García, M., Ercilla, G., Alonso, B., Estrada, F., Jané, G., Mena, A., Alvés, T. and Juan, C., 2015. Deep-water turbidite systems: a review of their elements, sedimentary processes and depositional models. Their characteristics on the Iberian margins. *Boletín Geológico y Minero,* 126 (2-3): 189-218
ISSN: 0366-0176

Deep-water turbidite systems: a review of their elements, sedimentary processes and depositional models. Their characteristics on the Iberian margins

M. García(1), G. Ercilla(2), B. Alonso(2), F. Estrada(2), G. Jané(3), A. Mena(4), T. Alvés(5) and C. Juan(2)

(1) Instituto Andaluz de Ciencias de la Tierra, CSIC-Universidad de Granada,
Avenida de las Palmeras nº 4, 18010 Armilla (Granada), Spain.
m.garcia@csic.es; marguita.garcia@gmail.com
(2) Institut de Ciències del Mar, CSIC. Passeig Marítim de la Barceloneta 37-49, 08003, Barcelona, Spain.
gemma@icm.csic.es, belen@icm.csic.es, festrada@icm.csic.es, cjuan@icm.csic.es
(3) Instituto Geológico y Minero de España, Ríos Rosas 23, 28003, Madrid, Spain.
g.jane@igme.es
(4) Facultad de Ciencias do Mar, Universidade de Vigo, 36310 Vigo, Spain.
anxomena@uvigo.es
(5) 3D Seismic Lab, School of Earth and Ocean Sciences, Cardiff University, Cardiff, United Kingdom.
AlvesT@cf.ac.uk

ABSTRACT

Turbidite systems or submarine fans are considered the most important clastic accumulations in the deep sea and represent the sediment-transfer system between the hinterland source area and the deep-sea depositional sink. Their deposits contain information about global factors and local factors. Different scales and varying observational methods have contributed to the lack of a unifying terminology. In order to solve this problem several authors have proposed an "elemental approach". The main architectural elements defining a turbidite system are: large-scale erosive features (mass-movements and canyons), channels and channel-fill deposits, overbank deposits and lobes. The sediment making up these elements is principally from gravity flow deposits, the most widely recognised being the turbidite, and other submarine mass movements. The genesis and character of these elements, as well as the overall geometry of the systems, indicate they are formed by a complex interaction between global and local factors. Various turbidite-system classifications are found in the literature, the most widely-used being based on grain size and feeder systems. Besides the scientific importance of turbiditic systems, they are predominantly studied because of the economic interest in them, as turbidite sandstones constitute important gas and oil reservoirs. Turbidite systems shape the seafloor of the Iberian continental margins and contribute in a large part to their outbuilding and basin infilling. They are hugely variable in size, location within the physiographic domains, style and overall geometry of the architectural elements, as well as sediment composition. The most studied Iberian turbidite fans are in the Mediterranean Sea whereas those of the Atlantic Ocean remain poorly known.

Key words: architectural element, Iberia, sedimentary processes, submarine fan, turbidite system.

Sistemas turbidíticos de aguas profundas: revisión de sus elementos, procesos sedimentarios y modelos deposicionales. Sus características en los márgenes Ibéricos

RESUMEN

Los sistemas turbidíticos son considerados las acumulaciones clásticas más importantes en los márgenes continentales distales y representan los principales sistemas de transferencia del sedimento desde el continente hasta el medio marino profundo. Su registro sedimentario contiene información sobre los factores globales y locales que han controlado la formación y evolución de nuestros mares y océanos. Sus diferentes escalas y métodos de observación han contribuido a la falta de una terminología unificadora. Para resolver este proble-

ma su estudio se aborda a través de la identificación de los elementos arquitectónicos que los conforman. Los principales elementos arquitectónicos que definen un sistema turbidítico son: elementos erosivos de gran escala (inestabilidades sedimentarias y cañones), canales y depósitos de canal, depósitos de desbordamiento y lóbulos. Estos elementos están compuestos principalmente por depósitos de flujos gravitativos, siendo las turbiditas los sedimentos más reconocidos, y por depósitos de movimiento de masas. La génesis y el carácter de estos elementos, así como la geometría general de los sistemas, indican que se forman por una compleja interacción entre factores locales y globales. Existen diversas clasificaciones de los sistemas, siendo la más utilizada la que se basa en el tamaño de grano y sistemas de área fuente. Además del gran interés científico que poseen los sistemas turbidíticos, estos tienen un gran interés económico, ya que las arenas turbidíticas constituyen reservorios en potencia de gas y petróleo. Los sistemas turbidíticos en los márgenes ibéricos presentan una gran variedad de tamaños, distribución en los dominios fisiográficos, estilo y geometría de los elementos arquitectónicos, y tipos de sedimentos. Los más estudiados son los del Mar Mediterráneo mientras que los del Océano Atlántico aún siguen siendo poco conocidos.

Palabras clave: elemento arquitectónico, Iberia, procesos sedimentario, abanico submarino, sistema turbidítico.

VERSION ABREVIADA EN CASTELLANO

Introducción

Los sistemas turbidíticos profundos representan las acumulaciones clásticas más importantes desde el punto de vista volumétrico en los ambientes marinos profundos (margen continental distal y cuencas adyacentes). Además, representan áreas importantes para la acumulación de hidrocarburos, por lo que su exploración por parte de las compañías de hidrocarburos es importante. Históricamente el estudio de los sistemas turbidíticos comenzó con el descubrimiento de los cañones submarinos. Solamente cuando las ecosondas multihaz comenzaron a formar parte de la investigación de forma habitual, se descubrió la complejidad de los sistemas deposicionales que se desarrollaban aguas abajo de la desembocadura de los cañones.

La gran variedad de técnicas de investigación y la gran diversidad de los propios sistemas turbidíticos han hecho que surjan conceptos y teorías sobre la formación y evolución, en ocasiones divergentes. Las dificultades de desarrollar un modelo unificador que encaje con las observaciones e interpretaciones de los sistemas en mar y tierra, y que por lo tanto sea capaz de explicar los principales procesos deposicionales responsables de su edificación, vienen del diferente carácter de las observaciones.

Arquitectura

Otra problemática asociada con el estudio de los sistemas turbidíticos es la ausencia de una terminología estandarizada. Esto genera aún más confusión entre los investigadores que afecta a la disciplina. La terminología debe ser definida objetivamente. Hoy en día, el estudio de la sedimentología de los sistemas turbidíticos modernos se aborda mediante la identificación y análisis de al menos cuatro elementos arquitectónicos principales, que por consenso fueron escogidos por el "Committee on Fans" en los años 90, dada su presencia en la práctica totalidad de los sistemas turbidíticos antiguos y modernos. Estos elementos son: elementos erosivos de gran escala, canales y depósitos de canal, depósitos de desbordamiento y lóbulos (Fig. 1).

Los elementos erosivos de gran escala comprenden cañones e inestabilidades gravitacionales, siendo los primeros los más representativos (Fig. 2A). Los cañones representan el área fuente interna de los sistemas turbidíticos y transfieren al sistema turbidítico material sedimentario de un amplio espectro granulométrico, que varía desde gravas y arenas hasta fangos. El transporte de estos sedimentos se efectúa principalmente mediante flujos gravitativos de alta densidad y energía (Fig. 3). Los canales representan, dentro de un sistema turbidítico, los mayores y principales conductos de transporte de sedimento que son originados y/o mantenidos por flujos gravitativos, especialmente turbidíticos (Fig. 2B). Se desarrollan a partir de la desembocadura de los cañones y en sus sectores más proximales es donde se localizan los canales principales que alimentan al sistema, con dimensiones kilométricas y márgenes o diques bien desarrollados. A medida que evolucionan mar adentro, sus dimensiones disminuyen y se ramifican evolucionando a canales de carácter distributario. El tipo de sedimento que transporta el canal constituye un factor importante en las características geométricas y en los atributos erosivos o deposicionales, y condiciona sus dimensiones, sinuosidades, desarrollo de diques y migraciones. A pesar de la gran variabilidad textural que presenta el sedimento que circula por el canal, éste representa el área donde preferencialmente se deposita el material más grueso, predominando las arenas masivas limpias. Los depósitos de desbordamiento se desarrollan a ambos márgenes de los canales, y se forman por desbordamiento del material fino que viaja en suspensión en los flujos gravitativos que circulan por el canal

(Fig. 2B). Estos procesos son más importantes en los canales proximales donde los diques están más desarrollados, y van perdiendo entidad aguas abajo, en los canales distributarios, donde la morfología del depósito de desbordamiento es prácticamente plana.

En los sistemas turbidíticos modernos los depósitos de lóbulo se desarrollan inmediatamente después del canal o canales principales que alimentan al sistema y en general la mayoría de ellos tienen canales distributarios sin diques o con diques muy poco desarrollados en sus zonas proximales (Fig. 2C). Los lóbulos comparten dos características: forma lobular y baja topografía. Son áreas deposicionales de gran extensión en comparación con su bajo relieve. Los lóbulos son el elemento más prominente en un sistema turbidítico desde el punto de vista sedimentológico, porque representan el ambiente donde se depositan los sedimentos gruesos (arenas y limos) de mayor espesor y mayor extensión lateral.

El dominio de transición entre el canal y lóbulo es importante para entender el ambiente deposicional y la distribución de sistemas turbidíticos así como la evolución de sus elementos arquitectónicos.

Modelos y factores de control

La génesis y el carácter de los elementos arquitectónicos reflejan que los sistemas turbidíticos resultan de una compleja interacción entre factores de control (Fig. 4). El encuadre tectónico, tanto local como regional, los cambios del nivel del mar, el aporte de sedimento y las corrientes de fondo, así como sus interacciones son los principales factores que controlan el tamaño, la geometría, la configuración interna y las características de las facies de estos elementos arquitectónicos. Estos factores, en general, son interdependientes y como resultado se puede decir que no existe un modelo universal que se pueda utilizar para describir y predecir las facies y la arquitectura estratigráfica de los sistemas turbidíticos (Figs. 5, 6 y 7). Han existido muchos intentos de clasificación de los sistemas turbidíticos y la más ampliamente empleada es aquella que presenta 12 modelos diferentes agrupados en cuatro categorías en base a la textura de sedimento que alimenta y circula por los sistemas turbidíticos (Fig. 5).

Sistemas turbidíticos en los márgenes continentales de Iberia

Los sistemas de turbidíticos modelan el fondo marino y contribuyen a la edificación de los márgenes continentales distales y cuencas adyacentes. Los cañones y canales representan las principales vías de transferencia de sedimentos desde el continente hacia las zonas de aguas profundas que rodean la Península Ibérica, como son la Fosa de Valencia y las llanuras abisales de Baleares, Iberia y Vizcaya. Los sistemas turbidíticos mejor estudiados son los que se desarrollan en el Mar Mediterráneo, mientras que siguen estando pocos estudiados los del océano Atlántico, a pesar de que en este margen se localizan los cañones más grandes que hay en el Atlántico europeo. Los sistemas turbidíticos en los márgenes de Iberia muestran una gran variabilidad en tamaño, ubicación en los dominios fisiográficas, estilo y geometría general de los elementos arquitectónicos, así como en la composición de los sedimentos. Es por ello que no hay un modelo simple que los defina. La variabilidad natural de los sistemas turbidíticos modernos en Iberia hace que su registro sedimentario tenga un gran interés científico ya que contiene información sobre las áreas continentales de la península, por ejemplo, áreas de drenaje, topografía, pendientes, subsidencia, clima, así como de las áreas submarinas, por ejemplo, topografía del margen y de las cuencas, circulación oceanográfica, cambios del nivel del mar, etc.

Los dos sistemas turbidíticos principales en el margen NO del Mar Mediterráneo - Ebro y Valencia - han sido ampliamente investigados y son clasificados respectivamente como sistemas rampa con fuentes múltiples y abanicos de talud fango-arenosos, y como un sistema de aporte puntual alimentado por un canal medio-oceánico, rico en fango (Fig. 8). En el Mar de Alborán se desarrollan nueve sistemas turbidíticos más pequeños, que de este a oeste son: Almería, Calahonda, Sacratif, Salobreña, Fuengirola, Torrenueva, Baños, Guadiaro y La Línea (Fig. 9). Los nueve sistemas turbidíticos se clasifican como abanicos submarinos y rampas submarinos. Los sistemas turbidíticos en el margen del Golfo de Cádiz están integrados por cañones submarinos que ocurren sólo en la parte occidental del margen del Algarve (cañones de Faro, Portimao y Lagos) y su estudio se ha centrado principalmente en la interacción con el Sistema Contornítico del Golfo de Cádiz (Fig. 10). Los depósitos transportados por estos cañones contribuyen al relleno de la llanura abisal de Iberia. El estudio en conjunto de estos sistemas aún no ha sido abordado. Un caso similar es el margen del Atlántico portugués, donde sólo los grandes cañones submarinos en el sector central del margen, Nazaré, Cascais y Setúbal-Lisboa, han sido bien descritos (Fig. 11). En el margen occidental de Galicia, también se han caracterizado de forma individual elementos arquitectónicos, y aunque el margen está ampliamente erosionado por cañones y cárcavas, sólo dos sistemas principales han sido cartografiados- sistemas múltiples en rampa y de abanico de talud. Por último, los sistemas turbidíticos en el margen de Cantabria están representados por los cañones de Cap Ferret, Capbreton y Torrelavega que desembocan en la llanura abisal de Vizcaya, formando canales, depósitos de desbordamiento y lóbulos (Figs. 12 y 13).

Introduction

Turbidite systems or submarine fans have been the focus of research since the first descriptions of density currents in lakes and the identification of submarine avalanches as the cause of cable breaks in submarine canyons, prior to the 1950s. Since then, research on turbidite systems has evolved and become the subject of various controversies (Shanmugam 2000, 2002). Turbidite systems have aroused enthusiastic interest from the scientific community as they are considered to be the most important clastic accumulations in the deep seas and are potential hydrocarbon reservoirs. Turbidite systems are also interesting due to the way they shape the seafloor with impressive reliefs, both erosional and depositional in nature. Their major erosive elements (i.e., canyons and channels) represent the main routes of sediment transfer from hinterland areas to the deep sea and are, in fact, the connection between the continents and the deepest marine basins. Because of this the sedimentary history of turbidite systems is important, not only for understanding the history of the oceans and seas, but also for decoding the Earth's past climate and oceanographic history.

Our understanding of turbidite systems has increased considerably over the past decades due to great advances in surveying methods and the high quality of the data obtained (acoustic, seismic and sedimentological).This has enabled new and unprecedented images of turbidite systems to be obtained, demonstrating their complexity and highlighting the numerous gaps that still exist in our knowledge of the sedimentary processes involved in turbidite flows and the factors controlling them.

The Iberian continental margins are shaped and outbuilt by the morphosedimentary features of turbidite systems. Our knowledge of these systems varies greatly, the most well-studied being those located in the Mediterranean Sea.

A brief history of scientific exploration and study methods

The history of turbidite system research has been compiled by Bouma and Stone (2000), Stow and Johansson (2000), Shanmugam (2000), Mutti *et al.* (2009) and Mulder *et al.* (2011), who contextualise the trend of scientific thinking over the past 50 years. The study of deep water systems started with the discovery of submarine canyons. The extensive and comprehensive list of discoveries and contributions begins prior to the 1950s, with the first descriptions of and experimentation on density currents in lakes and deep seas, the recognition of cable breaks in submarine canyons related to submarine avalanches and the introduction of the term *turbidity current* (Johnson, 1938). The concept of a turbidite as a deposit was originally defined by Kuenen and Migliorini (1950). In the 1950s, laboratory experiments were being carried out while at the same time processes, criteria and controlling factors were being established through research on ancient and modern systems. Deposits generated by turbidity currents were subsequently christened *turbidites* (Kuenen, 1957). In the 1960s the Bouma sequence was formulated as the first vertical facies model for turbidites (Bouma, 1962). Bill Normark pioneered the work on "modern" submarine fans (Normark, 1970). In the 1970s and 80s further modern systems were studied, models on modern submarine fans (at that time, the submarine feeding canyon was not considered part of the fan) were produced and turbidite facies schemes were proposed thanks to the development of deep-sea exploration techniques, the sequence stratigraphic approach and the establishment of comparisons between outcrop and marine systems. Normark (1970 and 1978) proposed the first general model based on the morphological aspects of Californian Pleistocene fans. Side-scan sonar surveys allowed detailed plan-view observations of submarine canyons and deep systems. In the 1980s the first meeting of the COMFAN (Committee on Fans) addressed the complexity of turbidite research in an attempt to produce a widely-accepted nomenclature and models that could apply to both ancient and modern systems. The integration of outcrop and marine observations enabled the recognition of common architectural elements (Mutti and Normark, 1987) and classifications based on geodynamic context were published (Shanmugam *et al.,* 1988; Shanmugam and Moiola, 1988). In the 1990s models based on source and dominant lithology were proposed (Reading and Richards, 1994). The models continued to be reviewed and several books on the topic were published (Mutti and Normark, 1991; Alonso and Ercilla, 2000; among others). More recently, the basis of most turbidite models has become the subject of strong criticism and the 'turbidite paradigm' is being questioned, with emphasis on the misinterpretation of thick massive sands related to debris flows as high-density turbidites (Shanmugam, 2000). Recently, the 'source-to-sink integration' approach has been applied to the study of turbidite systems, including the entire sediment-routing pathway and processes involved in the development of turbidites (Saller *et al.,* 2004; Sømme *et al.,* 2009; Ercilla *et al.,* 2008).

Methods for studying turbidite systems have evolved remarkably during the past few decades. They range from direct observation and sampling at outcrop permitting the study of ancient systems onshore, to geophysical and geological methods of investigating deep-sea turbidite systems, laboratory experiments, and analogue and numerical modelling. This variety of methods and available data sets is, at least in part, responsible for the controversies in turbidite research (Normark *et al.,* 1993). In the study of deep-sea systems, techniques include geophysical methods for obtaining images of the seafloor. Bathymetric maps and backscatter images are obtained using multibeam sounders and side-scan sonar with resolutions of up to 0.5 m. Samples of seafloor sediment can be extracted using a wide range of coring equipment. Seismic systems are used to obtain cross-section profiles of the seafloor and sub-bottom record. The equipment ranges from very high-resolution sounders (parametric sounders, chirp profilers, etc.) to very high-penetration systems that can provide information on the thicknesses of the sediment cover, from hundreds of metres to kilometre-scale, and even the underlying continental or oceanic crust. 3D-seismics has proved a very useful tool in the investigation of the temporal and spatial evolution of the morphology and facies of the architectural elements of turbidite systems. From its extensive use in industry it is beginning to be used in academic research, too. Finally, laboratory facilities are used to construct analogues for the study of turbidity currents and associated flows, whilst numerical modelling is applied for constraining the rheological conditions of flows and establishing the sedimentary processes involved in the development of turbidite systems.

