2011

Geo-Mar Lett (2011) 31:285–300
DOI 10.1007/s00367-011-0261-z

INTRODUCTION

Deep-water Circulation: Processes & Products (16–18 June 2010, Baiona): introduction and future challenges

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Received: 12 September 2011 / Accepted: 26 September 2011

Abstract Deep-water circulation is a critical part of the global conveyor belt that regulates Earth's climate. The bottom (contour)-current component of this circulation is of key significance in shaping the deep seafloor through erosion, transport, and deposition. As a result, there exists a high variety of large-scale erosional and depositional features (drifts) that together form more complex contourite depositional systems on continental slopes and rises as well as in ocean basins, generated by different water masses flowing at different depths and at different speeds either in the same or in opposite directions. Yet, the nature of these deep-water processes and the deposited contourites is still poorly understood in detail. Their ultimate decoding will undoubtedly yield information of fundamental importance to the earth and ocean sciences. The international congress *Deep-water Circulation: Processes & Products* was held from 16–18 June 2010 in Baiona, Spain, hosted by the University of Vigo. Volume 31(5/6) of Geo-Marine Letters is a special double issue containing 17 selected contributions from the congress, guest edited by F. J. Hernández-Molina, D.A.V. Stow, E. Llave, M. Rebesco, G. Ercilla, D. Van Rooij, A. Mena, J.-T. Vázquez and A.H.L. Voelker. The papers and discussions at the congress and the articles in this special issue provide a truly multidisciplinary perspective of interest to both academic and industrial participants, contributing to the advancement of knowledge on deep-water bottom circulation and related processes, as well as contourite sedimentation. The multidisciplinary contributions (including geomorphology, tectonics, stratigraphy, sedimentology, paleoceanography, physical oceanography, and deep-water ecology) have demonstrated that

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advances in paleoceanographic reconstructions and our understanding of the ocean's role in the global climate system depend largely on the feedbacks among disciplines. New insights into the link between the biota of deep-water ecosystems and bottom currents confirm the need for this field to be investigated and mapped in detail. Likewise, it is confirmed that deep-water contourites are not only of academic interest but also potential resources of economic value. Cumulatively, both the congress and the present volume serve to demonstrate that the role of bottom currents in shaping the seafloor has to date been generally underestimated, and that our understanding of such systems is still in its infancy. Future research on contourites, using new and more advanced techniques, should focus on a more detailed visualization of water-mass circulation and its variability, in order to decipher the physical processes involved and the associations between drifts and other common bedforms. Moreover, contourite facies models should be better established, including their associations with other deep-water sedimentary environments both in modern and ancient submarine domains. The rapid increase in deep-water exploration and the new deep-water technologies available to the oil industry and academic institutions will undoubtedly lead to spectacular advances in contourite research in terms of processes, morphology, sediment stacking patterns, facies, and their relationships with other deep-marine depositional systems.

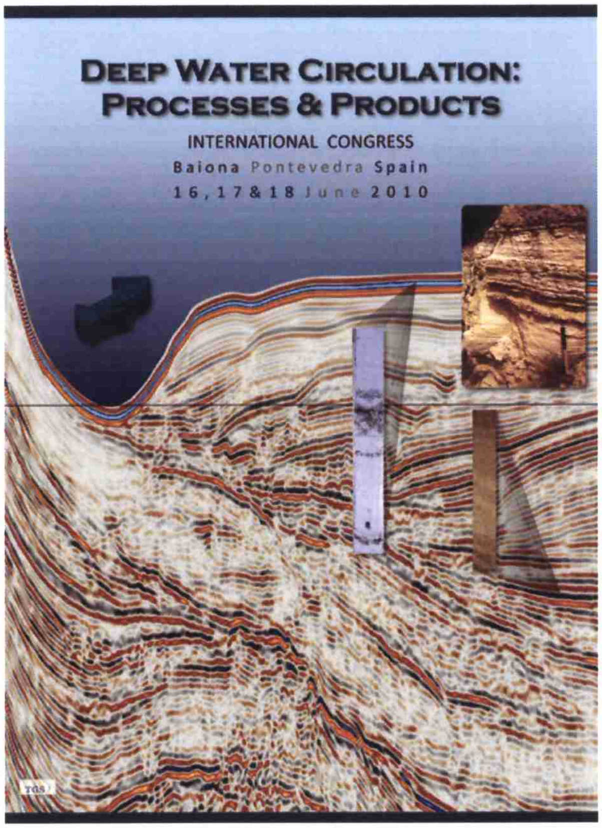


Fig. 1 Official frontispiece of the international congress *Deep-water Circulation: Processes & Products*, Baiona, Pontevedra, Spain, 16–18 June 2010

Preamble

The international congress on *Deep-water Circulation: Processes & Products* was held on 16–18 June 2010 in Baiona (Pontevedra), Spain, hosted by the University of Vigo (Fig. 1). It received wide European and global support, and was attended by many of the principal specialists in the field. The congress was organized by the following institutions: the University of Vigo (Spain), the Heriot Watt University (UK), the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS, Italy), the Instituto Geológico y Minero de España (IGME, Spain), the Renard Centre of Marine Geology, Ghent University (Belgium), the Instituto Español de Oceanografía (IEO, Spain), the Laboratorio Nacional de Energia e Geologia (LNEG, Portugal), the Instituto de Ciencias del Mar-CSIC (ICM-CSIC, Spain), and the Edinburgh Collaborative of Subsurface Science and Engineering (ECOSSE, UK).

The main aim of the congress was to integrate knowledge on deep bottom-current circulation, sedimentary processes and deposits, and their implications for paleoceanographic reconstructions not only to improve our understanding of the oceans' role in the global climate system, but also as a new exploration target for economic resources (http://www.facultadeccdomar.es/contourites/). This integrated approach includes the dominant currents related to geostrophic and thermohaline circulation (THC), internal tides and waves, canyon currents, and up-/downwelling slope currents. Thus, the main topics covered during the meeting were geostrophic/thermohaline circulation and bottom currents; modern contourite deposits; ancient contourite examples; internal-wave and internal-tide deposits; implications for paleoceanography and slope stability; relationships between deep-water circulation and gravity flows; numerical and physical modeling of processes; environmental, tectonic and other control factors of processes and deposits; innovation and new technologies and methods; deep-water ecosystem drivers; factors of economic importance (fishing, minerals such as Fe-Mn nodules, crusts), and energy resources (oil, gas, shallow gas, hydrates, etc.). The international congress *Deep-water Circulation: Processes & Products* was the first meeting of its kind, and both organizers and delegates agreed to hold similar events every 4 years, the next one being aimed for 2014 in Ghent (Belgium), to be hosted by the Renard Centre of Marine Geology (RCMG, Ghent University).

