upwards and seawards (e.g., Farrán and Maldonado, 1990), with the amount of progradation particularly increased after the Messinian erosional surface.

(2) The low-supply shelves are represented by the rest of the Mediterranean continental shelves. They can be categorized as low supply, being influenced by short, steep rivers with a seasonal discharge regime delivering a sediment load with coarser-grained compositions. We identify three sub-types of low-supply shelves based on the amount of restriction for shelf progradation. (2.1) The simple case, a shelf with a sedimentary architecture similar to the high-supply case but with a more reduced seaward extension due to the coarser-grained composition and to the lower sediment supply (Fig. 10B). This pattern is found off small rivers but significant at a regional scale, such as Llobregat or Guadalfeo (e.g., Liquete *et al*., 2008; Gámez *et al*., 2009). (2.2) A canyon-influenced shelf, whose seaward growth is limited by canyon occurrence (Figure 10C). Shelf sequences may partially fill part of the canyon, but generally shelf outbuild is limited by erosional surfaces (e.g. Lastras *et al*., 2011; García-García *et al*., 2012). This subtype of shelf is frequent along the entire Mediterranean margin, as in many cases canyon origin is linked to the Messinian event. (2.3) A shelf with morpho-structural control is also a common sub-type of shelf found in the Mediterranean Iberian shelves (Fig. 10D). Morpho-structural features may appear in the inner shelf, favouring to some extent shelf progradation, or instead outcrop in the outer shelf, acting in these cases as barriers for shelf growth (e.g., Catafau *et al*., 1994).

Conclusions

The sedimentary architecture and evolution of continental shelves around Iberia reflect to a large-extent the dominant glacio-eustatic control, with strong modulation by the combination of amount of sediment supply and the oceanographic regime. Regressive to lowstand sequences constitute the most important portion of the Pliocene-Quaternary record, with the transgressive to highstand record preserved favourably in structurally-controlled regions. During the Middle and Late Quaternary, the generation of shelf sequences appears to be linked to the onset of 100 ka Milankovitch cycles. Within these sequences, falling-stage deposition has been favoured. Postglacial transgressive deposition shows a higher spatial variability than the Holocene highstand, indicating the activity of allocyclic processes during the sea-level rise.

The Atlantic Iberian continental shelves evolve basically as the product of the interaction between depositional regimes and contrasted oceanographic regimes, resulting in a latitudinal gradation of environments. Some continental shelves with strong structural control (e.g., rias) show significant departures from the general model. In contrast, the Mediterranean Iberian continental shelves develop mainly as the primary influence of fluvial sediment supply; as a consequence, most of these shelves show limited development, the only exception being the highly supplied Ebro continental shelf. The shelves around the Iberian Peninsula constitute an exceptional environment for the understanding of the modulation of glacio-eustatic signals by environmental factors and its imprint in their long-term constructional patterns.

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