Turbidite systems: an overview

Nomenclature

The term "turbidite system" is equivalent to "submarine fan" and today both are used interchangeably by scientists. Historically, *turbidite system* was a term used by Mutti and Normark (1987, 1991) for ancient/outcrop deposits, and the term submarine fan was used to describe modern accumulations on the seafloor. The term *turbidite system* is also used to define deep-sea clastic systems where the dominant process is a turbidity current (e.g., Hernández-Molina *et al.,* 2011) but which is not necessarily fan shaped. Other types of gravity processes, as well as hemipelagic and pelagic sedimentation, may also occur in these systems.

There are two major reasons contributing to the lack of a unified terminology and the confusion and misuse of a series of terms, such as channel and lobe (Normark *et al.,* 1993). These are: 1) the resolution and type of methods and techniques available for the investigation of both ancient and modern turbidite systems has led to different scales of observations and dataset types; and 2) the complex interaction between global and local factors that govern the onset and evolution of turbidite systems results in a huge variety of morphologies and stratigraphical architectures (Normark *et al.,* 1993). In an attempt to solve this terminology problem, outcrop and marine observations have been integrated, allowing the recognition of common architectural elements (Mutti and Normark, 1987). Mutti and Normark (1991) propose an "elemental approach" including a definition of the common elements that can be recognised and mapped in most of the modern and ancient turbidite systems (Figs. 1 and 2).

Architectural elements composing turbidite systems

Architectural elements typically recognised in deep-sea fans are identified by the nature of their base and top surface and their external, 3D and internal geom-

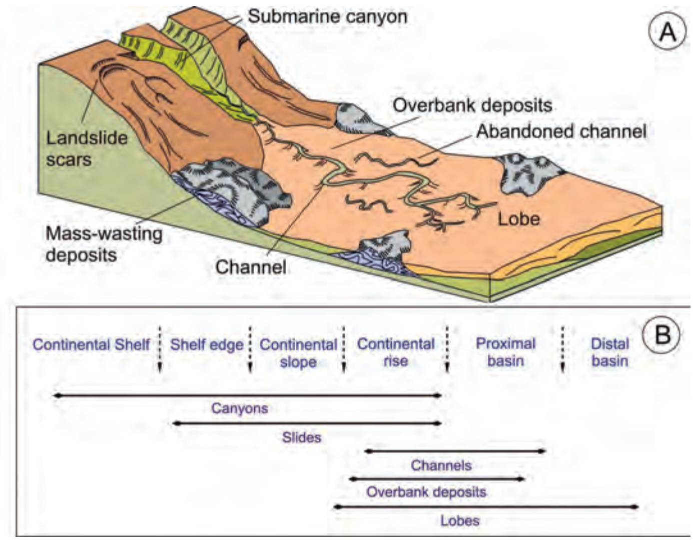

Figure 1. A) Major architectural elements composing modern turbidite systems. B) Generic distribution of the architectural elements in the physiographic domains, from the continental shelf to the deep basin. Modified from Normark *et al.* (1993).

Figura 1*. A) Principales elementos arquitectónicos que componen los sistemas turbidíticos modernos. B) Distribución general de los elementos arquitectónicos en los dominios fisiográficos, desde la plataforma continental hasta la cuenca profunda. Modificado a partir de Normark* et al. *(1993).*

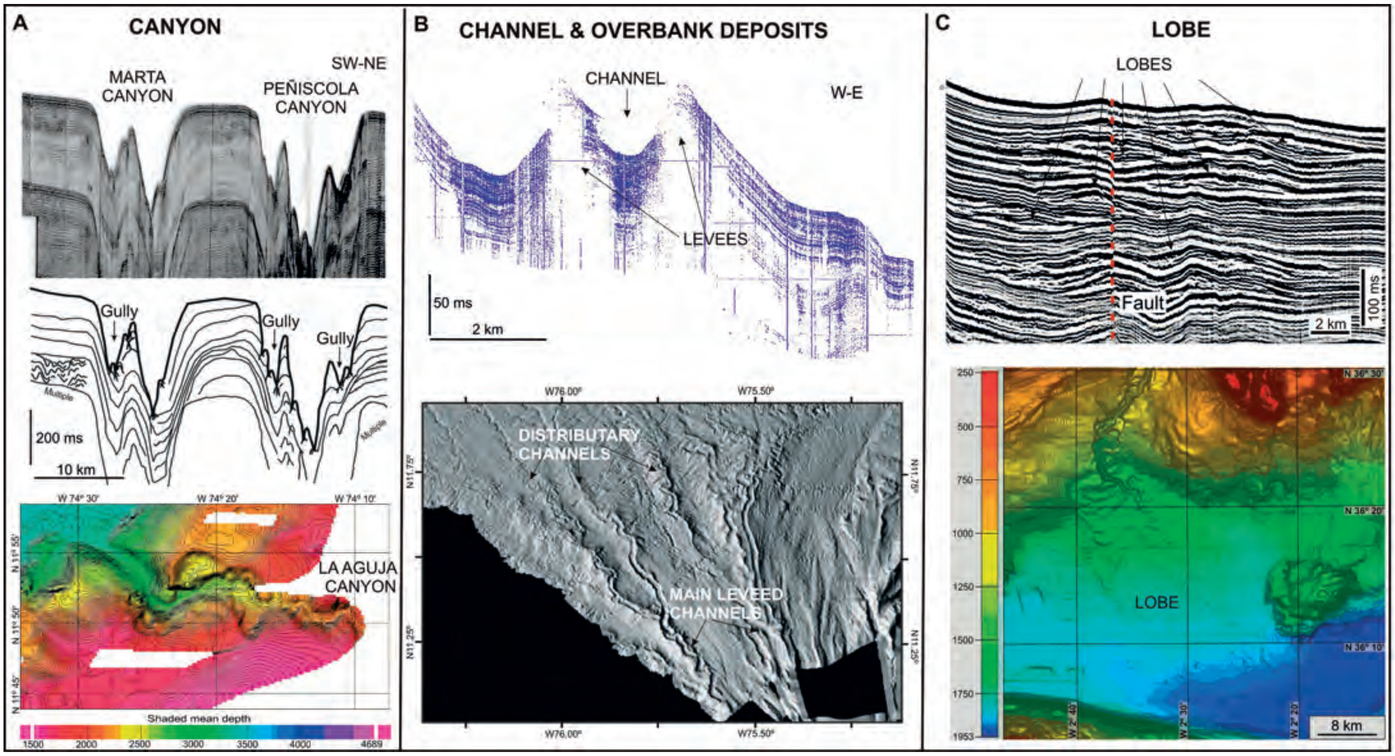

Figure 2. Seismic cross-sections and plan-view multibeam bathymetric images of the main architectural elements defining a turbidite system: A) canyon; B) channel and overbank (levee) deposits; and C) lobe.

Figura 2. *Secciones sísmicas e imágenes de batimetría multihaz de los principales elementos arquitectónicos que definen un sistema turbidítico: A) cañón; B) canal y depósitos de dique (levee); y C) lóbulo.*

etry (Miall, 1985). Mutti and Normark (1991) consider the main elements defining a turbidite system to be large-scale erosive features, channels and channel-fill deposits, overbank deposits and lobes. These architectural elements have been grouped, described and interpreted in different ways by the various fan models(e.g., inner, middle, outer for modern fans; upper, middle and lower for ancient fans; and suprafans that group together leveed channels and lobes).The main characteristics of the architectural elements are summarised in the following sections.

Large-scale erosive features

These include submarine valleys (canyons and gullies) and mass-movements, the canyons being the most important features. Canyons are the main conduits for sediment transport from the continental shelves to the deep ocean and represent the main, long-term point sediment source for turbidite systems (Figs. 1 and 2A). They transport a great variety of grain sizes (gravels to clay) and are associated with practically all the stages of evolution of a turbidite system. They typically occur as narrow (a few km) and deep (hundreds of m), V-shaped valleys with steep walls and can be directly connected to onshore river mouths. Their formation can initiate due to subaerial erosion by a river system, retrogressive submarine erosion of sedimentary instabilities, erosion of fault-related depressions, forward erosion by continuous steady flows and bypassing on prograding margins (Shepard, 1981; Mulder *et al.,* 2004). They can also result from alternations of filling and incision stages (Gaudin *et al.,* 2006). Canyons are often associated with tributary gullies and/or minor order canyons that incise the continental slope and shelf.

Channels and channel deposits

Channels represent the main conduits (kilometric in scale) of sediment transport within turbidite systems (Figs. 1 and 2B). They develop from the canyon mouth, and their dimensions decrease basinward, with common bifurcations, branching and development of complex networks of minor distributary channels that progressively disappear down slope. Channels are considered to be mixed features since they are maintained by erosion and outbuilt by deposition from turbidity currents and related flows (Normark *et al.,* 1993). Erosion incises the channel while deposition occurs on the margins producing the aggradation of the channel on the slope. Thus, channels act as conduits that transport and distribute sediment along the continental margin rather than merely transferring sediment to the deep sea areas.

Turbidite channels are generally characterised by coarse sediment associated to the infilling of aggrading and laterally migrating channel floor deposits that generate high-amplitude reflections beneath the channel axis (HARs; Flood *et al.,* 1991; Deptuck *et al.,* 2003), while the finer sediment is deposited on the flanks forming the levees. Coarse sediment deposited from flows spreading laterally from a channel mouth, or from erosive flows opening breaks into the levees (channel-avulsion events), generate laterally extensive high-amplitude reflection packets (HARPs) at the bases of channel-levee systems (Flood *et al.,* 1991). Channels have trajectories ranging from rectilinear to highly meandriform, and lateral migration has been linked to changes in energy conditions (Wynn *et al.,* 2007).

Quantitative studies on submarine channels, although rare, have increased in number in recent years (Estrada *et al.,* 2005). This type of study in combination with experimental numerical modelling of flow behaviour has enabled advances in the knowledge of the characteristics of turbidity currents and related flows (velocity, thickness, type of sediment load) and their evolution along the channels (Schumm, 1981; Mulder *et al.,* 1998; Imran *et al.,* 1999; Pratson *et al.,* 2001; Peakall *et al.,* 2000; Mulder and Alexander, 2001; Pirmez and Imran, 2003; Mohrig and Buttles, 2013).

Overbank deposits

These are typically fine-grained, thin-bedded sediments located adjacent to the main turbidite channels as the result of the spillover and stripping of the upper part of turbidity currents or centrifugal force when the channel abruptly changes direction (Fig.s 1 and 2B; Piper and Normark, 1983; Normark *et al.,* 1993; Hiscott *et al.,* 1997; Mulder, 2011). The overbank area has two morphological domains: the proximal levee, with a constructive positive relief, and its lateral prolongation, where the deposit evolves laterally from the channel to a practically flat domain. A great variety of morphosedimentary features have been mapped in overbank deposits (e.g., sediment waves, furrows and crevasse splays). The levee deposition, together with the aggradation of the channel floor, result in the vertical growth of channel-levee systems (Mulder, 2011) and explain the formation of prominent bulges on the seafloor, even in tectonically active contexts (Estrada *et al.,* 2005). Levees are usually asymmetrical due to the Coriolis force, with the right-hand levee being more developed than the left (downflow, in the northern hemisphere; the opposite is true for the southern hemisphere). This effect is inversely proportional to flow velocity (Cremer, 1983) and affects systems at mid-latitude locations.

Lobes

Lobes occur in the distal part of a turbidite system (Figs. 1 and 2C). They are lobe-shaped in plan view and display low topographic relief on the distal margin and/or in proximal basin environments (Mulder *et al.,* 2011). They are fed by channelised or unchannelised flows from the margin area, often showing thickening and coarsening upward cycles (Normark *et al.,* 1993). Lobes represent the areas within a turbidite system where sandy levels may reach their thickest and largest lateral extensions. Here, sand levels display good lateral continuity, forming important hydrocarbon reservoir systems.

Lobes usually display three morphosedimentary domains: proximal, dominated by distributary channels; middle, where lens-shaped bodies are stacked vertically; and distal, known as lobe fringe, and dominated by thin levels of fine sediment, silty clay and clay. The occurrence and extension of these domains vary depending the type of system, sand-rich, mud/silt-rich or mud-rich (Bourget *et al.,* 2010), and the developmental stage. Two end-members of lobe architecture have been defined, based on the characteristics of the sediment (Bonnel, 2005; Mulder, 2011): large mud-dominated systems, composed of massive sands and debrites with mud clasts in the upper and middle parts of the channel axis and fine sediments in the rest of the lobe; and sand-dominated systems composed of massive sands with mud clasts in the upper part of the channel axis and massive sand beds alternating with clayey levels in the rest.

Channel-lobe transition zone (CLTZ)

The CLTZ has been defined as a transitional zone dominated by erosional and bypass processes where the turbidity flows undergo hydraulic jumps (Bouma *et al.,* 1985; Wynn *et al.,* 2002; Mulder, 2011). CLTZs have been identified in modern turbidite systems due to the increasing use of multibeam echo sounders and side scan sonars. Their occurrence is related to the efficiency of the system, the basin/margin morphology, and near surface sediment (Wynn *et al.,* 2002). This zone has not been mapped in all fans, due to lack of adequate acoustic/seismic data or they do not develop as in the muddy fans of Mississippi or Zaire (Twichell*et al.,* 1992; Savoye *et al.,* 2000). In fact, its occurrence has been registered mainly in sandy fans, e.g, the Valencia, Laurentian fans (Morris *et al.,* 1998; Normark *et al.,* 1983). From proximal to distal, sedimentary features generally identified in this zone include furrows oriented parallel to the flow direction, scours and sand waves. Recent studies (Palanques *et al.,* 1995; Bourget *et al.,* 2010; Mulder *et al.,* 2011) have included this zone within the proximal lobe domain, not considering them to be a transitional element between the channel and lobe, as was originally proposed by Mutti and Normark (1991).

Sedimentary processes

Turbidite systems probably contain the elements that best reflect the occurrence of long distance particle transport by gravity flows. Slumps, turbidity flows and mass flows/debris flows are the most frequent processes that contribute to the construction of the architectural elements (Shepard and Dill, 1966; Normark and Piper, 1969; May *et al.,* 1983; Shepard, 1981; Farre *et al.,* 1983; Hagen *et al.,* 1994; Pratson and Coakley, 1996; Mullenbach *et al.,* 2004). Flood-generated gravity flows, or hyperpycnal flows, and dense shelf water cascading episodes can occur (Lastras *et al.,* 2007). The most important processes affecting deep clastic systems are summarised in Figure 3.

Canyons are mainly characterised by erosive processes. Slumping and mass transport occurs principally on the canyon walls and heads and deposition is from hyperconcentrated flows (Gervais *et al.,* 2006). These flows which do not spill over canyon walls, are characterised by their high energy, and erode seafloor sediments that then mix with the running flow and the surrounding water masses.

Channels are characterised by the interplay between depositional and erosive processes. The geometry and architecture of the channels are usually related to the type of sediment load running along them: muds in long and sinuous channels, and sands in straight, short channels. High-density currents dominate sandy systems, and low-density currents with frequencies from high to moderate characterise muddy systems, particularly those with a meandering

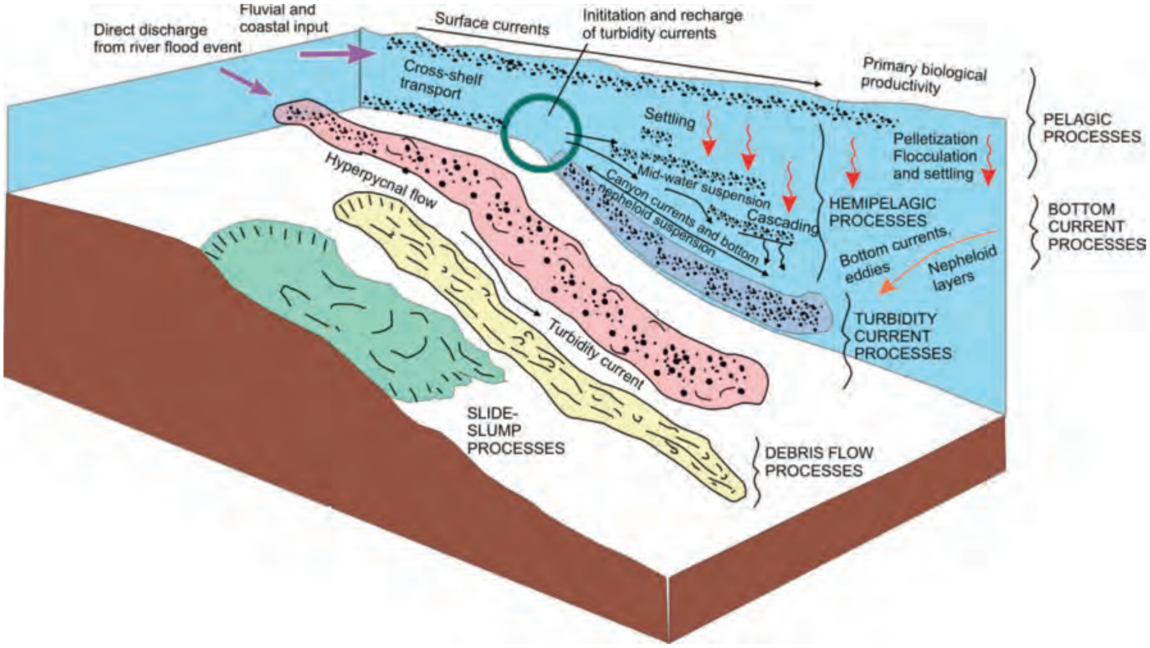

Figure 3. Diagram showing the most important processes shaping deep clastic systems, including pelagic, hemipelagic, bottom current, turbidity current, debris flow and slide-slump processes. The area of turbidity current initiation and recharge at the shelf-break is marked. Modified from Normark *et al.* (1993).