Nearly 100 abstracts from 255 contributors were received for the meeting (see Hernández-Molina et al. 2010), providing a truly multidisciplinary platform addressing both academic and industrial participants. The oral presentations and discussions at this congress have contributed greatly to the advancement of knowledge on deep-water bottom circulation and related processes, including contourite sedimentation. The variety of multidisciplinary contributions, which included geomorphology, tectonics, stratigraphy, sedimentology, paleoceanography, physical oceanography, and deep-water ecology, demonstrated that advances in paleoceanographic reconstructions and our understanding of the role of the oceans in the global climate system depend largely on the feedbacks among disciplines. New insights into the links between the biota of deep-water ecosystems and bottom currents confirm the need for this field of research to be investigated and mapped in much greater detail than hitherto possible. Likewise, it is very clear that deep-water contourites are not only of academic interest but also represent potential resources of economic value.

Volume 31(5/6) of Geo-Marine Letters is a special double issue containing selected contributions presented at the congress. The guest editors are F.J. Hernández-Molina (University of Vigo, Spain), D.A.V. Stow (Heriot-Watt University, Edinburgh, UK), E. Llave (IGME, Spain), M. Rebesco (OGS, Italy), G. Ercilla (ICM-CSIC, Spain), D. Van Rooij (Ghent University, Belgium), A. Mena (University of Vigo, Spain), J.-T. Vázquez (IEO, Spain), and A.H.L. Voelker (LNEG, Portugal). Of the 27 initially submitted manuscripts, 17 (63%) were ultimately accepted for publication on the basis of the recommendations from 55 reviewers. Together with the authors, the conscientious work of the reviewers and the editors contributed to the high scientific standard of the articles appearing in this special issue, reflecting the research of 69 authors from 35 research institutions and companies residing in 12 countries on four continents.

Deep-water circulation: processes and products

Deep-water circulation is a critical part of the global conveyor belt (Fig. 2) that regulates Earth's climate (Broecker 1987, 1991; Rahmstorf 2006; Kuhlbrodt et al. 2007). The bottom-current component of this circulation contributes significantly to shaping the deep seafloor (Stow et al. 2009) through alongslope oceanographic processes (Figs. 3 and 4). The general term 'bottom current' is here preferred to denote those semi-permanent deep-water currents that are capable of eroding, transporting, and depositing sediments at the seafloor (Rebesco and Camerlenghi 2008). Bottom currents are the result of both thermohaline and wind-driven circulation in the oceans. Generally, these currents flow alongslope, although they can be extremely variable in direction and velocity, with strong spatiotemporal variations,

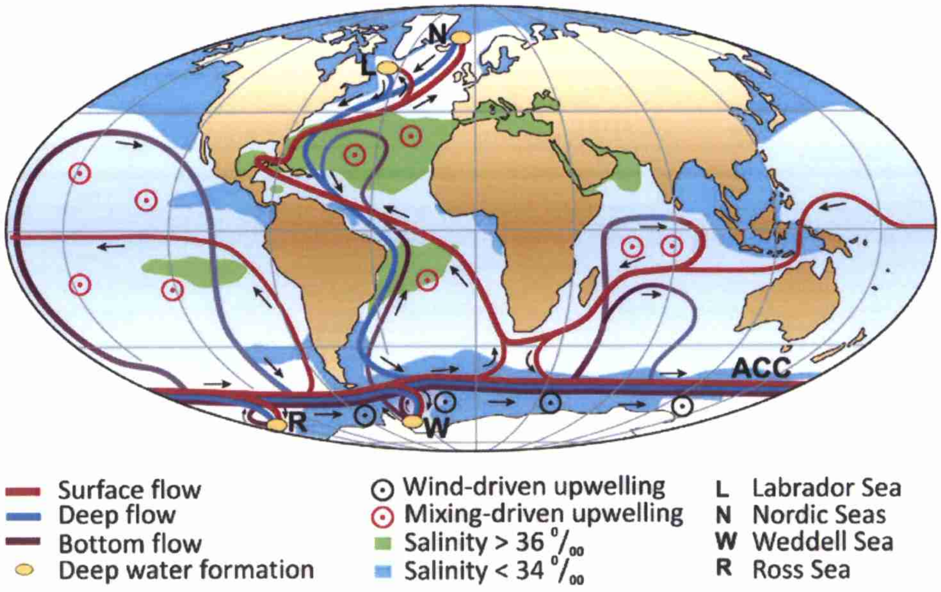


Fig. 2 Schematic representation of the global thermohaline circulation: *red* surface currents, *light blue* deep waters, *dark blue* bottom waters, *orange* main deep-water formation sites. In the Atlantic, warm and saline waters flow northward from the Southern Ocean into the Labrador and Nordic seas. By contrast, there is no deep-water formation in the North Pacific, and its surface waters are therefore fresher. Deep waters formed in the Southern Ocean become denser and thus spread at deeper levels than those from the North Atlantic. Note the small, localized deep-water formation areas in comparison to the widespread zones of mixing-driven upwelling. Wind-driven upwelling occurs along the Antarctic Circumpolar Current (high-quality image courtesy of T. Kuhlbrodt, University of Reading, UK, from Rahmstorf 2006; Kuhlbrodt et al. 2007; reproduced by permission of American Geophysical Union)