Figura 3*. Diagrama que muestra los procesos más importantes que modelan los sistemas clásticos profundos, incluyendo procesos pelágicos, hemipelágicos, corrientes de fondo, corrientes de turbidez, flujos de derrubios y deslizamientos. Se señala el área de iniciación y recarga de las corrientes de turbidez en el borde de plataforma. Modificado a partir de Normark et al. (1993).*

course (Babonneau *et al.,* 2004). The characteristics of the flow may change during the evolution of a turbidite system, and some observations suggest that sinuosity reflects the maturity of a system (Babonneau *et al.,* 2002). Flows channelised along channels are usually turbulent with laminar basal concentrated flow (Gervais*et al.,* 2006) and may be fed by the self-cannibalisation of the channel during migration (Deptuck *et al.,* 2003). Avulsion processes are frequent in channels, and only one channel is active in a system at any time (Normark *et al.,* 1979; Twichell *et al.,* 1992; Zaragosi *et al.,* 2000; Klaucke *et al.,* 2004). This process favours the formation of knickpoints (Pirmez *et al.,* 2000; Estrada *et al.,* 2005). The break-up of channel walls facilitates the expansion of the confined flow, the coarse load being deposited forming HARPs in the depressions between the leveed channels due to the rapid deceleration of the flow (Flood *et al.,* 1991). Side wall slumping is an additional process that can affect the internal walls, favouring channel erosion and enlargement (Kenyon *et al.,* 1995; Berné *et al.,* 1999). This process can form internal terraces, although their occurrence may also reflect channel entrenchment phases, formation of internal levees, meander cut-offs, levee margin growth faults and slumped levees (Hackbarth and Shew, 1994; Clark and Pickering, 1996; Possamentier, 2003; Posamentier *et al.,* 2003). In addition, avulsion processes favour the incorporation of mud clasts into sandy sediments, increasing the concentration of the running confined basal gravity flows. This may provoke rapid deposition of the basal part, while the rest of the flow continues down the channel. The flows progressively lose their finer fraction down channel through spill-over processes, explaining the basinward decrease in channel relief, whereas the coarser fraction is transported down channel in a confined way. The spill-over process may also favour the formation of sediment wave fields on the external side of the levees. If the energy of the processes is high, break-up of the levee may occur favouring the local formation of crevasse splays scours, furrows, and cut-off loops (Kenyon *et al.,* 1995; Masson *et al.,* 1995; Pirmez *et al.,* 2000; Possamentier *et al.,* 2003). Additionally, slumping may contribute to the reworking of seafloor deposits (Migeon *et al.,* 2001). The progressive vertical aggradation of the levee through time prevents spill, increasing the fining upwards character of levee deposits.

The loss of fine sediment by overspilling processes favours the deposition of coarser sediment in the lobe domains. Here, erosional and bypass processes characterising the channel domain are progressively replaced by depositional processes as the flow quickly decelerates and loses its efficiency after exiting the main distributary channels. Flows with different concentrations, both mass/debris flows and turbidity flows occur, which may be affected by hydraulic jumps favouring the formation of the CLTZ. Mass/debris flows and turbidity flows evolve into small avulsions, resulting in the formation of distributary channels at various scales, as well as their lateral migration. This branching process controls the sand connectivity and leads to the development of complex vertical and horizontal distributions of sandy bodies. Deposition of thick sandy bodies occurs through one or more of four mechanisms: a) the freezing of a sandy debris flow plug, b) collapse fallout from the turbulent flow of a high-density turbidite, c) continuous aggradation beneath a sustained high-density turbidite, or d) continuous traction beneath a sustained high-density turbidite. These depositional mechanisms may interchange throughout any one event (Stow and Johansson, 2000).

Controlling factors

The genesis and character of the architectural elements making up a turbidite system reflect the fact that they are formed by a complex interaction between different factors, both global and local. Four major interdependent controlling factors are generally recognised: regional basin tectonics, morphology, sea level fluctuations, and sediment supply rate, type and source (Fig. 4; Richards *et al.,* 1998). Tectonics controls the geometry and size of the basin where the systems are outbuilt, including the seafloor gradients. The morphology/topography, closely related to tectonism, may condition the degree of confinement of the flows. This parameter governs the 3D geometry and dimensions of the architectural elements, especially those of the leveed channels and lobes (Ercilla *et al.,* 1998; Alonso and Ercilla, 2000; Alonso and Ercilla, 2003). Glacioeustatic changes are probably the most important factor since sea level fluctuations affect all the physiographic environments where turbidite systems develop and condition the periods of activity and non-activity of the architectural elements (e.g., Alonso and Maldonado, 1992; Palanques *et al.,* 1994; Saller *et al.,* 2004). Sediment supply involves several factors such as texture of the sediment, volume and nature of the sediment supplied, and type of source (point, linear, etc.). Its relationship with fluvial drainage systems and coastal dynamic conditions is a relevant factor governing the architecture of the system (Normark, 1978; Bourget *et al.,* 2010). Physiographically, the width of the continental shelf

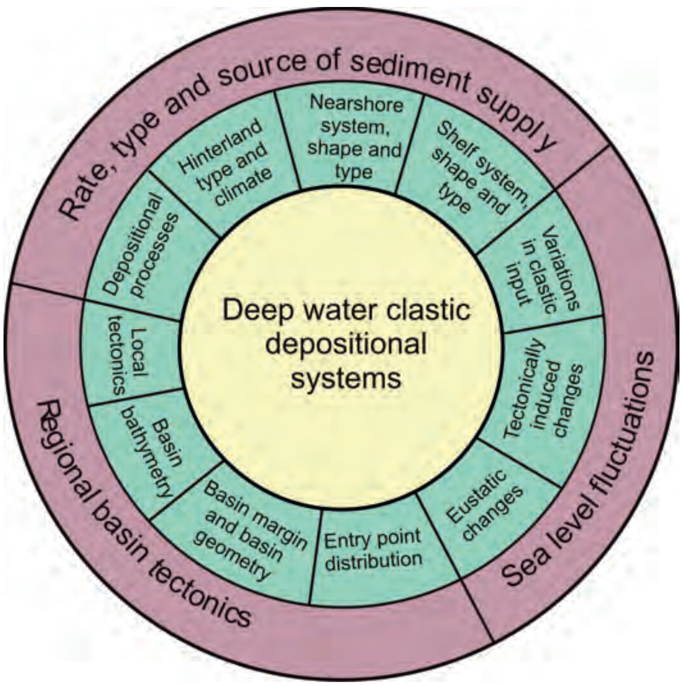

Figure 4. Main factors controlling the genesis and character of the architectural elements of turbidite systems. Modified from Richards *et al.* (1998).

***Figura 4**. Principales factores de control sobre el origen y el carácter de los elementos arquitectónicos de los sistemas turbidíticos. Modificado a partir de Richards* et al. *(1998).*

and/or the presence of canyon heads on the shelf may favour the catchment of sediment transported by littoral drift. The volume of sediment supply, grain size, and type of processes triggering the turbidity flows and other related flows are important factors controlling the style of the elements. Bottom currents may also condition the dispersion of turbidites and related sediments and their post-depositional reworking. When bottom currents are strong enough they may interact with the transverse component of the gravity flows (Fig. 3). This can cause the piracy of the finer fraction, conditioning the overall geometry of the lobes. In these cases, where the interaction between turbidity currents and bottom currents conditions transport and sedimentation, the resultant systems are classified as mixed systems (Faugeres *et al.,* 1999; Mulder *et al.,* 2008).

All these factors have an impact on the morphology of deep-sea turbidite systems, the extent depending on whether the margin is active or passive (Mulder, 2011). On active margins, the most important parameters are tectonic influence, particle load volume, sand/clay ratio and flow concentration. In contrast, systems on passive margins are more affected by eustacy and shelf extent as an indicator of the space available for sediment storage.

Models of turbidite system development

In recent years, several attempts have been made to classify submarine turbidite systems in order to provide predictive paradigms for outcrop and subsurface analysis (Richards *et al.,* 1998). The high variability in geometry, size and internal character of turbidite systems leads to differences in reservoir architecture, trapping style and *in situ* hydrocarbon volumes. Much of this variability is directly related to the fundamental controls influencing the development and characteristics of different deep-marine clastic systems (Richards *et al.,* 1998). A few turbidite system classifications are found in the literature, but here two of the most widely-used classifications, proposed by Richards *et al.* (1998); (Fig. 5) and Bouma (2000); (Fig. 6) are presented. A less well-known yet interesting model proposed by Kenyon *et al.* (2000) is also presented, as it establishes a link between hinterland areas and overall architecture of submarine fans (Fig. 7).

Reading and Richards (1994) published a review of the literature and a classification based on grain size and feeder systems. Later, twelve classes were presented based on a combination of the following parameters: mud-rich, mixed mud-sand-rich, sand-rich, gravel-rich, and slope apron, submarine fan and ramp (Fig. 5; Richards *et al.,* 1998). This classification is a continuum in which a number of basic models are defined. Each can be modified to suppress or emphasise specific features of an individual fan. *Gravel-rich systems* are commonly the down-dip marine equivalents of coarse-grained fan deltas, alluvial cones and braid plain environments (Fig. 5A). They are associated with high slope gradients. Examples are generally small scale and localised (up to 49 km in radius). They are characterised internally by complex and irregular gravels and sandstones with a high degree of facies variability. Net sand and gravel ratios are typically high and reservoir connectivity is good. Reservoir trapping mechanisms developed within gravel-rich systems are dominantly structural. Three main gravel-rich systems are recognised: gravel-rich slope aprons, gravel-rich submarine fans and gravel-rich submarine ramps.

Sand-rich systems contain more than 70% sand (Fig. 5B). This boundary is not arbitrary as it marks a major change in seismic character, reservoir architecture and trapping geometry, distinguishing the sand-rich systems from their gravelly and muddier counterparts. Sand-rich systems are typically small

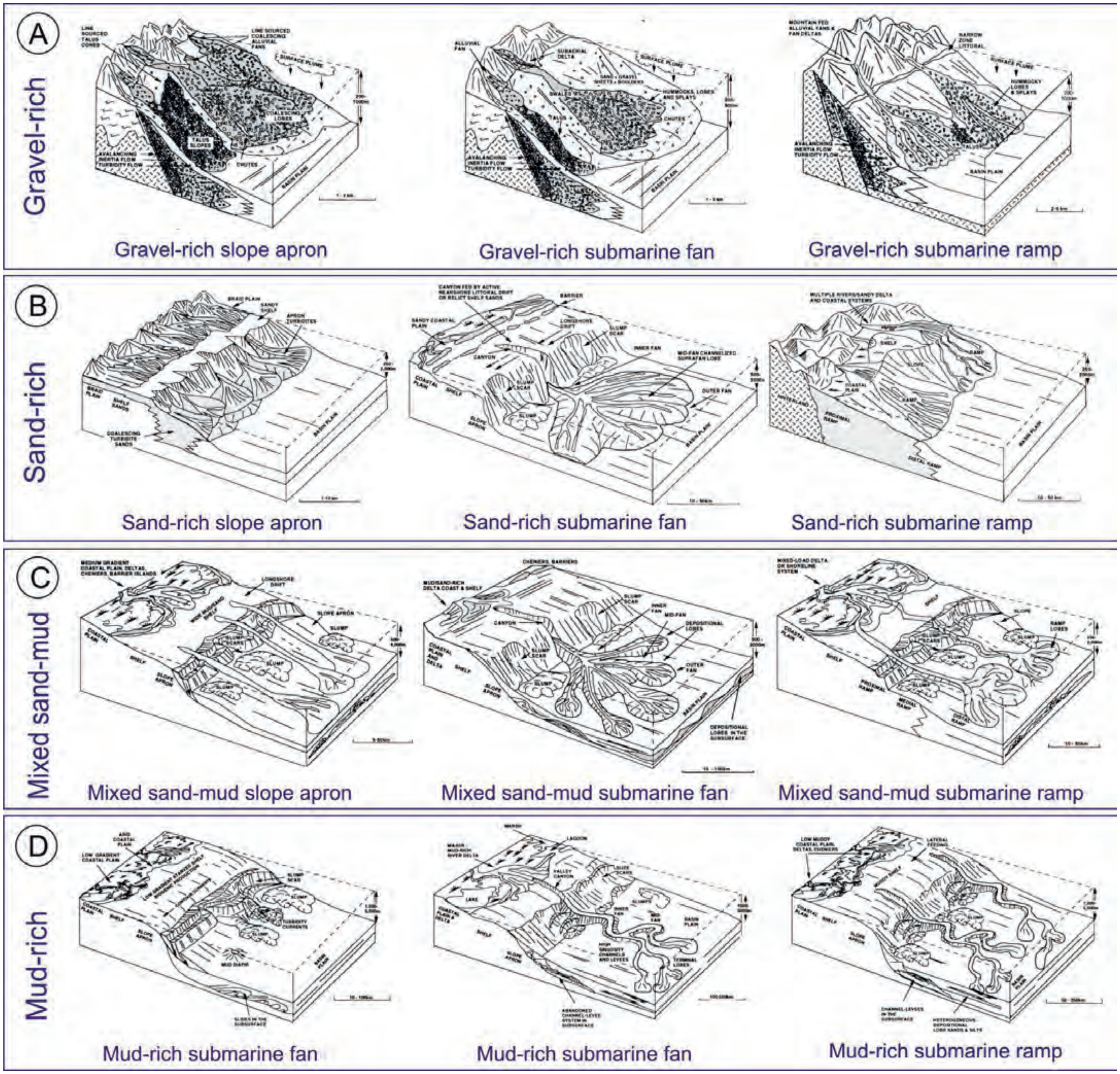

Figure 5. Summary sketch of the classification of turbidite systems based on grain size and feeder system, from gravel-rich to mud-rich dominated systems, and from apron to submarine ramp morphologies. Modified from Richards *et al.* (1998).

Figura 5*. Esquema de la clasificación de los sistemas turbidíticos basada en el tamaño de grano y el sistema de alimentación, desde sistemas dominados por gravas a sistemas dominados por fango, y desde morfologías tipo "apron" (abanico) hasta rampa. Modificado a partir de Richards* et al. *(1998).*

(generally 1-50 km radius) being sourced from either incision or the failure of relict sand-rich shelves or by direct canyon access to littoral drift cells. Because of their net reservoir volume, the trapping mechanisms are predominantly structural. Three main sand-rich systems are recognised: sand-rich slope aprons, sand-rich submarine-fans and sand-rich submarine ramps.

Mixed sand-mud systems form a continuous spectrum from more sandy to more muddy systems with

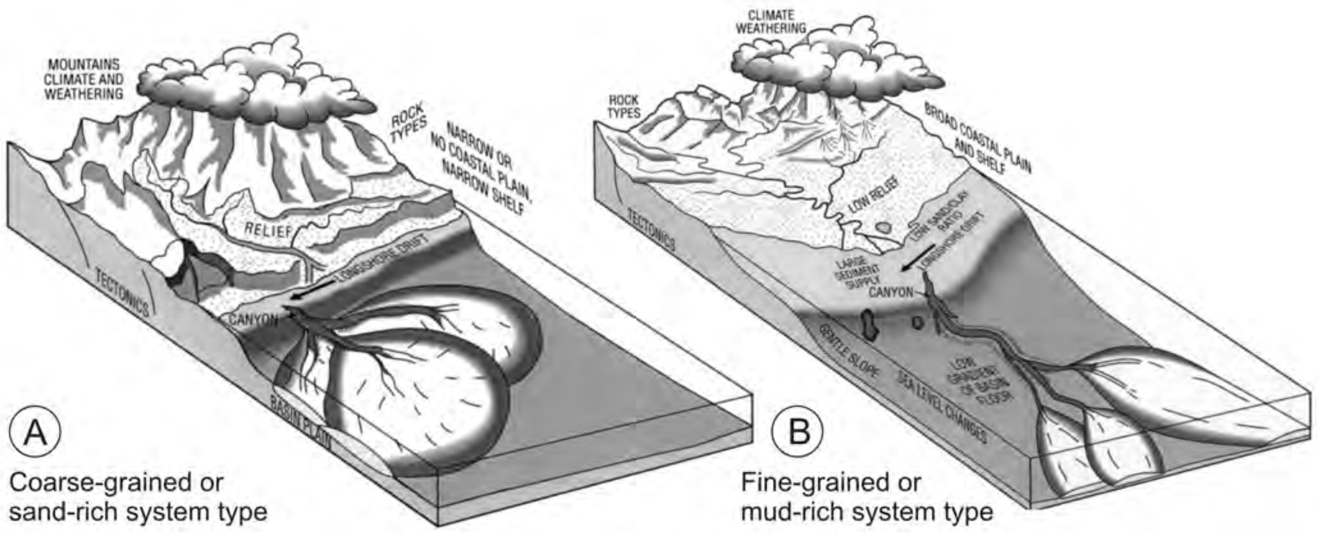

Figure 6. Sketch summarising the main elements of: A) the coarse-grained or sand-rich system type; and B) the fine-grained or mud-rich fan system. Modified from Bouma (2000).

Figura 6*. Esquema que sintetiza los principales elementos de: A) un sistema dominado por grano grueso o arena; y B) un sistema dominado por grano fino o fango. Modificado a partir de Bouma (2000).*

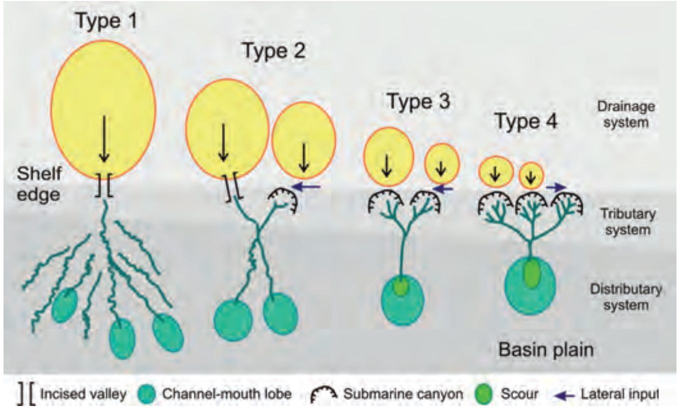

Figure 7. Types of turbidite systems based on channel and lobe characteristics related to sediment input. Four types of systems are defined, displaying defined drainage, tributary and distributary system morphologies. Modified from Kenyon *et al.* (2000).

Figura 7*. Clasificación de sistemas turbidíticos basada en las características de los canales y lóbulos en relación al aporte sedimentario. Se definen cuatro tipos de sistemas con morfologías típicas de drenaje, sistemas tributarios y sistemas distributarios. Modificado a partir de Kenyon* et al. *(2000).*

sand/shale ratios ranging between 30-70%. They are typically moderate-scale features (5-100 km radius) often being the product of erosion, failure and/or direct sediment input from large mixed-load delta, shoreline and coastal plain systems (Fig. 5C).The systems are typically highly organised with discrete well-developed architectural elements of which channel-levee complexes and lobes are the most important. In general, a higher mud content results in a reduction in topographic relief and increasing importance of channel-levee complexes as the principal architectural element. Three main systems are recognised: mixed sand-mud slope aprons, mixed sand-mud submarine-fans and mixed sand-mud submarine ramps.