Fig. 3 Isis ROV photograph from the Pacific margin of the Antarctic Peninsula taken along the axis of the channel north of the proximal part of Drift 5, at about 3,000 m depth. The appearance of the deep-water ripples is enhanced as a result of accumulation of phytodetritus on their lee sides. A stalked crinoid (Echinodermata, Crinoidea) is swept by the bottom current (courtesy of J.A. Dowdeswell, Scott Polar Research Institute, Cambridge, UK; P.A. Tyler and G. Griffiths, National Oceanography Centre, Southampton, UK; R.D. Larter, British Antarctic Survey, Cambridge, UK)

in addition to exhibiting giant eddies as well as local downslope, upslope or oblique-to-slope flow (Fig. 4), especially near the entrances or exits of gateways to or from ocean basins (Rebesco and Camerlenghi 2008). Bottom (contour) currents can be a relatively homogeneous water mass flowing along the sea bottom, or comprise several water masses flowing at different depths, and sometimes in opposite directions (Viana et al. 2002a, 2002b; Laberg et al. 2005). The impact of these currents is particularly marked on continental slopes, rises, and in ocean basins where their nature and gradients act as a major control on the THC. At these locations the current velocity is strongly affected by frictional stresses at the seabed (Fig. 5), and therefore the presence or absence of major morphological features (basin margins, oceanic gateways, local obstacles) are highly significant. When an impinging water mass interacts with the bottom relief, it is likely to develop a particular local and regional hydrodynamic signature (cores, branches, vortices, local turbulence, internal waves, helicoidal flows, vertical columns, etc.) that controls the dominant sedimentary processes (Hernández-Molina et al. 2008a). A sufficiently strong bottom current acting for a prolonged period of time will profoundly affect the seabed, ranging from winnowing of fine-grained sediments to large-scale erosion and deposition (Fig. 5; Heezen 1959; Heezen et al. 1959; Stow and Lovell 1979; Kennett 1982; Pickering et al. 1989; Stow 1994; Einsele 2000; Shanmugam 2006; Rebesco and Camerlenghi 2008; Stow et al. 2009; Seibold and Berger 2010).

The term ‘contourite’ is now generally accepted for those sediments deposited or substantially reworked by bottom currents and contour currents sensu stricto (Heezen et al. 1966; Gonthier et al. 1984; Stow et al. 2002; Rebesco 2005; Rebesco and Camerlenghi 2008; Faugères and Mulder 2011). Major accumulations of contourite deposits are referred to as *drifts* or *contourite drifts* (Figs. 5, 6), for which several classifications have been proposed based

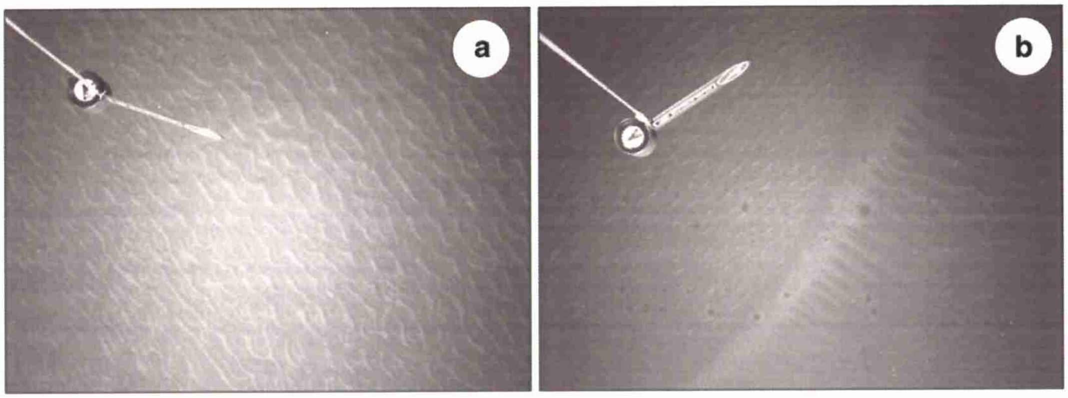


Fig. 4 Bottom photographs from along the Cadiz overspill channel (from Stow et al. 2008; Stow et al., unpublished data). **a** Linear to sinuous asymmetrical ripples (sharp-crested): ripple orientation indicates flow toward the west, whereas the current vane shows that the flow direction was toward the south when the photo was taken. **b** Sinuous to crescentic sand wave: note the stoss side with small, regular asymmetrical ripples, the lee side with linear erosional chutes, and the sand wave trough region with a more irregular ripple pattern. Both ripple and dune orientations indicate flow toward the west, whereas the current vane shows a more southerly flow direction when the photo was taken. Compass diameter is 7 cm, current vane 25 cm

mainly on their morphological, sedimentological, and seismic characteristics (McCave and Tucholke 1986; Faugères et al. 1993, 1999; Rebesco and Stow 2001; Stow et al. 2002; Rebesco 2005; Rebesco and Camerlenghi 2008; Faugères and Mulder 2011). Where currents are strong enough, a variety of erosional features are developed (Figs. 5, 7). Extensive erosion or non-deposition lead to the development of widespread *hiatuses* in the depositional record. Although several authors have studied erosional features in contourites (e.g., Nelson et al. 1993, 1999; Evans et al. 1998; Stow and Mayall 2000; Masson 2001; Hernández-Molina et al. 2003, 2008b, 2009; García et al. 2009; Stow et al. 2008, 2009), these have yet to be classified and integrated into a classification scheme that includes standard drift categories.

An association of various drifts and related erosional features is commonly termed a *contourite depositional system* (CDS), by analogy with, and of equal importance to, *turbidite depositional systems* (e.g., Stow et al. 1996, 2002; Faugères et al. 1999; Hernández-Molina et al. 2003, 2008a; Viana and Rebesco 2007; Rebesco and Camerlenghi 2008). Mixed contourite–turbidite systems are developed where bottom currents have interacted with downslope processes (Hollister and Heezen 1972; Faugères et al. 1999; Rebesco and Camerlenghi 2008; Faugères and Mulder 2011). However, when water masses flowing along continental slopes are energetic enough, they can mask the effects of downslope processes and generate complex CDSs comparable to large turbidite depositional systems (e.g., Gao et al. 1998; Faugères et al. 1999; Stow et al. 2002). Where different CDSs are connected laterally (and vertically), and are associated with the same water mass in the same or adjacent basins, they can be considered as a *contourite depositional complex* (Hernández-Molina et al. 2008a).

Hernández-Molina et al. (2008b) considered two end-members for CDSs in relation to flow behavior of the impinging water mass:

1. If different water masses flowing at different depths along the sea bottom have simple (unobstructed) current pathways, then separate contourite depositional elements can develop. These preferentially occur along passive margins devoid of complex seafloor physiography. In these settings, large drifts and erosional features develop that depend strongly on the position of the main current core, the velocity of the current, and sediment supply.
2. Along margins where recent tectonic activity has produced a complex seafloor morphology, more possibilities exist for the generation of multiple current pathways, including current branching, secondary flows, small fluxes (flow filaments), internal waves, local turbulence associated with eddies, overflows, and helicoidal flows. Topographic obstacles induce local acceleration or deceleration of currents. Under such conditions, very complex contourite depositional systems can be generated, including numerous types of depositional and erosional elements.

Ultimately, the presence of single or multiple current pathways depends on the particular physiography of the seafloor and, therefore, on both tectonic activity and sediment supply. Tectonic activity thus represents a key factor in generating morphological changes on the seafloor (producing slopes and basins, diapirs, uplifted fault blocks, banks, ridges, seamounts, etc.), thereby controlling the development of new pathways for the core and branches of the impinging current in the course of each evolutionary stage. Subsequently, this will influence drift stratigraphy, internal

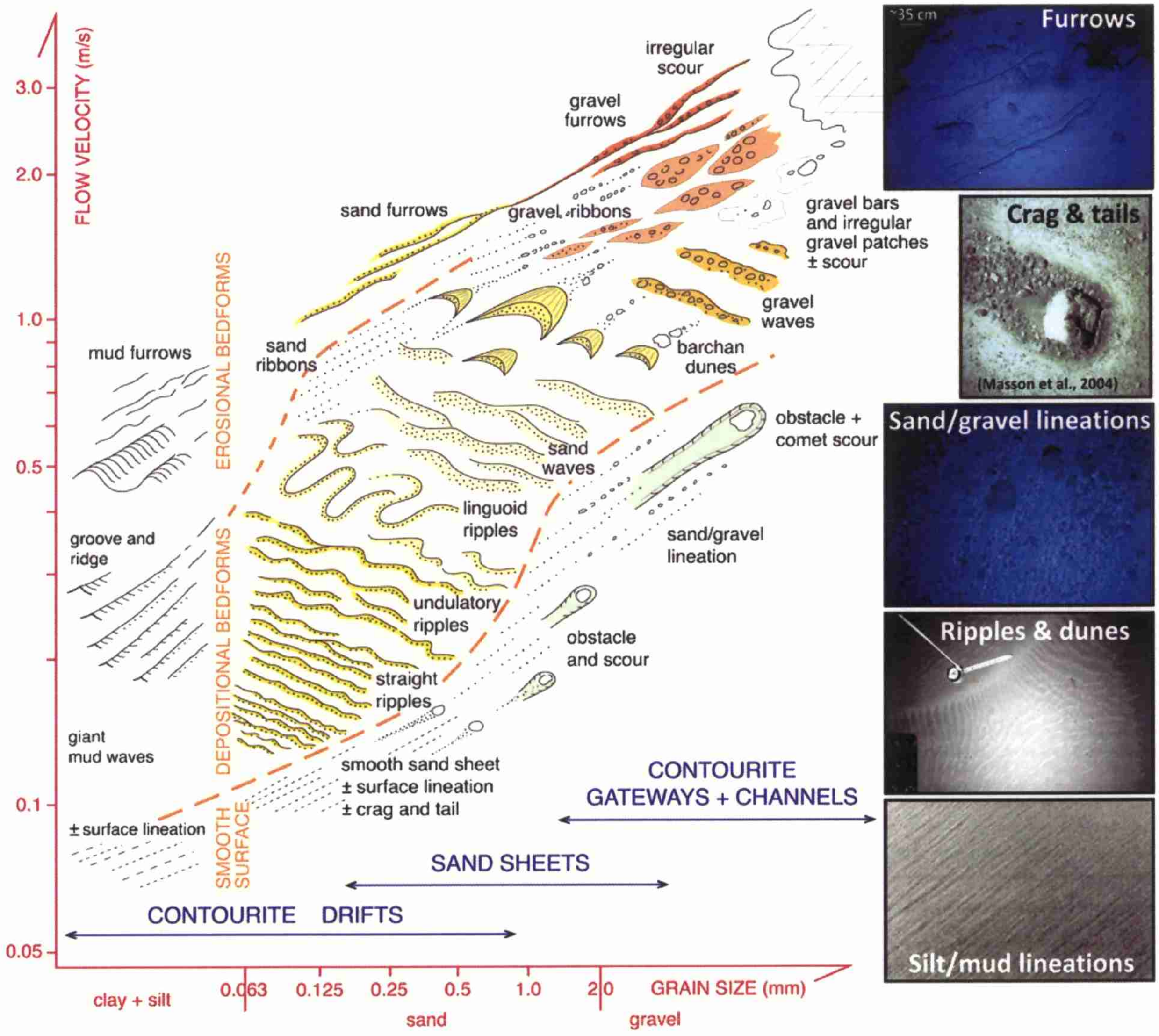


Fig. 5 Bedform–velocity matrix for deep-water bottom-current systems showing mean grain size of sediment versus flow velocity at or near the seafloor, with schematic representation of the bedforms present under specific velocity–grain size conditions (modified from Stow et al. 2009)

architecture, and the location of large-scale erosional features in the long term. Moreover, active slope tectonics may trigger other downslope processes that can partially or completely mask contourite activity.

Environmental (paleoclimatic or sea-level) and paleoceanographic changes are other essential factors controlling contourite evolution. In the short term, these control the vertical contourite stacking patterns, sequences, and facies. Climate plays an important role in the positioning of the core of a contour current, with two main effects: (1) vertical and lateral changes in the position of the current core, and (2) changes in the intensity of the currents. Such changes are not coeval and global. Along certain continental margins, some water masses are stronger during cold glacial intervals, whereas along other margins the water masses are more active during warmer interglacial intervals (Knutz 2008; Hernández-Molina et al. 2008b; Brackenridge et al. 2011, this volume). Moreover, some currents are continuously active, but their effects may be masked by downslope processes, mainly during regressive and lowstand sea-level stages (Mulder et al. 2008; Hüneke and Mulder 2011).