Mud-rich systems have a sand/shale ratio of less than 30%. They are common in basins with mature drainage patterns, large source areas and where rivers and deltas are dominated by fine-grained suspended loads (Fig. 5D). Mud-rich systems are volumetrically the most important deep-water clastic systems in the world's oceans today and they form large-scale, widespread systems (50-3000 km radius). Finding and developing reservoirs within these systems is a major challenge for exploration along many continental margins because reservoir-quality sands are confined to specific parts of the system. Three main mud-rich systems are recognised: mud-rich slope aprons, mud-rich submarine-fans and mud-rich submarine ramps.

Bouma (2000) proposed two end members, coarse-grained and fine grained turbidite systems, based on the criteria of efficiency (Fig. 6). The terms 'poorly efficient' and 'efficient' were introduced by Mutti (1979) to indicate the efficiency of density currents in transporting sand over short or long distances. The sand/clay ratio and size range dictate how far a sediment can be transported (Bouma, 2000). The coarse-grained or sand-rich system has a high net-to-gross percentage throughout, that gradually decreases with water depth along with thickness and grain size, and has excellent connectivity characteristics (Fig. 6A). This type of fan gradually progrades into the basin. The fine-grained or mud-rich fan is a bypassing system with a sand-rich channel complex at the entrance to the basin (base of slope), a sand-rich leveed channel with mud-rich levee-overbank deposits in the mid-fan, and very high net-to-gross sheet sands/depositional lobes in the outer fan (Fig. 6B).

During the 1990s, the generalised use of multibeam systems and side scan sonar enabled plan view images of turbidite system features to be obtained for the first time, revealing the great morphological complexity of their architectural elements. The plan view emphasis allowed the creation of a turbidite system classification linking the channel and lobe characteristics with the long-term average rate of sediment input which is directly related to the size and gradient of the drainage system (Fig. 7). This classification was applied to the Mediterranean systems by Kenyon *et al*. (2000) and later utilised for the turbidite systems in the Alboran Sea and Atlantic Ocean (Alonso and Ercilla, 2002).The classification comprises four types: Type 1, defined by high inputs from a large point source and a large distributary channel system with sinuous channels, numerous avulsions, and low fan gradients; Type 2, characterised by a medium-sized drainage system (about 100 000 km^2) and a distributary pattern of channels with at least one avulsion; Type 3, formed by drainage systems with medium to small, steep canyons and relatively rectilinear channels; and Type 4, characterised by drainage systems with relatively low inputs and submarine tributaries formed mostly by canyons with less significant, or a total absence of, channel-levee systems, and the development of lobe deposits with braided distribution patterns at the mouths of the canyons.

Turbidite systems on the Iberian continental margins

Turbidite systems on the Iberian continental margins are described in the following sections, based on published scientific work that reflects the variability in both the systems themselves and in the level of development of research in the different geographical areas where the systems are located.

In the NW Mediterranean Sea

The largest modern turbidite systems in the NW Mediterranean Sea are the Ebro and Valencia turbidite systems, both occurring in a passive margin setting (Alonso and Maldonado, 1990; Alonso *et al.,* 1990; Maestro *et al.,* 2013).

The *Ebro turbidite system* is located on the Ebro continental slope and base of slope at 400-1800 m water depth (Fig. 8). It is elongated in shape (50 km long x 111 km wide) and is fed by the Ebro River, with shelf prograding wedges and multiple short slope canyons (< 10 km) perpendicular to a steep continental margin (Nelson and Maldonado 1988; Alonso and Maldonado, 1990). The architectural model comprises canyon-fill deposits, mostly southwards-migrating channel-levee complexes, and apron deposits (Alonso *et al.,* 1990; Alonso *et al.,* 1991). The channel-levee complex is an elongate lenticular body that extends from the mouth of the slope canyon (Fig. 8A). The length of the channels ranges from 25 to 52 km. Channels of the northern area mouth into the Valencia mid-ocean Channel (Fig. 8).The growth pattern of the Ebro turbidite system is of particular interest because it differs from that of a typical fan, which evolves from a single canyon to a leveed channel, a trough fan channel bifurcation and finally depositional lobes. The system initiated at the end of the Pliocene and the major growth took place during the Quaternary as a result of the abundant sediment supply and low-stand progradation of the river depocentre onto the outer shelf (Alonso *et al.,* 1990; Medialdea *et al.,* 1986).The Ebro turbidite system can be classified as a multiple-source ramp turbidite system based on the submarine feeder system criteria (Alonso and Ercilla, 2002) and as a mixed sand-mud slope apron (Fig. 5).

The *Valencia turbidite system* is one of the largest deep-sea fans in the western Mediterranean Sea. It is located in a large depression between the Valencia Trough and the Balearic Basin Plain (Fig. 8). It has an elongate lobe-shape (164 km long and 88 km wide) that develops at the distal part of the Valencia Channel at 2 500 m water depth, extending down to the Balearic Basin Plain, to a water depth of 2 700 m. It is fed by two main sources: one longitudinal, represented by the Valencia Channel (over 400 km long) and the other lateral, represented by the Catalan canyon systems on the Iberian margin and sedimentary instabilities on the Balearic margin (Fig. 8) (Alonso *et al.,* 1995). The architectural model comprises canyon-fill deposits, channel-levee complexes, and channel-lobe transition deposits (Fig. 8C, D). The growth pattern of the Valencia turbidite system could be expected to differ from those developed at the base of a continental slope, since sediment is transported along the Valencia Channel over 100km in a direction approximately parallel to two margins (the Iberian and Balearic Islands) (Fig. 8). Fan deposition

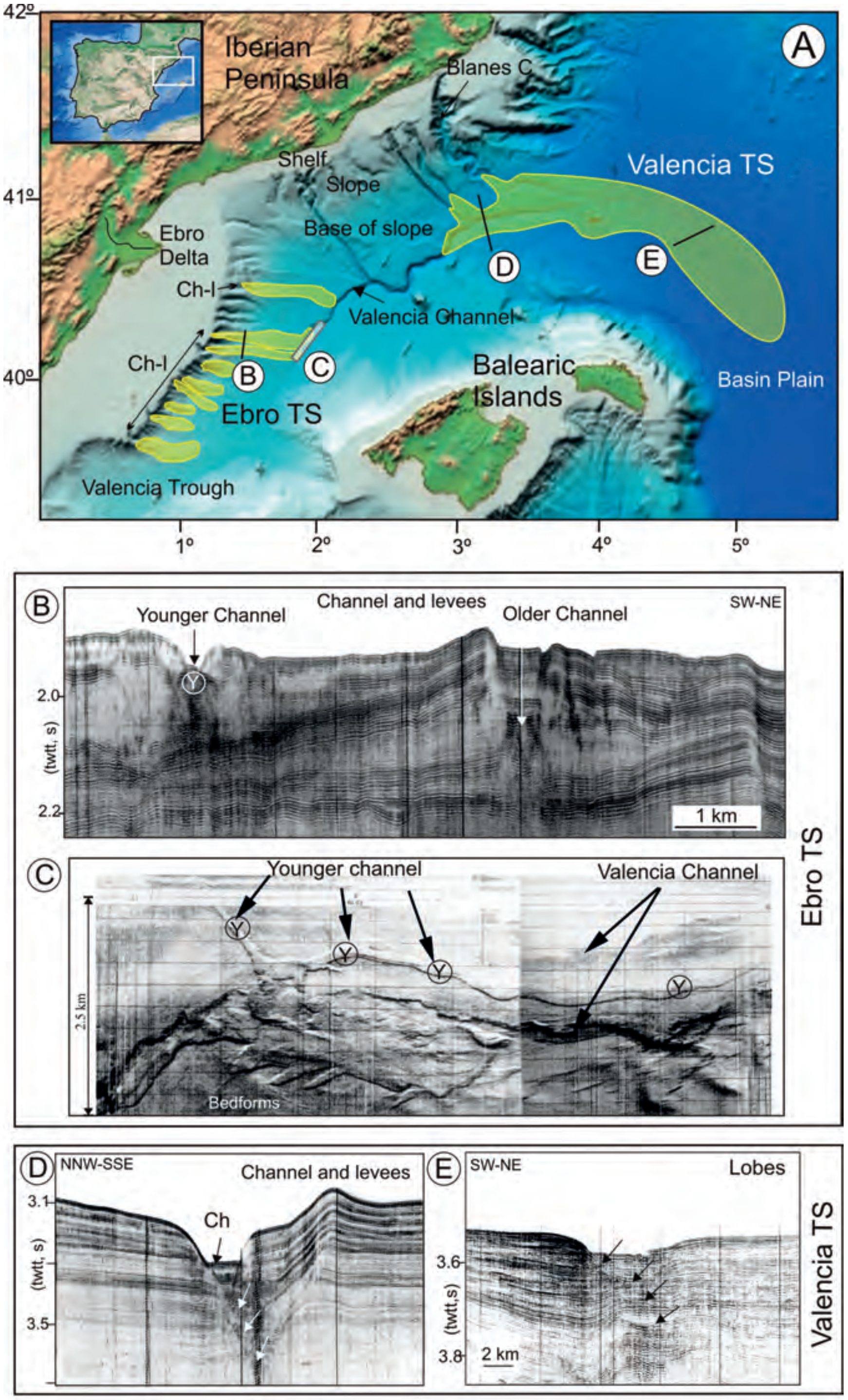

Figure 8. The Ebro and Valencia turbidite systems of the NW Mediterranean Sea: A) Bathymetric map of the NW Mediterranean showing the location of the Ebro and Valencia turbidite systems; B) Sparker seismic profile showing the architecture of the Ebro turbidite system; C) Detail of morpho-acoustic features of the channel and levee deposits of the Ebro turbidite system in a side-scan sonar mosaic; D) Sparker seismic profile showing the Plio-Quaternary cut-and-fill structures of the Valencia Channel (Ch) deposits; E) Sparker seismic profile showing the lobe deposits and distributary channels (marked with arrows) in the deepest part of the Valencia turbidite system.

Figura 8*. Sistemas Turbidíticos del Ebro y Valencia en el Mediterráneo Noroccidental. A) mapa batimétrico del Mediterráneo Noroccidental mostrando la localización de ambos sistemas; B) perfil sísmico de sparker mostrando la arquitectura del sistema turbidítico del Ebro; C) mosaico de sonar de barrido lateral mostrando los rasgos morfo-acústicos del canal y los depósitos de dique del sistema turbidítico del Ebro; D) perfil sísmico de sparker mostrando las estructuras Plio-Cuaternarias de corte y relleno del Canal de Valencia; E) perfil sísmico de sparker mostrando los depósitos de lóbulo y canales distributarios (marcados con flechas) en la zona más profunda del sistema turbidítico de Valencia.*

begins at the mount of the channel beyond which there is a break in slope at the distal part of the Valencia Trough (Maldonado *et al.,* 1985). This system initiated at the end of the Pliocene and its major growth took place during the Quaternary. The spatial and temporal distributions of the turbidite deposits involve significant upslope/downslope migrations at the lower end of the Valencia Channel and the Blanes Canyon (Fig. 8). The morphosedimentary features indicate updip-downdip migrations of the fan depocentre during the Plio-Pleistocene caused by changes in sediment supply related to climatic-eustatic sea level variations (Palanques *et al.,* 1994). On the basis of the submarine feeder system, the Valencia turbidite system can be classified as a point-source turbidite system by a mid-ocean channel (Alonso and Ercilla, 2002) and its morphological characteristics point to it being a mud-rich system (Fig. 5).

In the Alboran Sea

Nine turbidite systems have been mapped on the SW Mediterranean Spanish margin (Ercilla *et al.,* 2013) (Fig. 9A). The main east to west morphological characteristics of these turbidite systems, their sedimentary models and processes are summarised here and their morphological parameters are presented in Table 1.

The *Almeria turbidite system* is the largest turbidite system of the Alboran Sea. It is composed of a 55 km long submarine canyon with a sinuous to meandering thalweg, three important tributary systems (Gata, Andarax and Dalias) and a leveed channel (García *et al.,* 2006). At the base of the slope (1,200 m water depth) the canyon evolves into the Almeria leveed channel and enters into the Alboran Trough at about 1 500 m water depth. At this point the overbank area increases in width as the main leveed channel branches into distributary channels that make up the lobe deposits extending down to 1800 m (Fig. 9A; Alonso and Ercilla, 2003).

The *Calahonda turbidite system* is defined by four relatively small slope canyons and gullies eroding the front of shelf deltas. Canyons evolve into leveed channels with rectilinear to slightly sinuous trajectories. The *Sacratif turbidite system* is composed of two canyons whose heads are a few kilometres onto the outer shelf. Both canyons evolve into short leveed channels that mouth into small elongated channelled lobes with distributary channels having rectilinear to sinuous pathways. The *Salobreña turbidite system TS* is characterised by two major gullies with heads located on the shelf-break scarp, and fed by other small-scale, 3-8 km long gullies. Distally, the gullies mouth evolves into an unhandled apron-shaped lobe (Fig. 9A). The *Fuengirola turbidite system* is defined by a canyon whose head is about 1 km onto the shelf. It evolves to a sinuous main leveed channel that mouths into a lobe with rectilinear distributary leveed channels displaying a lobate shape. The *Torrenueva turbidite system* is characterised by a short canyon that evolves into a rectilinear leveed channel and at about 1 000 m water depth transforms into a less incised and amalgamated channel, down to 1 185 m water depth. There, it evolves into an elongated lobe. The *Baños turbidite system* comprises a relatively long canyon whose head incises onto the outer shelf. It evolves into a short-leveed sinuous channel. This leveed channel bifurcates downslope into smaller distributary channels, forming a channelled lobe. The *Guadiaro turbidite system* consists of a canyon whose head incises 2.5 km onto the outer shelf and that evolves into a lobe incised by a single long-lev-

Turbidite system	Length/width (km x km)	Canyon length (km)	Gullies length (km)	Leveed channel length (km)	Lobe length (km)	Maximum lobe width (km)	Shape
1. Almeria	99 x 30	55	1-26	26	45	30	Lobated
2. Calahonda	15 x 15	1-3	13	11	12	15	Apron
3. Sacratif	30 x 14	8-9	No	< 7	24	14	Elongated
4. Salobreña	27 x 15	No	3-13	No	17	11	Apron
5. Fuengirola	40 x 20	12	No	8	25	20	Lobated
6. Torrenueva	57 x 7	11	No	15	12	7	Elongated
7. Baños	35 x 12	13	No	6	16	12	Lobated
8. Guadiaro	30 x 16	10	No	13	14	16	Lobated
9. La Linea	<17 x <8	7-9	No	<5	5	<8	Lobated

Table 1. Summary of the geometric parameters of the turbidite systems in the Alboran Sea.
Tabla 1. *Sumario de los parámetros geométricos de los sistemas turbidíticos del Mar de Alborán.*

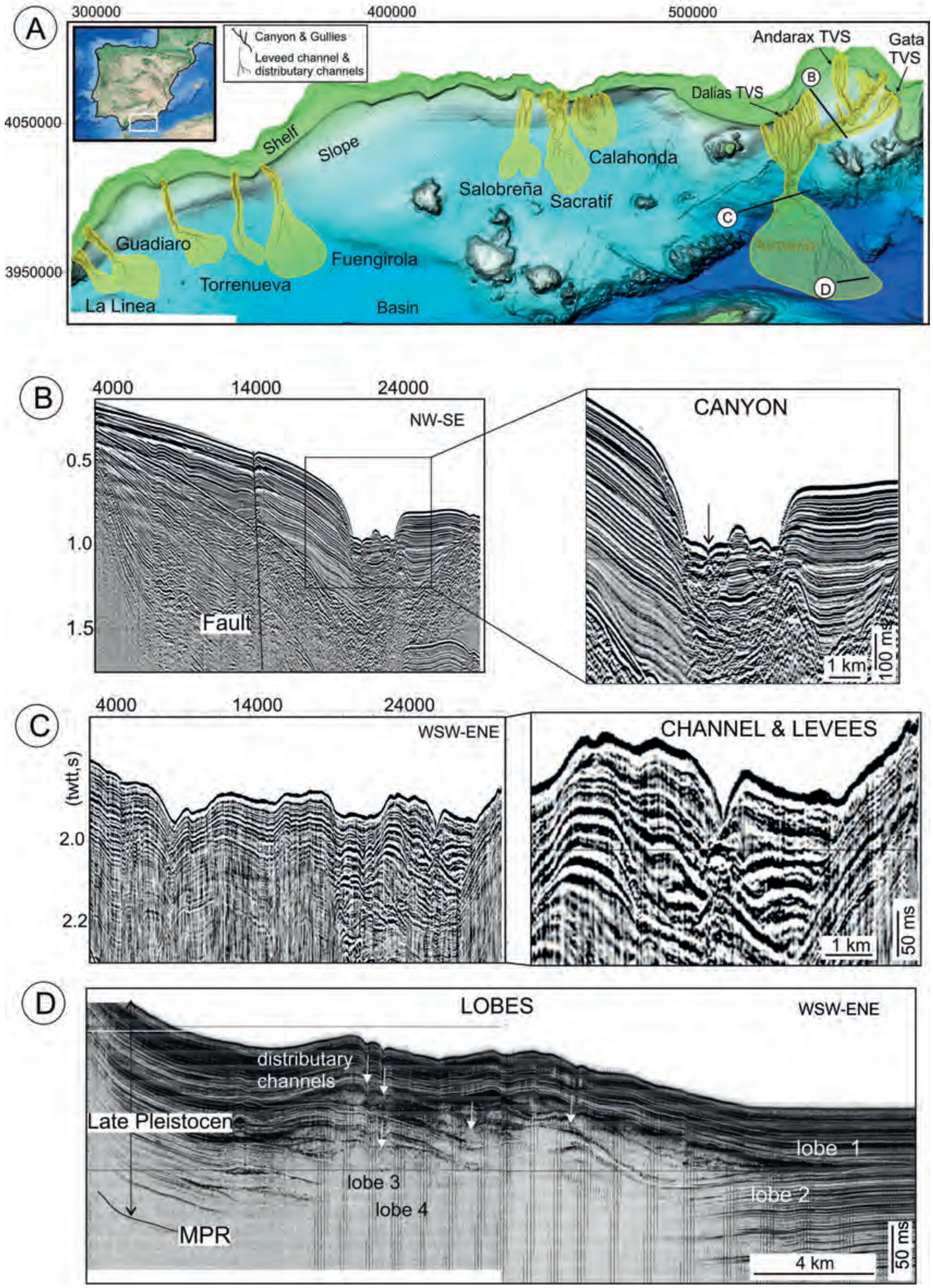

Figure 9. Location and characteristics of the turbidite systems in the Alboran Sea. A) Bathymetric map of the Spanish margin in the Alboran Sea showing the location of the turbidite systems; B) Airgun seismic reflection profile across the Almeria Canyon; C) Airgun seismic reflection profile showing the Almeria channel and levee deposits; D) TOPAS profile showing the lobe and distributary deposits of the Almeria turbidite system. Source: Alonso *et al.* (2012). TVS: tributary valley system (García *et al.,* 2006).