The study of alongslope processes and their deposits in general, and CDSs in particular, has been one of the most active lines of research in marine geology during the last decade (Fig. 8), mainly because of their high stratigraphic, sedimentological, paleoceanographic and paleoclimatological significance, their close link with sediment instability on continental slopes, and their direct relation to possible mineral

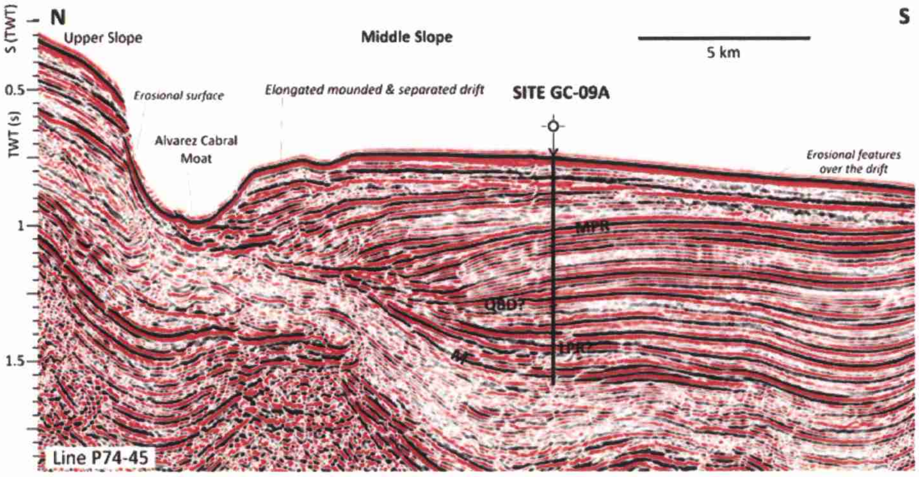


Fig. 6 Multichannel seismic (MCS) reflection profile P74-45 across the Faro-Albufeira Drift on the middle slope, showing the location of the proposed site GC-09A (MCS lines provided by REPSOL Oil Company). Four major low-resolution depositional sequences have been recognized in the Pliocene and Quaternary sedimentary record (Llave et al. 2001; Hernández-Molina et al. 2002, 2006), separated by four key discontinuities: M (late Messinian), LPR? (Early Pliocene revolution), QBD? (Quaternary base), and MPR (mid-Pleistocene revolution). *TWT* Two-way traveltime (modified from Stow et al. 2011)

and energy resources (e.g., Kennett 1982; Nowell and Hollister 1985; McCave and Tucholke 1986; Pickering et al. 1989; Faugères et al. 1993, 1999; Gao et al. 1998; Stow and Mayall 2000; Rebesco and Stow 2001; Stow et al. 2002; Shanmugam 2003, 2006; Rebesco 2005; Viana and Rebesco 2007; Rebesco and Camerlenghi 2008; Hernández-Molina et al. 2010; Hüneke and Mulder 2011). International projects such as the DSDP (Deep-Sea Drilling Project), ODP (Ocean Drilling Program), and IODP (Integrated Ocean Drilling Program) have corroborated this importance by underlining their very common occurrence along many ocean margins and in deep basins worldwide. Cumulatively, this work has also served to demonstrate that the role of bottom currents in shaping continental margins and abyssal plains has to date been generally underestimated, and that our understanding of such systems is still in its infancy (Fig. 8).

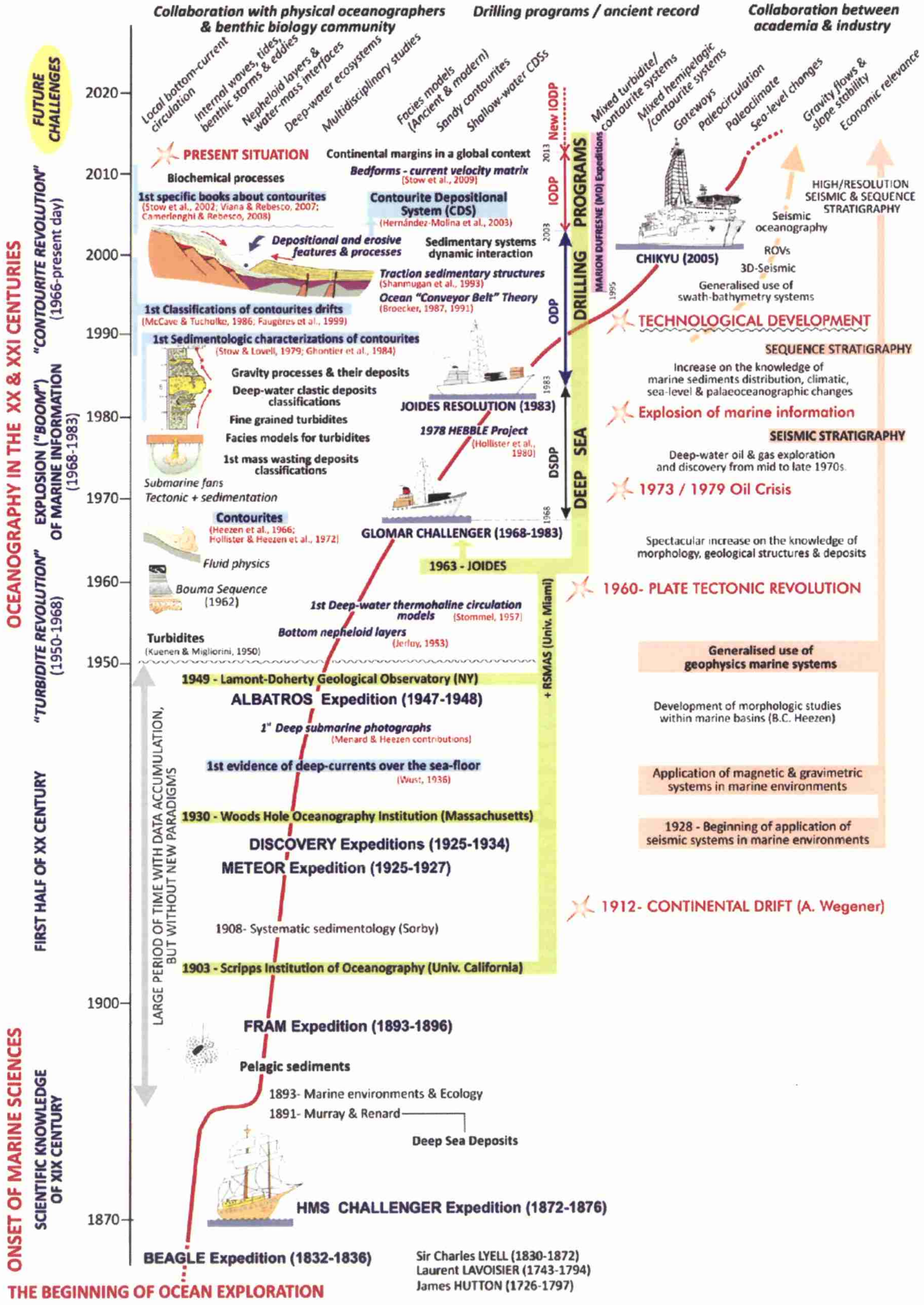
Fig. 7 Example of an erosional feature in the Gulf of Cadiz: the bottom photograph from the Cadiz Contourite Channel shows deep linear scours (or small furrows) with very rare starved ripples of coarse sediments (from Stow et al. 2008)