Figura 9. *Localización y características de los sistemas turbidíticos del Mar de Alborán. A) mapa batimétrico del margen ibérico del Mar de Alborán mostrando la localización de los sistemas turbidíticos; B) perfiles sísmicos de cañones de aire en el cañón de Almería; C) perfiles sísmicos de cañones de aire mostrando el canal de Almería y los depósitos de dique; D) perfil de TOPAS mostrando los lóbulos y depósitos de distributarios el sistema turbidítico de Almería. Fuente: Alonso* et al. *(2012). TVS: Tributary Valley System (García* et al., *2006).*

eed channel. The *Linea turbidite system* is the smallest system and is defined by two canyons that merge at the foot of the lower slope. Both canyons mouth into a lobe incised by rectilinear channels.

These architectural elements show differentiated seismic facies. The canyon fill deposits display complex facies patterns with chaotic, prograding, divergent and mounded fill facies (Fig. 9B).The channel fill deposits are mostly defined by chaotic facies (Fig. 9C). Their overbank deposits are formed by downlapping, continuous, conformable to wedging reflections. The lobes display facies that vary laterally, mostly chaotic and/or transparent for the distributary channels, and stratified, continuous and discontinuous, for the overbank, non-channelled and lobe fringes (Fig. 9D). On the basis of architecture, dimensions, and sediment type, these systems range from the sandy to mixed sand-mud fan model, and they describe a continuum between both end-member types from west to east (Alonso and Ercilla, 2003; Galimont *et al.,* 2000; Lebreiro *et al.,* 2000). Based on the submarine feeder system criteria the nine turbidite systems are grouped into two main sedimentary models: submarine fan and submarine ramp (Fig. 5). The submarine fan model (Almeria, Sacratif, Fuengirola, Torre Nueva, Baños, Guadiaro and La Linea) is characterised by a feeder canyon -locally also gullies- crossing the slope that directly mouths into a lobe with aggrading leveed channels. The lobes comprise a single linear to low sinuosity feeder channel, or a single linear to low-sinuosity channel linked downslope to sinuous distributary channels. The submarine ramp model (Calahonda and Salobreña) is defined by a few to several input points (canyons and gullies), which evolve downslope into a lobe with multiple leveed channels and distributary channels.

The development of the Alboran turbidite systems during the Plio-Quaternary interrupts the lateral continuity of terraced plastered drifts on the continental slope and sheeted drifts making up the base of slope to basin (Ercilla *et al.,* 2013). The context of the Alboran Sea as an oceanographic gateway between the Atlantic and Mediterranean waters, and the related contouritic processes, are the main factors responsible for the architectural model of these fans. As fine sediment arrives at the sea, it is pirated by the Atlantic water mass (0 to 250 m depth) and distributed by the two anticyclonic gyres that define its circulation. Fine sediment becomes part of a complex circulatory system formed principally of three underlying water masses, the Winter Intermediate Water (100 to 300 m) and Levantine Intermediate Water (200 to 600 m) on the Iberian margin, and the Western Mediterranean Deep Water (> 275 m) mainly on the African margin. Their contouritic processes contribute to the outbuilding of the margin and the infilling of the basins. Likewise, fine sediment winnowing processes can be so important they prevent the formation of major canyons offshore from large rives on the Iberian margin and mean these are also absent on the African margin (Ercilla *et al.,* 2013).

On the Gulf of Cadiz

The Gulf of Cadiz is a complex environment, located in the north-eastern Atlantic Ocean and extending west from the Strait of Gibraltar, along the Spanish and Portuguese margins to Cape San Vicente (Fig. 10A). This region has engendered a great deal of interest, especially with regard to the Gulf of Cadiz Contourite Depositional System, but other types of sedimentary processes and their interaction also affect the seafloor, including turbiditic and mass movement processes (Baraza *et al.,* 1999; Hernández-Molina *et al.,* 2006; Mulder *et al.,* 2003, 2006). Turbidite systems in the Gulf of Cadiz occur only in the western part of the Algarve margin (Hernández-Molina *et al.,* 2003, 2006; Mulder *et al.,* 2006; Marchès *et al.,* 2007, 2010). Submarine canyons cut through the sheeted and mounded elongated and separated contourite drifts comprising the Gulf of Cadiz Contourite Depositional System (Hernández-Molina *et al.,* 2003; Llave *et al.,* 2007). The most prominent submarine canyons are, from east to west, the Faro, the Portimao, and the Lagos canyons (Fig. 10B).

The *Faro Canyon* is 20 km long and mouths into the Faro Valley, merging with the Portimao Valley (Mulder *et al.,* 2006; Marchès *et al.,* 2007). Its location seems to be related to the Albufeira Fault. Erosion is not active in the present-day as evidenced by its relatively smooth flanks, and the canyon seems to be progressively infilled by sediment load (Mulder *et al.,* 2006; Marchès *et al.,* 2007). The *Portimao Canyon* is the most prominent canyon in the region, starting at about 120 m water depth, presenting slight sinuosity in its proximal area as well as gullied flanks and failure scars (*Mulder et al.,* 2006). It mouths into the Portimao Valley, more than 50 km long, that merges with the Lagos Valley and both discharge onto the Horseshoe Abyssal Plain. Turbidites have been identified on the valley floor (Mulder *et al.,* 2009). The Portimao Canyon has an important effect on the formation of the filaments and eddies that transport the Mediterranean waters long distances into the Atlantic Ocean (Cherubin *et al.,* 2000).The *Lagos Canyon* starts at a water depth of 760 m, on the middle slope.

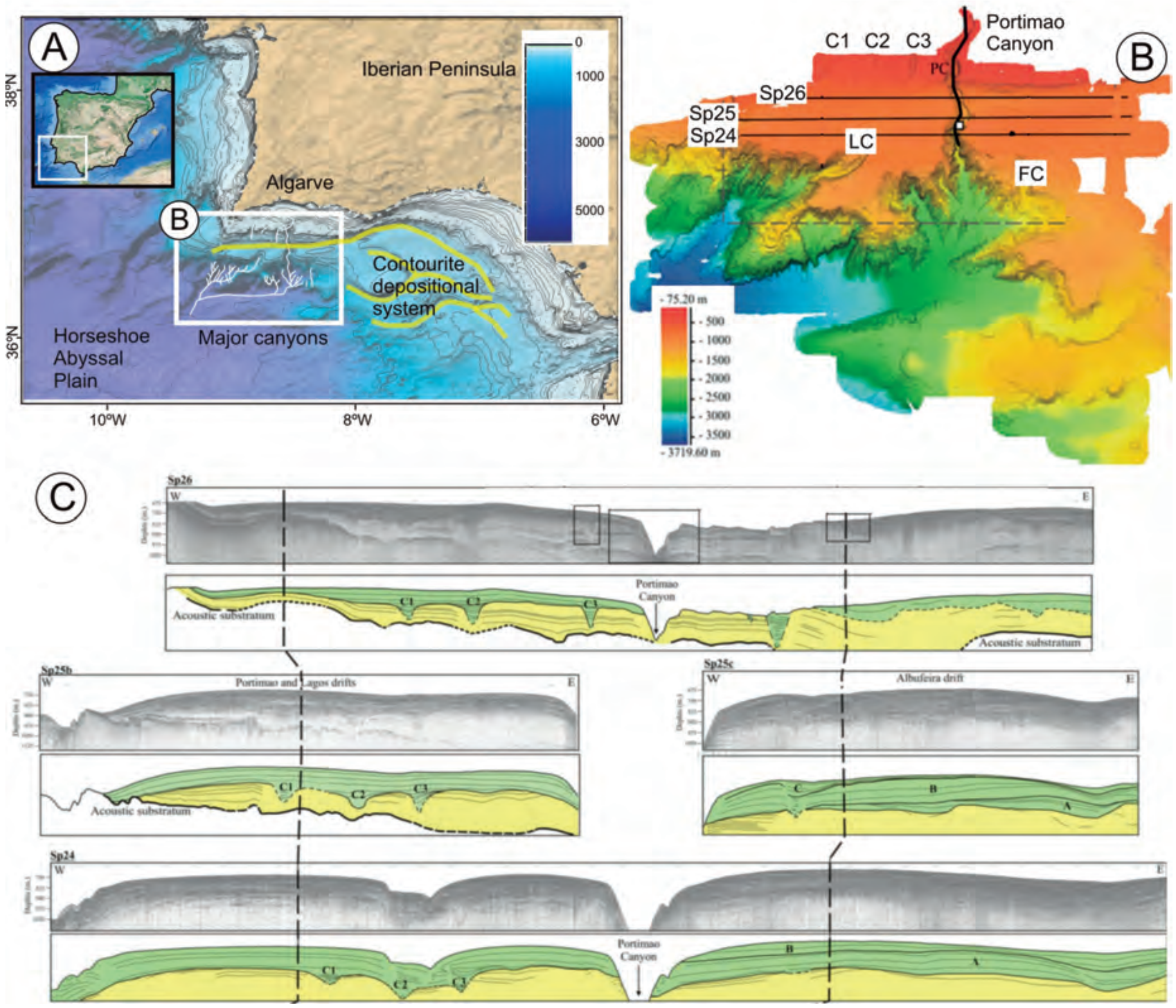

Figure 10. A) Location of the major canyons in the Algarve margin, at the western end of the Gulf of Cadiz, showing the spatial relationship with the contourite depositional system; B) Bathymetric map showing the major canyons: Portimao Canyon, Lagos Canyon (LC) and Faro Canyon (FC) and channels (C1 to C3); C) Seismic profiles showing the main seismic stratigraphic characteristics of the major canyons and channels. See profile location in Figure 10B. Figures 10B and 10C modified from Marches *et al.* (2007).

***Figura 10**. A) Localización de los principales cañones del margen del Algarve, en la zona occidental del Golfo de Cádiz, mostrando la relación espacial con el sistema deposicional contornítico; B) mapa batimétrico mostrando los principales cañones: Portimao, Lagos (LC) y Faro (FC) y canales (C1 a C3); C) perfiles sísmicos mostrando las características estratigráficas de los cañones y canales. Ver la localización de los perfiles en la Fig. 10B. Las Figs. 10B y C han sido modificadas a partir de Marches* et al. *(2007).*

It runs SSW for less than 10 km, and then turns westward after a double bend (Mulder *et al.,* 2006). There are two proximal steep chutes (10–11°), and the head and walls of the canyon display numerous gullies and mass-movement features. The thalweg deepens sharply to form the Lagos Valley, which runs NNE–SSW and merges with the Horseshoe Abyssal Plain. The canyon morphology suggests, as in the case of the Faro Canyon, progressive infilling by sediment load (Mulder *et al.,* 2006).Three minor straight channels, about 7 km long (C1, C2 and C3 in Figure 10B and C), are found on the continental shelf and upper slope, and do not appear to be connected with any other present-day valleys (Mulder *et al.,* 2006; Marchès *et al.,* 2007, 2010). These channels seem to have been active during cold periods when the sea level was lower, and have been infilled by contourite deposits during warm periods, when the sea level was higher (Marchès *et al.,* 2010).

All turbidite systems in the Gulf of Cadiz discharge onto the Horseshoe Abyssal Plain, where a 2.7 kyr^{-1} frequency of turbidite deposition has been established for the glacial period and 1 kyr^{-1} for the Holocene (Lebreiro *et al.,* 1997).

On the Portuguese margin

The Portuguese Atlantic margin has been characterised as a glacially influenced margin, dominated by canyon and channel processes (Weaver *et al.,* 2000). The present-day configuration of the margin is the result of tectonic events during the Messinian/early Pliocene in combination with subsequent Quaternary glacio-eustatic changes. Three sectors, separated by modern submarine canyons (several kilometres wide, few kilometres in relief), have been differentiated, which are from north to south: the Porto, Lisbon and Alentejo continental margins (Alves *et al.,* 2003). The main submarine canyons are: the Porto and Aveiro canyons on the Porto margin; the Nazaré, Cascais and Setúbal-Lisbon canyons on the Lisbon margin; and the São Vicente canyon on the Alentejo margin (Fig. 11A).

The *Porto and Aveiro canyons* are fed by dominantly terrigenous input from the Douro River (Abrantes and Rocha, 2007). Both canyons transport sediment into the fault-bounded depression forming the Don Carlos Valley (Mougenot, 1988). There, the seismic stratigraphy reveals two major sedimentary packages of Cenozoic age, the lithology of which is primarily the result of turbiditic processes, and secondarily hemipelagic and debris flow processes (Alves *et al.,* 2003). The Porto and Aveiro submarine canyons feed turbidite fans on the Iberia Abyssal Plain (Weaver *et al.,* 2000), where terrigenous turbidite deposition began in the late Pliocene, 2.6 Ma, with a frequency averaging one turbidite per 3200 years controlled at least partially by climatic changes (Milkert *et al.,* 1996).

The *Nazaré Canyon*has no direct fluvial input, but is highly activity in terms of sediment transport (Lastras *et al.,* 2009), being fed by fluvial sediment supplied by the Mondego and Douro Rivers to the north (Arzola *et al.,* 2008). The location of the canyon is controlled by the Nazaré Fault (Fig. 11B). It is deeply incised, with a narrow, V-shaped thalweg flanked by small gullies and terraces (Arzola *et al.,* 2008; Lastras *et al.,* 2009). The upper canyon is characterised by localised mass wasting, probably triggered by turbidity current erosion and/or regional earthquakes. Holocene sedimentation rates are anomalously high, probably related to oceanographic processes (Arzola *et al.,* 2008). The lower canyon and mouth floor have

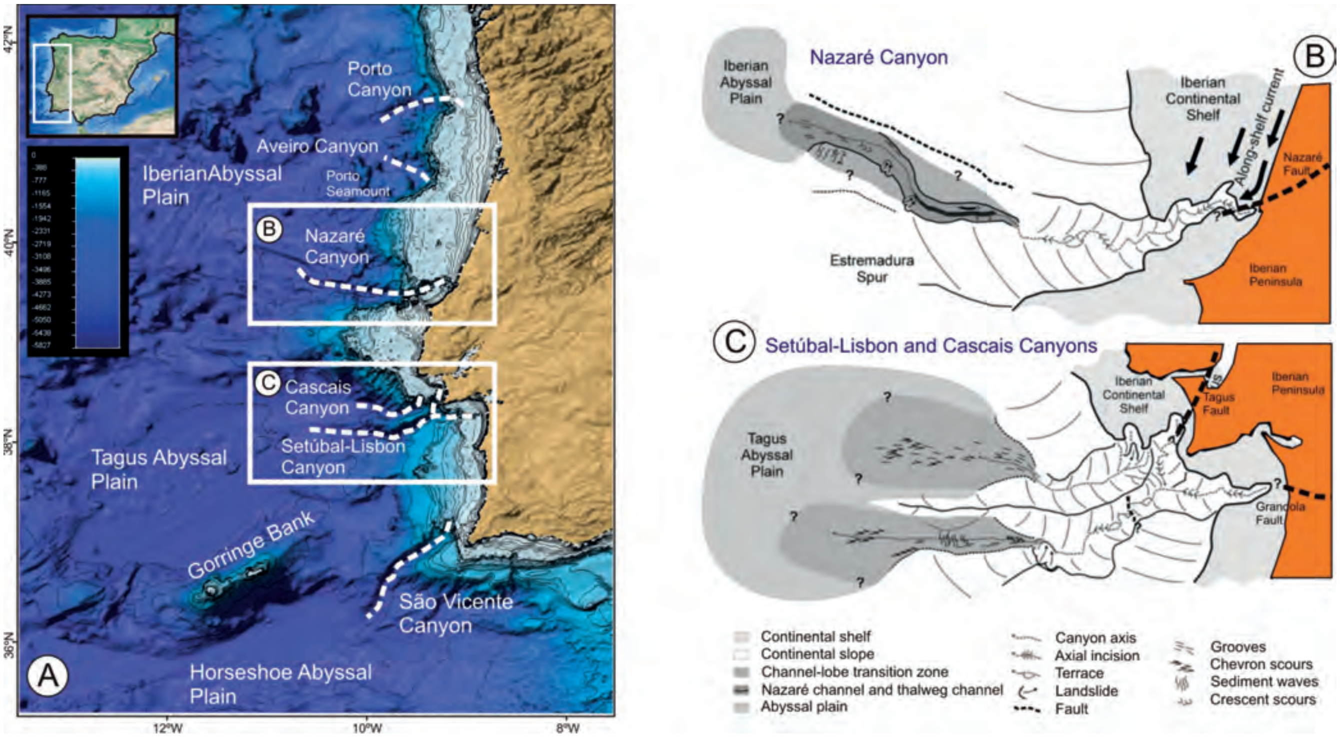

Figure 11. A) Location of the major canyons dissecting the Portuguese margin. B) and C) Sketch showing the morphology of the Nazaré and Cascais and Setúbal-Lisbon canyons, modified from Lastras *et al.* (2009).

Figura 11. *A) Localización de los principales cañones del margen portugués; B) y C) esquemas mostrando la morfología de los cañones de Nazaré y Cascais y Setúbal-Lisboa. Modificado a partir de Lastras* et al. *(2009).*

large-scale scours and grooves and it evolves into a turbidite channel (Lastras *et al.,* 2009). The Nazaré Canyon also discharges onto the Iberian Abyssal Plain.

The *Cascais Canyon* displays 'pinnate drainage', with multiple branches and gullies indenting the continental shelf, probably indicating that the canyon is in an initial phase of evolution (Lastras *et al.,* 2009). Unlike other canyons in the region, tectonic control has not been demonstrated and it is not directly fed by any fluvial course. It discharges onto the Tagus Abyssal Plain and presents overbank deposits in the lower sector (Alves *et al.,* 2003).

The *Setúbal-Lisbon Canyon* cuts into the inner shelf (Weaver *et al.,* 2000; Arzola *et al.,* 2008; Lastras *et al.,* 2009), the Lisbon segment being a tributary branch for the southernmost Setúbal Canyon (Fig. 10C). Its location is controlled by the Lower Tagus fault zone and the Grãndola fault (Lastras *et al.,* 2009), and it is directly fed by the Tagus and Sado Rivers. Pervasive scouring occurs in more distal areas of the canyon floor and groove features have been mapped at the mouth. Depositional bedforms such as sediment waves are common in the channel-lobe transition zone (Arzola *et al.,* 2008; Lastras *et al.,* 2009). The distal channel is presently an active source of the sediment entering the Tagus abyssal plain (Kenyon *et al.,* 2000; Alves *et al.,* 2003).

The *São Vicente Canyon* (Fig. 10A) is not directly fed by any major river course (Coppier and Mougenot, 1982; Lebreiro *et al.,* 1997). Its present-day location is related to tectonic events during the latest Tortonian-Pliocene (Alves *et al.,* 2003). It discharges onto the Horseshoe Abyssal Plain, which is dominated by turbidite deposition. The turbidites are formed of metre-thick beds intercalated with thinner decimetre-scale beds and pelagites; turbidite deposition frequencies of 2.7 kyr^{-1} during the glacial period and 1 kyr^{-1} during the Holocene have been established (Lebreiro *et al.,* 1997). Synchronous, widely-spaced turbidites are interpreted to have been triggered by Holocene earthquakes (Gracia *et al.,* 2010).

On the Galician margin

The western Galicia continental margin is morphologically complex as a result of two superimposed deformational stages. During the lower Cretaceous extensional rifting of the North American and European plates a series of horsts and half-grabens were developed (Boillot and Malod, 1988). The Galicia continental margin is defined by 5 physiographic domains (Fig. 12): 1) continental shelf (15 to 35 km wide) with a shelf-break down to 150 m; 2) continental slope extending down to 4 000 m water depth, dis-

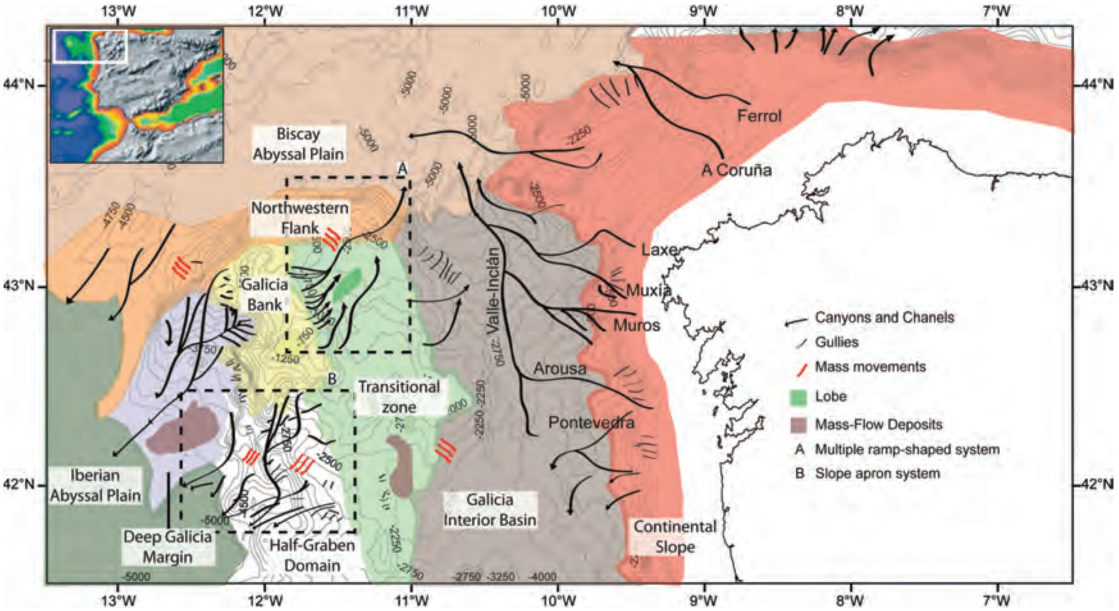

Figure 12. Location of the main canyons, channels, gullies, mass-transport deposits, mass-flow deposits and lobes on the Galician continental margin. The coloured areas represent the main physiographic domains defined in the Galicia continental margin (Ercilla *et al.,* 2011; Maestro *et al.,* 2013).

Figura 12. *Localización de los principales cañones, canales, cárcavas, depósitos de transporte en masas y lóbulos en el margen continental de Galicia. Las áreas coloreadas representan los dominios fisiográficos definidos en el margen (Ercilla* et al., *2011; Maestro* et al., *2013).*

playing a width that varies from 22 to 45 km; 3) the Galicia Interior Basin with depths from 3 000 to 4 000 m, and a width of 100 km; and 4) a continental rise, from 4 000 down to 5 300 m in depth; 5) the Galicia Bank, the most striking feature of this rise, which includes a series of structural banks (discontinuous tabular reliefs) named: Vigo (2 100 m depth), Vasco da Gama (1 750 m depth), Porto (2 200 m depth) and Galicia Bank (700 m depth) (Berthois *et al.,* 1965; Mauffret *et al.,* 1978; Roberts and Kidd, 1984; Mougenot *et al.,* 1986).

On the western Galicia margin, deep-sea clastic systems contribute much of the terrigenous sediment to distal areas (e.g., the Galicia Interior Basin) and abyssal plains (e.g., the Iberian Abyssal Plain). In contrast with other Iberian margins, fan systems are not well represented here. However, if turbidite systems are considered based on process rather than shape, the Galicia margin is characterised by several drainage canyons and channel systems related to multiple turbidity source areas conditioned by the complex geomorphology of the margin (Fig. 12). In this sense, the continental slope of the Galicia margin is a canyon-dominated slope. It is characterised by numerous canyons, gullies and channels at different scales, and spurs organised into at least two major drainage systems. The western drainage system extends to the Finisterre spur. The *Pontevedra, Arousa, Muros, Muxía* canyons with lengths of 68 km, 88 km, 81 km, 80 km respectively, together with other unnamed canyons (<40 km) and *gullies* (around 15 km long) densely erode the upper slope. The canyons converge on the lower slope and evolve into rectilinear channels that mouth into the Galicia Interior Basin. Here, the northern channels feed a main channel (~140 km long) named the Valle-Inclán channel (ITGE, 1994). This channel runs northwards, parallel to the Interior Basin, and extends down to the Biscay Abyssal Plain. The Galicia Interior Basin also distributes sediment towards the south, where it merges with sediments from the Portuguese continental rise (Vanney *et al.,* 1979). Between the Finisterre and Ortegal Spurs, the continental slope is dissected by the *Laxe, A Coruña and Ferrol* canyons. These three major canyons are ~90 km, 82 km and 63 km long respectively and mouth into the Biscay Abyssal Plain, merging with the turbidity flows coming from the Valle-Inclán channel.

The continental rise of the Galicia continental margin is also characterised by a complex interaction of multiple turbidity drainage systems, mainly provoked by the presence of the Galicia Bank (Ercilla *et al.,* 2011). This region forms a topographic bulge, separated from the continental slope by the Galicia Interior Basin, and is therefore isolated from continental sediment sources. Detailed geomorphological analysis (Ercilla *et al.,* 2011) has revealed a great variety of structural valleys (around 20 km wide and 600 to 1,800 m in relief), channels (hundreds of metres wide, 1 to 5 km long, and several tens of meters in relief) and gullies (hundreds of metres to a few kilometres long, and from a few to tens of metres in relief).These valleys display a predominantly radial pattern influenced by the mountainous morphology of the bank. Some of these features are isolated and others are interconnected in such a way that they feed and/or evolve into others. The exhumation and erosion of the structural scarps affecting the Galicia Bank region favours the formation of turbidity and related flows. The channelised turbidity flows running down these valleys contribute to several turbidity drainage systems that feed the Iberian and Biscay abyssal plains. Two major systems have been mapped: a *multiple ramp-shaped system*, with gullies that evolve into channels linked down dip to mass-flow deposits which represent amalgamated lobe deposits; and a *slope apron system*, with gullies that evolve either into inter-lobe channels that mouth into larger-scale channels or to slope-lobe complexes deposited just at, or near to, the footwall areas of the scarps. These turbiditic drainage systems interact with the unchannelised mass-transport deposits and the bottom component of the water masses.

The recurrence of the turbidites and their sedimentary imprint on the Galicia margin can be linked to various processes. The Galician Bank is affected by both tectonism and steep gradients (Alonso *et al.,* 2008; Vázquez *et al.,* 2008), while on the Galicia Continental Slope, besides the related trigger mechanisms, sea level plays a significant role. In the sedimentary infill of the Galician Margin turbidites are largely represented in the pre-Last Glacial Maximum record (Hall and McCave, 2000; Alonso *et al.,* 2008; Mena *et al.,* 2010; Bender *et al.,* 2012). On the slopes of the Galician Bank (east and west flanks) it is also possible to identify Holocene turbiditic events (Alonso *et al.,* 2008; Mena *et al.,* 2010).

On the Cantabrian margin

The morphological and sedimentary features analysed on the Cantabrian margin reveal a high incidence of turbiditic sedimentary processes (Fig. 13). This both deep and steep margin (Grady *et al.,* 2000) can be considered a bypass region for the mass-flows and turbidity currents that have contributed to the construction of the channelised lobe complex known as the *Cap Ferret Fan* (Cremer, 1983; Ercilla *et al.,* 2008). Sediments from the Cantabrian continental margin are transported down to the continental rise and Biscay abyssal plain areas principally by the Santander, Torrelavega, Lastres and Llanes canyon systems (Fig. 13). There, canyons coming from the French margin (Cap Ferret and Capbreton) also converge into the Cap Ferret leveed channel that evolves into a channelised lobe extending down to a water depth of more than 4 500 m and sloping towards the west (Fig. 13).

The Cap Ferret Channel is defined by a trough that is 5.5 km wide, several thousand metres in relief and whose direction changes from NE-SW to E-W (Iglesias, 2009). Close to the Aviles canyon the channel divides into several distributary channels. The southern channel, considered a minor-order distributary channel, flows parallel to the Cantabrian continental margin for about 90 km, with W-E rectilinear plan morphology. The northern system comprises three NW-SE channels and extends approximately 70 km, with straight plan morphology. The Cap Ferret Channel is bordered by an overbank deposit on its northern side that defines the Cap Ferret Levee (Cremer, 1983). This is an asymmetric ridge 120 km long, 50 km wide and 500 m high, progressively decreasing in size and disappearing at about 4,600 m water depth (Ercilla *et al.,* 2008; Iglesias, 2009). On the external face of this great levee and between the distal channels a sediment wave field is developed through the overspilling and spreading of the flows, following the maximum slope gradient. The sediment waves are asymmetrical and their dimensions are variable with a wave height of 1-25 m and wavelength of 534-2,600 m (Iglesias, 2009). Based on the morphology of the deposits, the flows are interpreted as moving towards the NW (Ercilla *et al.,* 2008).

In the most distal part of the channel-levee system the backscatter analysis preludes the observation of a Channelised Lobe Complex off the channels. Backscatter variations allow the identification of an E-W oriented first lobe with a width of 68 km. To the south, the smallest lobe covers an area of 1250 km^2 and has a NW-SE oriented oval plan morphology. The third, E-W to NW-SE oriented finger-shaped lobe, resembles a small-scale linear distributary channel, and is about 157 km long.

Concluding remarks: scientific and economic interest and further development in turbidite system research

Turbidite systems shape the Spanish seafloor and are the main contributors to the outbuilding of the distal continental margins and basin infilling. The canyons and channels represent the principal sediment transfer routes from the continent to the deep sea areas surrounding the Iberian Peninsula, such as the Valencia Trough and the Balearic, Iberian and Biscay abyssal plains. The most studied Spanish turbidite fans are those of the Mediterranean Sea, whereas those of the Atlantic Ocean remain relatively unknown, in spite of the fact that the largest canyons of the European Atlantic are located on this margin. The Spanish turbidite systems are very variable in their size, location in the physiographic domains, style and overall geometry of the architectural elements, as well as sediment composition. There is no simple model to define them that can encompass this

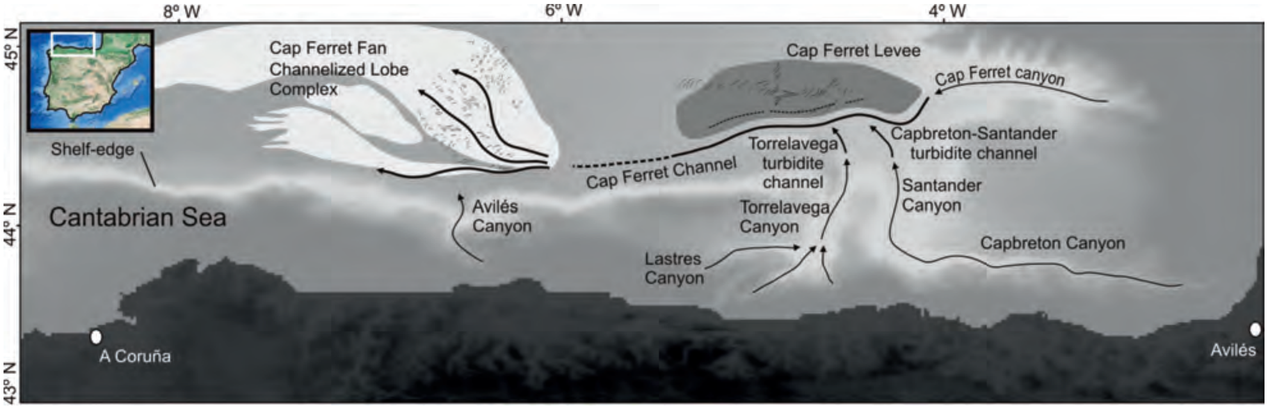

Figure 13. Location and morphology of the turbidite systems in the Cantabrian Sea. The major canyons, channels and deposits are shown.
Figura 13. *Localización y morfología de los sistemas turbidíticos del Mar Cantábrico, mostrando los principales cañones, canales y depósitos.*

variability. The varied nature of the Spanish turbidite systems means that their sediment register is scientifically interesting, as it contains information on the continental domain, e.g., drainage areas, topography, gradients, subsidence and climate, as well as on the submarine domain, e.g., margin-basin topography, oceanographic circulation, sea-level changes, and so on. The two major systems on the NW Mediterranean Sea margin – the Ebro and Valencia- have been widely studied and classified as a multiple-source ramp, mixed sand-mud slope apron, and a point-source system fed by a mid-ocean channel, mud-rich system, respectively (Alonso and Ercilla 2002). In the Alboran Sea nine smaller systems have also been characterised in detail. The Almeria system is the largest, consisting of a well-developed canyon, tributary systems, channel, transition zone and lobes, while the others comprise mainly short canyons and gullies, with distributary channels and small lobes (Ercilla *et al.,* 2013). The nine turbidite systems are classified as submarine fans and submarine ramps, based on the submarine feeder system. Turbidite systems in the Gulf of Cadiz occur only in the western part of the Algarve margin and their study has focused mainly on the interaction with the Gulf of Cadiz Contourite Depositional System. The most prominent submarine canyons - Faro, Portimao, and Lagos- have been described in detail (Mulder *et al.,* 2006; Marchès *et al.,* 2007; 2010), as have the turbiditic deposits from the deepest abyssal plains (Lebreiro *et al.,* 1997). Nevertheless, the study of turbidite systems has not been approached as a whole in this area. A similar case is the Portuguese Atlantic margin, where only the major submarine canyons of the central margin - Nazaré, Cascais and Setúbal-Lisbon canyons- are well described. On the Western Galicia margin, the architectural elements have also been characterised individually, and although the margin is widely eroded by canyons and gullies, only two major systems have been mapped – a multiple ramp-shaped system and a slope apron system- that interact with unchannelised mass-transport deposits and the bottom component of the water masses. Finally, the turbidite systems in the Cantabrian margin have been studied in detail, especially the Cap Ferret and Capbreton Canyon, and the related Cap Ferret levee, channel and fan (Cremer, 1983; Ercilla *et al.,* 2008).

Research on turbidite systems is important for improving our knowledge of both the regional and global factors governing their development. As has been shown, detailed study of the deep water clastic depositional system, using the most modern techniques, can contribute to the study of regional basin tectonics, sediment supply and sea level fluctuations (Richards *et al.,* 1998), which are key elements for analysing global climatic change. The study of the interaction of turbiditic processes with deep current processes is also highly important for determining global circulation patterns and climate (Hernández-Molina *et al.,* 2003; Llave *et al.,* 2007; Ercilla *et al.,* 2013).

Besides the scientific importance of turbiditic systems, they are mainly studied due to their economic importance, since turbidite sandstones constitute important gas and oil reservoirs. In fact, important hydrocarbon reservoirs in continental areas occur in Cretaceous and Tertiary submarine fans. High-density turbidite currents are, together with sandy debris flows, responsible for the deposition of deep-water massive sands (Stow and Johansson, 2000). These thick sequences are important subsurface reservoirs for hydrocarbons in a variety of depositional settings, although thin-bedded turbidites are also considered to have a good reservoir potential (White *et al.,* 1992). Furthermore, deepwater areas have concentrated progressively higher proportions of the global oil and gas exploration over the last 40 years (The Oil Drum; www.theoildrum.com). Most of these deepwater discoveries are confined to four basins: the Gulf of Mexico, Campos (Brazil), Lower Congo Basin (Angola, Congo) and Nigeria. Sands occur in many parts of a turbidite system. The volume of sediment supply and its grain size, the turbidity current initiation mechanism and basin morphology all help in the understanding of the sediment making up the architectural elements with highest sand content (channel, levee, distal overbank, lobes at the end of the channels, and ponded basin plain) as they condition the character of the flows, the size and changes in flow character, and determine the progradation or aggradation of turbidites as well as their overall geometry (Piper and Normark, 2001). Studies on the role of certain channel parameters including sinuosity, facies, repeated cutting and filling and stacking patterns, are also fundamental for determining the potential of a deep clastic system as a reservoir (Mayall *et al.,* 2006). Sediment waves have also been characterised as potential reservoirs (Migeon *et al.,* 2006). Turbidite systems on the Iberian margin constitute large to small-sized systems that are supplied with both sand and mud. This great variability makes the Iberian margin one of the best scenarios in which to analyse the variability in deposit architecture and growth pattern as well as the sedimentary processes and their resultant architectural elements. Due to all these reasons, research into the turbidite systems should be encouraged in order to investigate their reservoir characteristics and potential.

Acknowledgments

This manuscript was completed thanks to the support of the research projets MOWER (CTM 2012-39599-C03) and MONTERA (CTM-14157-C02-02/ MAR).

References

Abrantes, I. and Rocha, F. 2007. Sedimentary dynamics of the Aveiro shelf (Portugal). *Journal of Coastal Research*, 50, 1005-1009.

Alonso, B. and Ercilla, G. (eds.), 2000.*Valles Submarinos y Sistemas Turbidíticos Modernos*. Consejo Superior de Investigaciones Científicas, Barcelona. 292 pp.

Alonso, B. and Ercilla, G. 2002. Architecture of modern turbidite systems in different geologic settings on the Spanish margins (NW and SW Mediterranean). *CIESM Workshop Series ISSN* 1563-2727, 19-22.