Contributions to this special issue

The present double issue of Geo-Marine Letters contains 17 selected contributions to the congress, which deal with some of the most important topics in deep-water circulation processes and their products: physical processes; contourite depositional systems; oceanic gateways; depositional features; erosional features; obstacles/recent tectonics; contourite facies; ichnological analyses; and innovation and new methods.

Deep water-mass circulation, including the local flow of bottom currents, and their behavior, variability, and role in the construction of drifts and bedforms, while still being poorly understood, is essential for an in-depth comprehension of the *physical processes* and their variability, in particular with respect to the association between processes and products. In this volume, Gasser et al. (2011) examine the structure and variability of the nascent Mediterranean Outflow Water (MOW) immediately west of the Espartel Sill, the westernmost sill in the Strait of Gibraltar. Measurements indicate that the nascent MOW behaves as a very energetic downslope gravity current responsible for seafloor erosion and the development of a narrow V-shaped channel.

An association of various drifts and related erosional features has been termed a *contourite depositional system.* In the present volume there are two studies directly related to CDSs: (1) Hernández-Molina et al. (2011) describe regional contourite (alongslope) processes and their sedimentary impacts around the Iberian margin, combining numerically simulated bottom currents with existing knowledge of contourite depositional and erosional features. Circulation of water masses is correlated with major contourite depositional systems, and potential areas where new CDSs may be


Collaboration with physical oceanographers & benthic biology community
Drilling programs / ancient record
Collaboration between academia & industry
Local bottom-current circulation
Internal waves, tides, benthic storms & eddies
Nepheloid layers & water-mass interfaces
Deep-water ecosystems
Multidisciplinary studies
Facies models (Ancient & modern)
Sandy contourites
Shallow-water CDSs
Mixed turbidite/ contourite systems
Mixed hemipelagic /contourite systems
Gateways
Paleocirculation
Paleoclimate
Sea-level changes
Gravity flows & slope stability
Economic relevance
FUTURE CHALLENGES
OCEANOGRAPHY IN THE XX & XXI CENTURIES
"CONTOURITE REVOLUTION" (1966-present day)
EXPLOSION ("BOOM") OF MARINE INFORMATION (1968-1983)
"TURBIDITE REVOLUTION" (1950-1968)
FIRST HALF OF XX CENTURY
ONSET OF MARINE SCIENCES
SCIENTIFIC KNOWLEDGE OF XIX CENTURY
2020
2010
2000
1990
1980
1970
1960
1950
1900
1870
PRESENT SITUATION
Continental margins in a global context
Biochemical processes
Bedforms - current velocity matrix
(Stow et al., 2009)
1st specific books about contourites
(Stow et al., 2002; Viana & Rebesco, 2007; Camerlenghi & Rebesco, 2008)
Contourite Depositional System (CDS)
(Hernández-Molina et al., 2003)
Depositional and erosive features & processes
Sedimentary systems dynamic interaction
Traction sedimentary structures
(Shanmugan et al., 1993)
Ocean "Conveyor Belt" Theory
(Broecker, 1987, 1991)
1st Classifications of contourites drifts
(McCave & Tucholke, 1986; Faugères et al., 1999)
1st Sedimentologic characterizations of contourites
(Stow & Lovell, 1979; Ghontier et al., 1984)
Gravity processes & their deposits
Deep-water clastic deposits classifications
Fine grained turbidites
Facies models for turbidites
1st mass wasting deposits classifications
Submarine fans
Tectonic + sedimentation
Contourites
(Heezen et al., 1966; Hollister & Heezen et al., 1972)
Fluid physics
Bouma Sequence (1962)
Turbidites
(Kuenen & Migliorini, 1950)
1st Deep-water thermohaline circulation models
(Stommel, 1957)
Bottom nepheloid layers
(Jerlov, 1953)
JOIDES RESOLUTION (1983)
1978 HEBBLE Project
(Hollister et al., 1980)
GLOMAR CHALLENGER (1968-1983)
1963 - JOIDES
New IODP
2013
IODP
2003
ODP
1983
DSDP
1968
DRILLING PROGRAMS
DEEP SEA
MARION DUFRESNE (MD) Expeditions
1995
+ RSMAS (Univ. Miami)
CHIKYU (2005)
HIGH/RESOLUTION SEISMIC & SEQUENCE STRATIGRAPHY
Seismic oceanography
ROVs
3D-Seismic
Generalised use of swath-bathymetry systems
TECHNOLOGICAL DEVELOPMENT
SEQUENCE STRATIGRAPHY
Increase on the knowledge of marine sediments distribution, climatic, sea-level & palaeoceanographic changes
Explosion of marine information
SEISMIC STRATIGRAPHY
Deep-water oil & gas exploration and discovery from mid to late 1970s
1973 / 1979 Oil Crisis
Spectacular increase on the knowledge of morphology, geological structures & deposits
1960- PLATE TECTONIC REVOLUTION
Generalised use of geophysics marine systems
Development of morphologic studies within marine basins (B.C. Heezen)
Application of magnetic & gravimetric systems in marine environments
1928 - Beginning of application of seismic systems in marine environments
1912- CONTINENTAL DRIFT (A. Wegener)
1949 - Lamont-Doherty Geological Observatory (NY)
ALBATROS Expedition (1947-1948)
1st Deep submarine photographs
(Menard & Heezen contributions)
1st evidence of deep-currents over the sea-floor
(Wust, 1936)
1930 - Woods Hole Oceanography Institution (Massachusetts)
DISCOVERY Expeditions (1925-1934)
METEOR Expedition (1925-1927)
1908- Systematic sedimentology (Sorby)
1903 - Scripps Institution of Oceanography (Univ. California)
LARGE PERIOD OF TIME WITH DATA ACCUMULATION, BUT WITHOUT NEW PARADIGMS
FRAM Expedition (1893-1896)
Pelagic sediments
1893- Marine environments & Ecology
1891- Murray & Renard
Deep Sea Deposits
HMS CHALLENGER Expedition (1872-1876)
BEAGLE Expedition (1832-1836)
Sir Charles LYELL (1830-1872)
Laurent LAVOISIER (1743-1794)
James HUTTON (1726-1797)
THE BEGINNING OF OCEAN EXPLORATION

◀ **Fig. 8** Sketch showing the recent evolution of knowledge on contourite processes and products in the very general context of oceanography and marine geology development, including the future potential challenges. Only those four American institutions are shown that joined together to develop the JOIDES program and the DSDP, but of course many others were internationally involved in this field of research (adapted from Stow 1985, 1986; Vera 1989; Stow et al. 1996)

found are identified. The authors provide evidence proving that the role of bottom currents in shaping continental margins and abyssal plains has to date been generally underestimated. (2) Brackenridge et al. (2011) for the first time attempt to place contourite depositional systems firmly within a sequence stratigraphic framework, based on the detailed examination of over 20 CDSs worldwide. They also present a novel view of how sea-level variation influences bottom-current generation and intensity. Two new preliminary sequence stratigraphic models are proposed (comprising both downslope and alongslope processes), where bottom-current activity is markedly more vigorous during times of sea-level highstand or lowstand.

Typically, a CDS has a marked basal discontinuity that represents the onset of bottom-current activity along the slope, being commonly related to the opening or deepening of an *oceanic gateway* due to long-term plate-tectonic evolution, and/or to large-scale paleoceanographic changes associated with climate change. Usually, the discontinuity represents a truncation surface, and/or a change in the style of the continental margin stacking pattern. In the current volume, Estrada et al. (2011) characterize the Messinian top surface of the Alboran Basin in detail, identifying a huge erosional channel that originated from the direct impact of Atlantic water inflow during the Zanclean flooding due to the opening of the Gibraltar gateway. They recognize two major inflow phases, the circulation pathways and local variations in erosive capacity being controlled by the regional basin topography and the presence of local obstacles.

Five articles relate to the study of *depositional contourite features* associated with large contourite drifts, which represent good examples of how these can be used for the reconstruction of paleoceanographic changes, and for the decoding of major control factors in basin evolution such as climate, sea-level variations, tectonics, and sediment input: (1) Llave et al. (2011) report novel findings on the *Pliocene-Quaternary* history of the northern Gulf of Cadiz margin, and the spatiotemporal evolution of the associated contourite depositional system. Major seismic units in the contourite drifts generated by the MOW are identified and the tectonic activity is evaluated. (2) Vandorpe et al. (2011) provide evidence for shallow-water *Pliocene-Quaternary* contourite drifts on the SW shelf and the shelf edge off Mallorca, ascribed to the Balearic Current. They suggest tectonic control of water circulation and drift geometry, as well as a pronounced cyclicity in deposition ascribed to climatic and eustatic fluctuations. (3) Gruetzner et al. (2011) studied the Valentin Feilberg contourite terrace along the southern continental margin of Argentina. Some variations and intensification periods in deep-water current effects are described from *Late Miocene to Recent* times, due to the influence of Antarctic Bottom Water and Circumpolar Deepwater. (4) Nielsen et al. (2011) recognize a contourite drift complex of *Middle Miocene to Recent* age in the southeastern Davis Strait and the adjacent Labrador Sea slope offshore West Greenland. Changes in the prevailing deep-water current system during the *Early Pliocene* are decoded and explained. (5) Preu et al. (2011) studied a plastered drift at the southwestern exit of the Mozambique Channel along the continental margin of Mozambique off the Limpopo River. The reconstruction of the drift complex from the *Early Miocene to the Present* suggests a quasi-continuous influence of the eddy-dominated Mozambique Current and Antarctic Intermediate Water in this region.

A variety of *erosional contourite features* such as abraded surfaces, terraces, channels, moats and furrows are produced by deep bottom currents, but to date their genesis and related oceanographic processes are not well understood. Two articles focus on furrows, the findings significantly updating the existing model of furrow formation mechanisms in deep-water settings: (1) Kilhams et al. (2011) present a seismic-stratigraphic and geometric description of buried furrows discovered in a deep-water intracratonic basin of the central North Sea off the UK. An interesting model is proposed of initial pockmark crater formation, followed by bottom current-induced elongation and subsequent amalgamation of these structures to form furrows. (2) Lobo et al. (2011) reveal numerous elongated depressions identified as furrows in the Scan Basin (south-central Scotia Sea, Antarctica), generated by the Weddell Sea Deep Water. The furrows result from the interaction between bottom-current flows and tectonic features, thereby emphasizing the importance of tectonic influences on bottom-flow patterns.