Alonso, B. and Ercilla, G. 2003. Small turbidite systems in a complex tectonic complex setting(SW Mediterranean): Morphology and Growth Patterns. *Marine and Petroleum Geology*, 19, 1225-1240.

Alonso, B. and Maldonado, A. 1990. Late Quaternary sedimentation patterns of the Ebro turbidite systems (northwestern Mediterranean): Two styles of deep-sea deposition. *Marine Geology*, 95 (3/4), 353-378.

Alonso, B., Field, M.E., Gardner, J.V. and Maldonado, A. 1990. Sedimentary evolution of the Pliocene and Pleistocene Ebro margin, northwestern Spain. *Marine Geology*, 95 (3/4), 313-332.

Alonso, B., Canals, M., Got, H. and Maldonado, A. 1991. Sea valleys and related depositional systems in the Gulf of Lion and Ebro continental margins. *American Association of Petroleum Geologists Bulletin*, 77, 1195-1214.

Alonso, B., Canals, M., Palanques, A. and Rehault, J.P. 1995. A deep-sea channel in the northwestern Mediterranean Sea: Morphosedimentary evolution of the Valencia Channel and its surroundings. *Marine Geophysical Researches*, 17, 469-484.

Alonso, B., Ercilla, G., Martínez-Ruiz, F., Baraza, J. and Galimont, A. 1999. Plio-Pleistocene sedimentary facies at Site 976, ODP Leg. 161: Depositional history in the Northwestern Alboran Sea. In: R., Zahn, Comas, M.C., and Klaus, A. (eds.), *Scientific Results Ocean Drilling Program*,.161, 57-68.

Alonso, B., Ercilla, G., Casas, D., Estrada, F., Farrán, M., García, M., Rey, D. and Rubio, B. 2008. Late Pleistocene and Holocene sedimentary facies on the SW Galicia Bank (Atlantic NW Iberian Peninsula).*Marine Geology*, 249, 46–63.

Alves, T.M., Gawthorpe, R.L., Hung, D.W. and Monteiro, J.H. 2003. Cenozoic tectono-sedimentary evolution of the western Iberian margin. *Marine Geology,* 195, 75-108.

Armitage, D.A., McHargue, T., Fildani, A. and Grahan, S.A., 2012. Postavulsion channel evolution: Niger delta continental slope. *American Association of Petroleum Geologists*, 96 (5), 823-843.

Arzola, R., Wynn, R.B., Lastras, G., Masson, D.G. and Weaver, P.P.E. 2008. Sedimentary features and processes in submarine canyons: A case study from the Nazaré and Setúbal Canyons, west Iberian margin. *Marine Geology*, 250, 64–88.

Babonneau, N., Savoye, B., Cremer, M. and Klein, B. 2002. Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan. *Marine and Petroleum Geology*, 19, 445-467.

Babonneau, N., Savoye, B., Cremer, M. and Bez, M. 2004. Multiple terraces within the deep incised Zaire Valley (ZaiAngo Project): Are they confined levees. In: Lomas, S. and Joseph, P. (eds.), *Confined Turbidite Systems*, Geological Society, London, Special Publication, 222, 91–114.

Baraza, J., Ercilla, G. and Nelson, C.H. 1999. Potential geologic hazards on the Eastern Gulf of Cadiz slope (SW Spain). *Marine Geology*, 155, 191-215.

Bender, V.B., Hanebuth, T.J.J., Mena, A., Baumann, K.H., Francés, G. and von Dobeneck, T. 2012. Control of sediment supply, palaeoceanography and morphology on late Quaternary sediment dynamics at the Galicia continental slope. *Geo-Marine Letters*, 23, 313-335.

Berné, S., Loubrieu, B., and THE CALMAR Shipboard Party. 1999. Canyons et processus sédimentaires récents sur la marge occidentale du Golfe du Lion. Premiers résultats de la campagne Calmar. *Comptes Rendus de l'Académie des Sciences Paris,* 328, 471–477.

Berthois, L., Brenot, R. and Ailloud, P. 1965. Essai sur l'interpretation morphologique et géologique de la pente continentale à l'ouest de la Péninsule Ibérique. *Revue des Travaux de l'Institut des Pêches Maritimes,* 29 (3), 343–350.

Boillot, G. and Malod, J. 1988. The north and north-west Spanish continental margin: A review. *Revista de la Sociedad Geológica de España*, 1, 295–316.

Bonnel, C., Dennielou, B., Droz, L., Mulder, T. and Berné, S., 2005. Architecture and depositional pattern of the Rhone neofan and recent gravity activity in the Gulf of Lions (Western Mediterranean). *Marine and Petroleum Geology*, 22, 827–843.

Bouma, A.H. 1962. *Sedimentology of Some Flysh Deposits: A Graphic Approach To Facies Interpretation*. Elsevier, Amsterdam, 168 pp.

Bouma, A.H. 1985. Introduction to submarine fans and related turbidite systems. In: Bouma, A., Normark, W. and Barnes, N. (eds.), *Submarine Fans and Related Turbidite Systems*. Springer-Verlag, New York, 3–6.

Bouma, A.H. 2000. Coarse-grained and fine-grained turbidite systems as end member models: Applicability and dangers. *Marine and Petroleum Geology,* 17, 137-143.

Bouma, A.H. and Stone, C.G. 2000. *Fine Grained Turbidite Systems*. American Assocaition of Petroleum Geologist, Memoir 72, SPEM Special Publication, 68, 342 pp.

Bourget, J., Zaragosi, S., Mulder, T., Schneider, J.-L., Garlan, T., Van Toer, A., Mas, V. and Ellouz-Zimmermann, N. 2010. Hyperpycnal-fed turbidite lobe architecture and recent sedimentary processes: A case study from the Al Batha turbidite system, Oman margin. *Sedimentary Geology*, 229, 144-159.

Cherubin, L., Carton, X., Paillet, J., Morel, Y. and Serpette, A. 2000. Instability of the Mediterranean Water undercurrents southwest of Portugal: Effects of baroclinicity and of topography. *Oceanologica Acta*, 23, 551-773.

Clark, J.D. and Pickering, K.T. 1996. *Submarine Channels: Processes and Architecture*. Vallis Press, London, 231 pp.

Coppier, G. and Mougenot, D. 1982.Stratigraphie sismique et évolution géologique des formations néogènes et quaternaires de la plate-forme continentale portugaise au Sud de Lisbonne. *Bulletin de la Societé Géologique de France*, 24, 421–431.

Covault, J. A., 2011. Submarine Fans and Canyon-Channel Systems: A Review of Processes, Products, and Models. *Nature Education Knowledge,* 3(10), 4.

Cremer, M. 1983. Approches sédimentologiques et géophysiques des accumulations turbiditiques. L'éventail profond du Cap-Ferret (Golfe de Gascogne), La série des grès d'Annot (Alpes de Hautes Provence). *Unpublished PhD* Thesis, Université de Bordeaux 1, 344 pp.

Dalla Valle, G., Gamberi, F., Trincardi, F., Bagliono, L., Errera, A. and Rocchini, P. 2013. Contrasting slope cannel styles on a porgrading mud-prone margin. *Marine and Petroleum Geology*, 41, 72-82.

Deptuck, M.E., Steffens, G.S., Barton, M. and Pirmez, C. 2003.Architecture and evolution of upper fan channel-belts on the Niger Delta slope and in the Arabian Sea.*Marine and Petroleum Geology*, 20, 649-676.

Ercilla, G., Alonso, B., Pérez-Belzuz, F., Estrada, F., Baraza, J., Farran, M., Canals, M. and Masson, D., 1998. Origen, sedimentary processes and depostional evolution of the Agadir turbidite system, central Eastern Atlantic. *Journal of the Geological Society of London*, 155, 929-939.

Ercilla, G., Casas, D., Estrada, F., Vázquez, J.T., Iglesias, J., García, M., Gómez, M., Acosta, J., Gallart, J., Maestro, A. and Marconi Team. 2008. Morphosedimentary features and recent depositional arquitectural model of the Cantabrian continental margin. *Marine Geology*, 247 (1-2), 61-83.

Ercilla, G., Casas, D., Vázquez , J.T., Iglesias, J., Somoza, L., Juan, C., Medialdea, T., León, R., Estrada, F., García-Gil, S., Farran, M., Bohoyo, F., García, M. and Maestro, A. 2011. ERGAP Project and Cruise Teams. Imaging the recent sediment dynamics of the Galicia Bank region (Atlantic, NW Iberian Peninsula).*Marine Geophysical Researches,* 32, 99-126.

Ercilla, G., Alonso, B., Juan, C., Hernández-Molina, J., Estrada, F., Casas, D, Llave, E., Farran, M., García, M., Gorini, Ch., D'acremont, E., Medialdea, T., Vázquez, T. and El Moumni, B., Contouriber and Montera teams. 2013. The hither to unknown parameters in the architecture model of the Alboran Sea turbiditic fans: The contouritic processes. *American Association of Petroleum GeologistSearch and Discovery Article* #90161.

Estrada, F., Ercilla, G. and Alonso, B. 1997.The tecto-sedimentary evolution of the Northeastern Alboran Sea during the Plio-Quaternary. *Tectonophysics*, 382 (1-4), 423-442.

Estrada, F., Ercilla, G. and Alonso, B. 2005. Quantitative study of a Magdalena submarine cannel (Caribbean Sea): Implications for sedimentary dynamics. *Marine and Petroleum Geology*, 22 (5), 623-635.

Farre, J.A., McGregor, B.A., Ryan, W.B.F. and Robb, J.M. 1983. Breaching the shelfbreak: passage from youthful to mature phase in submarine canyon evolution.*The Society of Economic Paleontologists and Mineralogists Special Publication*, 33, 25-39.

Faugères, J. C., Stow, D. A. V., Imbert, P. and Viana, A., 1999. Seismic features diagnostic of contourite drifts. *Marine Geology*, 162, 1-38.

Fildani, A., Hubbard, S.M., Covault, J.A., Maier, L., Romans, B.W., Traer, M. and Rowland, J.C., 2013.Erosion at inception of deep-sea channels. *Marine and Petroleum Geology*, 41, 48-61.

Flood, R.D., Manley, P.L., Kowsmann, R.O., Appi, C.J. and Pirmez, C. 1991. Seismic facies and late Quaternary growth of Amazon submarine fan. In: Weimer, P. and Link, M.H. (eds.), *Seismic Facies and Sedimentary Processes of Modern and Ancient Submarine Fans and turbidite systems*. Frontiers in sedimentary geology. Springer-Verlag, New York, 415–433.

Gamboa, D., Alvers, T.M. and Cartwright, J.A. 2013. A submarine channel confluence for topographically confined slopes. *Marine and Petroleum Geology*, 35, 176-189.

Galimont, A., Alonso, B., Pérez-Belzuz, F. and Ercilla, G. 2000. Caracterización sedimentológica reciente de dos sistemas turbidíticos del área de Motril (NE Alborán). *Geo-temas,* 1 (4): 143-148.

García, M., Alonso, B., Ercilla, G. and Gràcia, E. 2006. The tributary valley systems of the Almeria Canyon (Alboran Sea, SW Mediterranean): Sedimentary architecture. *Marine Geology*, 226, 207-223.

Gaudin, M., Mulder, T., Cirac, P., Berné, S and Imbert, P. 2006. Past and present sedimentary activity in the Capbreton Canyon, southern Bay of Biscay.*Geo-Marine Letters*, 26, 331-345.

Gee, M.J.R., Gawthorpe, R.L., Bakke, K. and Friedmann, S.J. 2007. Seismic geomorphology and evolution of submarine channels from the Angolan contintental margin. *Journal of Sedimentary Research*, 77, 433-446.

Gervais, A., Mulder, T. and Savoye, B. 2006. Sandy modern turbidite lobes: a new insight from high resolution seismic data. *Marine and Petroleum Geology*, 23, 485–502.

Gràcia, E., Vizcaino, A., Escutia, C., Asioli, A., Rodés, A., Pallàs, R., Garcia-Orellana, J., Lebreiro, S. and Goldfinger, C. 2010. Holocene earthquake record offshore Portugal (SW Iberia): testing turbidite paleoseismology in a slow-convergence margin. *Quaternary Science Reviews*, 29, 1156-1172.

Grady, D.B.O., Syvitski, J.P.M., Pratsom, L.F. and Sarg, J.F. 2000.Categorizing the morphologic variability of siliciclastic passive continental margins. *Geology*, 28, 207–210.

Hackbarth, C.J. and Shew, R.D. 1994. Morphology and stratigraphy of a mid-Pleistocene turbidite leveed channel from seismic, core and log data, northeastern Gulf of Mexico. In: Weimer, P., Bouma, A.H. and Perkins, B.F. (eds), *Submarine Fans And Turbidite Systems,* 15th Annual Research Conference, Society for Sedimentary Geology, Gulf Coast Section, Houston, Texas, 127-140.

Hall, I.R. and McCave, I.N. 2000. Palaeocurrent reconstruction, sediment and thorium focussing on the Iberian margin over the last 140 ka. *Earth and Planetary Science Letter* 178, 151-164.

Hagen, R.A., Bergersen, D.D., Moberly, R. and Coulbourn, W.T. 1994. Morphology of a large meandering submarine canyon system on the Peru-Chile forearc. *Marine Geology*, 119, 7–38.

Hernández-Molina, J., Llave, E., Somoza, L., Fernández-Puga, M.C., Maestro, A., León, R., Medialdea, T., Barnolas, A., García, M., Díaz del Río, V., Fernández-Salas, L.M., Vázquez, J.T., Lobo, F., Alveirinho Dias, J.M., Rodero, J. and Gardner, J. 2003. Looking for clues to paleoceanographic imprints: A diagnosis of the Gulf of Cadiz contourite depositional systems. *Geology*, 31 (1), 19-22.

Hernández-Molina, J., Llave, E., Stow, D.A.V., García, M., Somoza, L., Vázquez, J.T., Lobo, F.J., Maestro, A., Díaz del Río, V., León, R., Medialdea, T. and Gardner, J. 2006. The contourite depositional system of the Gulf of Cadiz: A sedimentary model related to the bottom current activity of the Mediterranean outflow water and its interaction with the continental margin. *Deep-Sea Research II*, 53, 1420-1463.

Hernández-Molina, F.J., Stow, D.A.V., Llave, E., Rebesco, M., Ercilla, G., Van Rooij, D., Mena, A., Vázquez, J.-T. and Voelker, A.H.L. 2011. Deep-water Circulation: Processes & Products (16-18 June 2010, Baiona): Introduction and future challenges. *Geo-Marine Letters*, 31, 285-300.

Hiscott, R.N., Hall, F.R. and Pirmez, C. 1997. Turbidity current overspill from the Amazon Channel: texture of the silt/sand load, paleoflow from anysotropy of magnetic susceptibility, and implications for flow processes. In: Flood, R.D., Piper, D.J.W., Klaus, A. and Peterson, L.C. (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, 155, College Station, TX, 53–78.

Iglesias, J. 2009. Sedimentation on the Cantabrian continental margin from Late Oligocene to Quaternary. *Unpublished PhD Thesis*, University of Vigo, 214 pp.

Inram, J., Parker, G. and Pirmez, C.1999. A nonlinear model of flow in meandering submarine and subaerial channels.*Journal of Fluid Mechanics*, 400, 295–331.

ITGE, 1994. *Mapa Geológico de la Plataforma Continental Española y Zonas Adyacentes. Escala 1:200,000.* Instituto Tecnológico y GeoMinero de España. Ministerio de Industria y Energía, Madrid, 73 pp.

Janoko, M., Nemec, W., Henriksen, S. and Warchol, M., 2013.The diversity of deep-water sinuous channel belts and slope complexes. *Marine and Petroleum Geology*, 41, 7-34.

Johnson, D. 1938. The origin of submarine canyons. *Journal of Geomorphology*, 1, 111-340.

Kenyon, N.H. 2001. *Channelised deep-sea depositional systems in the Mediterranean: The value of sonar backscatter mapping*. IOC. Workshop Report, 175, 6-10.

Kenyon, N.H., Amir, A. and Cramp, A. 1995.Geometry of the younger sediment bodies of the Indus Fan. In: Pickering, K.T., Hiscott, R.N., Kenyon, N.H., Lucchi, RR. and Smith, R.D.A. (eds.), *Atlas of Deep-Water Environments: Architectural Style in Turbidite Systems*. Chapman & Hall, London, 89–93.

Kenyon, N.H., Monteiro, J., Shashkin, P. and Ivanov, M., 2000. OKEAN sidescan sonar data. In: Kenyon, N.H., Ivanov, M.K., Akhmetzhanov, A.M. and Akhmanov, G.G. (eds.), *Multidisciplinary Study of Geological Processes on the North East Atlantic and Western Mediterranean Margins*. UNESCO-IOC Technical Series, vol. 56, 50–51.

Klaucke, I., Masson, D.G., Kenyon, N.H. and Gardner, J.V. 2004. Sedimentary processes of the lower Monterey Fan channel and channel-mouth lobe. *Marine Geology*, 206, 181–198.

Kuenen, P.H., and Migliorini, C.I. 1950. Turbidity currents as a cause of graded bedding. *Journal of Geology*, 58 (2), 91-127.

Kuenen, P.H. 1957. Sole markings of graded greywacke beds. *Journal of Geology*, 65, 231-258.

Lastras, G., Canals, M., Urgeles, R., Amblas, D., Ivanov, M., Droz., L., Dennielou, B., Fabrés, J., Schoolmeester, T., Akhmetzhanov, A., Orange, D. and García-García, A. 2007. A walk down the Cap de Creus Canyon, Northwestern Mediterranean Sea: Recent processes inferred from morphology and sediment bedforms. *Marine Geology*, 246, 176-192.

Lastras, G., Arzola, R.G., Masson, D.G., Wynn, R.B., Huvenne, V.A.I., Hühnerbach, V. and Canals, M., 2009. Geomorphology and sedimentary features in the Central Portuguese submarine canyons, Western Iberian margin. *Geomorphology,* 103, 310-329.

Lebreiro, S. and Alonso, B. 2000. Sedimentary activity of the Guadiaro Turbidite Systems during the Last deglaciation to Holocene (SW Alboran). EAGE *Geology and Petroleum Geology of the Mediterranean and Circum-Mediterranean Basins.* Supported by AAPG. Malta. P-35, pp. 4.

Lebreiro, S.M., McCave, N. and Weaver, P.P.E. 1997. Late Quaternary turbidite emplacement on the Horseshoe Abyssal Plain (Iberian margin). *Journal of Sedimentary Research*, 67, 856-870.

Llave, E., Hernández-Molina, F.J., Somoza, L., Stow, D.A.V. and Díaz del Río, V. 2007. Quaternary evolution of the contourite depositional system in the Gulf of Cadiz. In: Viana, A.R. and Rebesco, M. (eds). *Economic and Palaeoceanographic Significance of Contourite Deposits.*Geological Society, London, Special Publications, 276, 49-79.

Maestro, A., López-Martínez, J., Llave,. E., Bohoyo, F., Acosta, J., Hernández-Molina, F.J., Muñioz, A. and Jané, G. 2013. Geomorphology of the Iberian Continental Margin. *Geomorphology*, 196, 13-35.

Maldonado, A., Got, H., Monaco, A., O'connnell, S. and Mirabile, L., 1985. Valencia fan (Northwestern Mediterranean): Dista1 deposition fan variant. *Marine Geology,* 62, 295-319.

Marchès, E., Mulder, T., Cremer, M., Bonnel, C., Hanquiez, V., Gonthier, E. and Lecroart, P. 2007. Contourite drift construction influenced by capture of Mediterranean Outflow Water deep-sea current by the Portimao submarine canyon (Gulf of Cadiz, South Portugal). *Marine Geology*, 242 (4), 247–260.

Marchès, E., Mulder, T., Gonthier, E., Cremer, M., Hanquiez, V., Garlan, T. and Lecroart, P. 2010. Perched lobe formation in the Gulf of Cadiz: Interactions between gravity processes and contour currents (Algarve Margin, Southern Portugal). *Sedimentary Geology*, 229, 81-94.

Masson, D.G., Kenyon, N.H., Gardner, J.V. and Field, M.E. 1995. Monterey fan: Channel and overbank morphology. In: Pickering, K.T., Hiscott, R.N., Kenyon, N.H., Ricci, L. and Smith, R.D.A. (eds.), *Atlas of Deep-Water Environments: Architectural Style in Turbidite Systems*. Chapman & Hall, London, 74–79.

Mauffret, A., Boillot, G., Auxietre, J.L. and Dunand, J.P., 1978. Evolution structurale de la marge continentale au Nord-Ouest de la péninsule Ibérique. *Bulletin de la Societé Geologuique de France*, 20, 375–388.

May, J.A., Warme, J.E. and Slater, R.A. 1983. Role of submarine canyons on shelfbreak erosion and sedimentation: Modern and ancient examples. In: Stanley, D.J. and Moore, G.T. (eds.), *The Shelfbreak: Critical Interface on continental Margins*. Society of Economic Paleontology and Mineralogy Special Publication, 33, 315-332.

Mayall, M., Jones, E. and Casey, M. 2006. Turbidite channel reservoirs –Key elements in facies prediction and effective development. *Marine and Petroleum Geologists*, 23, 821-841.

Medialdea, T., Maldonado, A., Alonso, B., Díaz, Jl., Farrán, M., Giró, S., Vázquez, A., Sainz-Amor, E., Martínez, A. and Medialdea, T. 1986. *Mapa Geológico de la plataforma española y zonas adyacentes. E: 200.000*. Instituto Geológico y Minero de España. Madrid. Hojas 42-42. 78 pp.

Mena, A., Francés, G., Pérez-Arlucea, M., Hanebuth, T.J.J. and Nombela, M.A. 2010. Sedimentary evolution of the Galicia Inner Basin during the last 70 ka. *Geo-temas* 11, 125-16.

Miall, A.D. 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth Science Reviews*, 22, 261–308.

Migeon, S., Savoye, B., Zanella, E., Mulder, T., Faugères, J.-C.and Weber, O. 2001. Detailed seismic-reflection and sedimentary study of turbidite sediment waves on the Var sedimentary Ridge (SE France): Significance for sediment transport and deposition and for the mechanisms of sediment-waves construction. *Marine and Petroleum Geology*, 18, 179–208.

Migeon S., Mulder T., Savoye B. and Sage F. 2006. The Var Turbidite System (Ligurian Sea, northwestern Mediterranean): Morphology, sediment supply, construction of turbidite levee, sediment waves and potential reservoirs, *Geo-Marine Letters*, 26 (6), 361-372.

Milkert, D. and Weaver, P.P.E., 1996. Pleistocene and Pliocene turbidites from the Iberia Abyssal Plain drilled during ODP Leg 149. *Proceedings of the ODP Initial Reports*, 149, Ocean Drilling Program, College Station, TX,281-294.

Mohrig S.A., and Buttles, J. 2013. Deep turbidity currents in shallow channels. *Geology*, 13, 155-158.

Morris, S.A., Alexander, J., Kenyon, N.H. and Limonoz, A.F. 1998. Turbidites around an active fault scarp on the lower Valencia Fan, northwestern Mediterranean. *Geo-Marine Letters*, 18, 165-171.

Mougenot, D., Vanney, J.R., Mauffret, A. and Kidd, R.B., 1986. Les montagnes sous-marines de la marge continentale nord-portugaise: morphologie et evolution structurale.*Bulletin de la Société Géologique de France*, 8 (II), 401-412.

Mougenot, D. 1988. Geologie de la marge Portugaise. *Unpublished PhD Thesis*, Université Pierre et Marie Curie, Paris, 155 pp.

Mulder, T. 2011. Gravity processes and deposits on continental slope, rise and abyssal plains. In: Hüneke, H. and Mulder, T. (eds.), *Deep-Sea Sediments.* Developments in Sedimentology, Elsevier, Amsterdam, 63, 1-24.

Mulder, T. and Alexander, J. 2001. Abrupt change in slope causes variation in the deposit thickness of concentrated particle-driven density currents. *Marine Geology*, 175, 221–235.

Mulder, T., Syvitski, J.P.M., and Skene, K.I. 1998. Modelling of erosion and deposition by turbidity currents generated at river mouths. *Journal of Sedimentary Research*, 68, 124–137.

Mulder, T., Voisset, M., Lecroart, P., Le Drezen, E., Gonthier, E., Hanquiez, V., Faugères, J.-C., Habgood, E., Hernandez-Molina, F.J., Estrada, F., Llave-Barranco, E., Poirier, D., Gorini, C., Fuchey, Y., Voelker, A., Freitas, P., Lobo Sanchez, F., Fernandez, L.M., Kenyon, N.H. and Morel, J. 2003. The Gulf of Cadiz: an unstable giant contouritic levee. *Geo-Marine Letters*, 23, 7-18.

Mulder, T., Cirac, P., Gaudin, M., Bourillet, J.-F., Tranier, J., Normand, A., Weber, O., Griboulard, R., Jouanneau, J.-M., Anschutz, P. and Jorissen, F.J. 2004. Understanding continent-ocean sediment transfer. *EOS American Geophysical Union Transaction,* 257, 261–262.

Mulder, T., Lecroart, P., Hanquiez, V., Marches, E., Gonthier, E., Guedes, J.-C., Thiébot, E., Jaaidi, B., Kenyon, N., Voisset, M., Perez, C., Sayago, M., Fuchey, Y. and Bujan, S. 2006. The western part of the Gulf of Cadiz: contour currents and turbidity currents interactions. *Geo-Marine Letters*, 26, 31-41.

Mulder, T., Faugères, J.C. and Gonthier, E. 2008. Mixed turbidite-contourite systems. In: Rebesco, M. and Camerlenghi, A. (eds.), *Contourites. Developments in Sedimentology*, Elsevier, Amsterdam, 60, 435-466.

Mulder, T., Gonthier, E., Lecroart, P., Hanquiez, V., Marches, E. and Voisset, M., 2009. Sediment failures and flows in the Gulf of Cadiz (western Atlantic), *Marine and Petroleum Geology*, , 26, 660-672.

Mulder, T., Hüneke, H. and Van Loon, A.J. 2011. Progress in Deep-Sea Sedimentology. In: Hüneke, H. and Mulder, T. (eds.), *Deep-Sea Sediments*. Developments in Sedimentology, Elsevier, Amsterdam, 63, 25-148.

Mullenbach, B.L., Nittrouer, C.A., Puig, P. and Orange, D.L. 2004. Sediment deposition in a modern submarine canyon: Eel Canyon, northern California. *Marine Geology*, 211, 101-119.

Mutti, E. 1979. Turbidities et cones sous-margins profonds. In: P. Homewood (ed.), *Sedimentation Detritique (Fluviatile, littorale et Marine)*. Institute Gologique Universite de Fribourg, Fribourg, 353-419.

Mutti, E. and Normark, W.R. 1987. Comparing examples of modern and ancient turbidite systems: problems and concepts. In: Legget, J.R. and Zuffa, G.G. (eds.). *Marine Clastic Sedimentology: Concepts And Case Studies*. G. Graham and Trotman, London, 1-37.

Mutti, E. and Normark, W.R. 1991. An integrated approach to the study of turbidite systems. In: Weimer, P. and Link, H. (eds.), *Seismic Facies And Sedimentary Processes Of Submarine Fans And Turbidite Systems.* Springer, New York, 75-106.

Mutti, E., Bernouilli, D., Ricci-Lucchi, F. and Tinerri, R., 2009. Turbidites and turbidity currents from Alpine "Flysch" to the exploration of continental. *Sedimentology*, 56, 267-318.

Nelson, H. and Maldonado, A. 1988. Factors controlling depositional patterns of Ebro turbidite systems, Mediterranean Sea. *American Association of Petroleum Geologists Bulletin*, 72 (6), 698-716.

Nelson, C.H., Escutia, C., Damuth, J.E. and Twichell, C. Jr. 2011. Interplay of mass-transport and turbidite-system deposits in different active tectonic and passive continental margin settings; external and local controlling factors. In: Shipp, R. Craig, R., Weimer, P. and Posamentier, H.W. (eds), *Mass Transport Deposits In Deep-Water Settings*. Socitey for Sedimentary Geology Tulsa, OK, 96, 39-66.

Normark, W.R. 1970. Growth patterns of deep sea fans, American Association of Petrologeum Geologists, 54, 2170-2195.

Normark, W.R. 1978. Fan valleys, channels, and depositional lobes on modern submarine fans: Ccharacters for recognition of sandy turbidite environments. *American Association of Petroleum Geologists Bulletin*, 62, 912-931.

Normark, W.R. and Piper, J.W. 1969. Deep-sea fan-valleys, past and present. *Geological Society of America Bulletin*, 80 (9), 1859-1866.

Normark, W.R., Piper, D.J.W. and Hess, G.R. 1979. Distributary channels, sand lobes, and mesotopography of navy submarine fan, California Borderland, with application to ancient fan sediments. *Sedimentology*, 26, 749–774.

Normark, W.R., Piper, D.J.W. and Stow, D.A.V. 1983. Quaternary development of channels , levees and lobes on the middle Laurentian Fan. *American Association of Petroleum Geologists Bulletin*, 67(9), 1400-1409.

Normark, W.R., Posamentier, H. and Mutti, E. 1993. Turbidite systems: state of the art and future directions. *Review of Geophysics*, 31 (2), 91-116.

Normark, W.R., Piper, D.J.W., Posamentier, H., Pirmez, C. and Migeon, S. 2002. Variability in form and growth of sediment waves on turbidite channel levees. *Marine Geology*, 192, 23-58.

Palanques, A., Alonso, B. and Farrán, M. 1994. Progradation and retreat of the Valencia fanlobes controlled by sea level changes during the Plio-Pleistocene (Northwestern Mediterranean). *Marine Geology*, 117, 195-205.

Palanques, A., Kenyon, N.H., Alonso, B. and Limonov, A. 1995. Erosional and depositional patterns in the Valencia Channel mouth: an example of a modern channel-lobe transition zone. *Marine Geophysical Researches*, 17, 503-517.

Peakall, J., McCaffrey, B. and Kneller, B.C. 2000. A process model for the evolution, morphology, and architecture of sinuous submarine channels. *Journal of Sedimentary Research*, 70 (3), 434–448.

Pérez-Belzuz, F., Alonso, B.and Ercilla, G. 2000. Modelos de sistemas turbidíticos en el área de Motril (NE Alboran). *Geo-temas,* 1 (4), 213-216.

Piper, D.J.W. and Normark, W.R. 1983. Turbidite depositional patterns and flow characteristics. Navy Submarine fan, California Borderland. *Sedimentology,* 30, 681–694.

Piper, D.J.W. and Normark, W.R. 2001. Sandy fans-form Amazon to Hueneme and beyond. *American Association of Petroleum Geologist*, 85 (8), 1407-1438.

Pirmez, C. and Imran, J. 2003. Reconstruction of turbidity currents in a meandering submarine channel. *Marine and Petroleum Geology*, 20 (6-8), 823-849.

Pirmez, C., Beauboueff, R.T., Friedmann, S.J. and Mohrig, D.C. 2000. Equilibrium profile and baselevel in submarine channels: examples from late Pleistocene systems and implications for the architecture of deep-water reservoir. In: Weimer, P., Slatt, R.M., Coleman, J., Rosen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J. and Lawrence, D.T. (eds.), *Deep-Water Reservoirs of the World,* SEPM Special Publication, 782–805.

Posamentier, H.W. 2003. Depositional elements associated with a basin floor channel-levee system: case study from the Gulf of Mexico. *Marine and Petroleum Geology*, 20 (6–8), 677–690.

Posamentier, H.W. and Kolla, V. 2003.Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. *Journal of Sedimentary Research*, 73, 367–388.

Pratson, L.F. and Coakley, B.J. 1996. A model for the headward erosion of submarine canyons induced by downslope-eroding sediment flows. *Geological Society of America Bulletin*, 108 (2), 225-234.

Pratson, L., Imran, J., Hutton, E., Parker, G. and Syvitski, J.P.M. 2001. BANG1D: a one dimensional, Lagrangian model of turbidity current mechanics. *Computers and Geoscience*, 27 (6), 701–716.

Reading, H.G. and Richards, M. 1994. Turbidite systems in deep-water basin margins classified by grain size and feeder system. *American Association of Petroleum Geologists Bulletin*, 78, 702-822.

Richards, M., Bowman, M. and Reading, H. 1998. Submarine-fans systems I: Characterization and stratigraphic prediction. *Marine and Petroleum Geology*, 15, 689-717.

Roberts, D.G. and Kidd, R.B., 1984. Sedimentary and structural patterns on the Iberian continental margin: an alternative view of continental margin sedimentation. *Marine and Petroleum Geology,* 1, 37-48.

Saller, A. H., J. T. Noah, Ruzuar, A.P. and Schneider R. 2004. Linked lowstand delta to basin-floor fan deposition, offshore Indonesia: An analog for deepwater reservoir systems. *American Association of Petroleum Geologists Bulletin*, 88, 21-46.

Savoye, B., Cochonat, P., Apprioual, R., Bain, O., Baltzer, A., et al. 2000. Structure et évolution récent de l'e ventail turbiditique du Zaire: premiers résultats scientifiques des missions d'explora-tion Zaiango 1&2 (marge Congo– Angola). *Comptes Rendus de l'Académie des Sciences*, Paris 331, 211 – 220.

Schumm, S.A. 1981. Evolution and response of the fluvial system, sedimentologic implications. *Society of Economic Paleontology and Mineralogy Special Publication*, 31, 19-29.

Shanmugam, G. and Moiola, R.J. 1988. Submarine fans: Characteristics, models, classification, and reservoir potential. *Earth-Science Reviews*, 24, 383-428.

Shanmugam, G., Moiola, R.J., McPherson, J.G. and O'Connell, S. 1988. Comparison of turbidite facies associations in modern passive-margin Mississippi Fan with ancient active-margin fans. *Sedimentary Geology*, 58, 63-77.

Shanmugam, G. 2000. 50 years of the turbidite paradigm (1950s-1990s): Deep-water processes and facies models – a critical perspective. *Marine and Petroleum Geology*, 17, 285-342.

Shanmugam, G. 2002. Ten turbidite myths. *Earth-Science Reviews*, 58 (3–4), 311-341.

Shepard, F.P. 1981. Submarine canyons: multiple causes and long-time persistence. *American Association of Petroleum Geologists Bulletin*, 65, 1062-1981.

Shepard, F.P. and Dill, R.F. 1966. Submarine Canyons and other sea-valleys.Rand McNally, Chicago, IL. 381pp.

Sømme, T. O., Helland-Hansen, W., Martinsen, O.J. and Thurmond, J.B. 2009. Relationships between morphological and sedimentological parameters in source-to-sink systems: A basis for predicting semi-quantitative characteristics in subsurface systems. *Basin Research,* 21, 361-387.

Stow, D.A.V. and Johansson, M. 2000. Deep-water massive sands: nature, origin and hydrocarbon implications. *Marine and Petroleum Geology*, 17, 145-174.

Twichell, D.C., Schwab, W.C., Nelson, C.H., Kenyon, N.H. and Lee, H.J. 1992. Characteristics of a sandy depositional lobe on the outer Mississippi Fan from SeaMARC 1A sidescan sonar images. *Geology*, 20, 693–696.

Vázquez, J.T., Medialdea, T., Ercilla, G., Somoza, L., Estrada, F., Fernández-Puga M.C., Gallart, J., Gràcia, E., Maestro, A. and Sayago, M. 2008. Cenozoic deformational structures on the Galicia Bank region (NW Iberian continental margin). *Marine Geology*, 249, 128-149.

Vanney, J.R., Auxiètre, J.L. and Dunand, J.P., 1979. Geomorphic provinces and the evolution of the northwestern Iberian Continental Margin. *Annales de l'Institut Océanographique*, Paris, 55 (1), 5–20.

Weaver, P.P.E., Wynn, R.B., Kenyon, N.H. and Evans, J., 2000. Continental margin sedimentation, with special reference to the north-east Atlantic margin. *Sedimentology,* 47, 239–256.

White, C. D., Bradburn, R. L., Brown, R.L. and Thieme, M. A., 1992. Reservoir potential of thin-bedded turbidites: Prospect Tahoe: 67th Annual Conference and Exhibition of the Society of Petroleum Engineers. Annual Technical Conference and Exhibition, Washington, SPE Paper No. 24875.

Wynn, R.B., Kenyon, N.H., Masson, D.G., Stow, D.A.V. and Weaver, P.P.E. 2002. Characterization and recognition of deep-water channel-lobe transition zones. *American Association of Petroleum Geologists Bulletin*, 86 (8), 1441–1446.

Wynn, R.B., Cronin, B.T. and Peakall, J. 2007. Sinuous deep-water channels: Genesis, geometry and architecture. *Marine and Petroleum Geology,* 24, 341-387.

Zaragosi, S., Auffret, G.A., Faugères, J.C., Garlan, T., Pujol, C. and Cortijo, E. 2000. Physiography and recent sediment distribution of the Celtic Deep-sea Fan, Bay of Biscay. *Marine Geology*, 169, 207-237.

Recibido: febrero 2014
Revisado: septiembre 2014
Aceptado: noviembre 2014
Publicado: junio 2015