Current velocity is heavily affected by frictional stresses at the seabed. Major morphologic features (seamounts, hills, mounds and banks, etc.) along ocean margins and in ocean basins are therefore highly significant as they represent *obstacles* for deep-water circulation, in many cases due to recent tectonics. When an impinging water mass interacts with the bottom relief, it is likely to develop a particular local and regional hydrodynamic signature (cores, branches, vortices, local turbulence, internal waves, helicoidal flows, vertical columns, etc.) that controls the dominant sedimentary processes. Two studies are related to this topic, constituting good examples of how local morphology is involved in the development of contourites by influencing the circulation patterns of Mediterranean water masses: (1) Palomino et al. (2011) analyze the seabed morphology in the vicinity of the seamounts on the Motril Marginal Plateau (northern Alboran Sea), and their importance in explaining recent geological processes, in particular those that control the associated contourite depositional system. (2) Martorelli et al. (2011) show the widespread occurrence of small contourite drifts, erosional elements, and biogenic build-ups colonized by deep-water corals in the Pantelleria offshore sector close to the narrowest part of the Sicily Channel. The coexistence of a high variety of contourite features in a constrained area seems to be largely related to the peculiar bottom-current regime in complex interaction with an uneven bathymetry mainly shaped by tectonic and volcanic activity.

Specific *contourite facies* have been described by numerous authors, but a revision of present facies models appears overdue in the light of new evidence from ancient outcrops and modern marine sediments, and their understanding in terms of bottom-current processes and variability. Two articles, one dealing with a modern situation, the other with an ancient example, focus on analyzing contourite facies: (1) Bozzano et al. (2011) present an interesting case study describing sedimentary contourite facies based on cores recovered from the northern continental slope of Argentina. Gravel-rich, sandy-silty and muddy contourites, as well as hemipelagic facies were identified, suggesting that deposition was controlled by both sea level, the depth range of Antarctic water masses, climate, and windborne supply of terrigenous material. (2) He et al. (2011) report evidence for internal-wave and internal-tide control of deposits in the Middle Ordovician Xujiajuan Formation of the Xiangshan Group, Ningxia (China). These ancient contourites reflect traction-current action where the laminae of the bidirectional and unidirectional cross-bedded units tend to dip either opposite to or at a large angle to the regional slope.

Contourite facies are commonly intensively bioturbated, and *ichnological analysis* has proved to be a valuable tool for identifying deep-water circulation changes. In this context, Rodríguez-Tovar and Uchman (2011) carried out an ichnological analysis of the Cenomanian-Turonian boundary interval in the western Tethys, demonstrating the usefulness of trace fossils in the characterization of minor-scale environmental changes in both deep-water dynamics and benthic habitats.

Several factors (e.g., sedimentation rates, hiatuses, bioturbation, compaction, cementation) can cause discontinuities in the sedimentary record. Proxies in cyclostratigraphic analyses of contourite sediments (e.g., grain-size parameters, color and Fe records, magnetic susceptibility, GRAPE density, and chromaticity) can record the discontinuous character caused by such factors. *Innovation and new methods* would therefore strongly boost future contourite research, the contribution by Pardo-Iguzquíza and Rodríguez-Tovar (2011) demonstrating that the implementation of the Lomb-Scargle periodogram can be a powerful tool in recognizing Milankovitch and sub-Milankovitch (centennial-to-millennial scale) signals related to paleoclimatic/paleoceanographic changes. The authors consider the method useful for contourite studies because it gives a higher resolution than the derivation of even time series by interpolation, or by considering an uneven time series as being even if the average sampling interval is assumed to be equal to the mean of the interdistances between the data.

Future challenges

The precise nature of deep-water processes and the contourites thereby deposited is still poorly understood, both in the deep ocean basins and along their margins. The ultimate decoding will undoubtedly yield information that will be of fundamental importance to the earth and ocean sciences. In the near future, new advances in the field of slope-contourite studies are anticipated through application of new technologies, including advanced geophysical techniques, submersibles, autonomous remotely operated vehicles (AROVs), sediment coring, ocean drilling (IODP), and accompanying land investigations. The availability of increasingly higher-resolution multibeam bathymetry, seismic geomorphology, seismic oceanography, and 3-D seismic technology, and the expansion of deep-water exploration by oil companies (Viana et al. 2007; Viana 2008) and academic institutions all promise a proliferation of spectacular new discoveries about contourite deposits and associated features (Fig. 8), their morphology, stacking patterns, facies, and their relations with other shallow and deep marine and glacio-marine depositional systems.

The results of new discoveries presented in the contributions both at the international congress on *Deep-water Circulation: Processes & Products* (see Hernández-Molina et al. 2010), and in this special issue of Geo-Marine Letters have been instrumental in defining some major short-term goals and in identifying a number of important topics for future research. Each offers a clear perspective of this intriguing exploration, and a glimpse into the formation and evolution of our oceans, past and present. These topics for future research can be arranged into three main groups (Fig. 8).

Geology and physical oceanography

An important future challenge is the achievement of close collaboration between geologists and physical oceanographers in multidisciplinary studies. Only then can our understanding of deep-water processes and products advance decisively. A major objective for future congresses on *Deep-water Circulation: Processes & Products* should

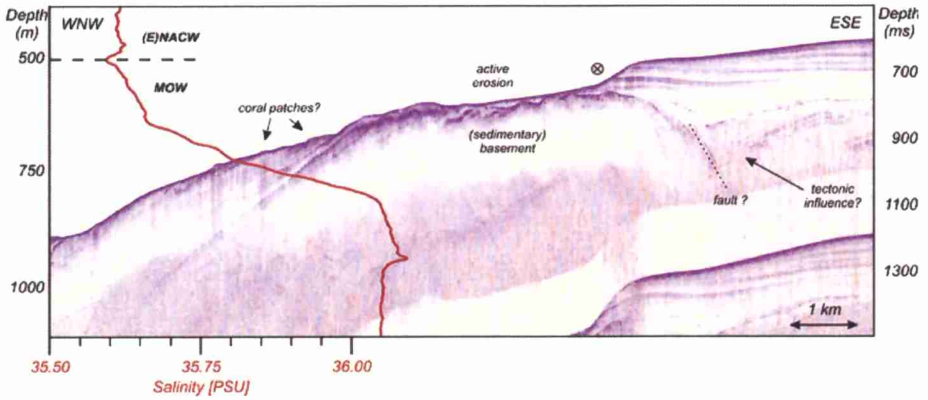


Fig. 9 High-resolution single-channel sparker profile from the Cape Ortegal continental margin, combined with the salinity profile of CTD cast B0914a-CTD01 (down to 1,500 m water depth) acquired during R/V Belgica campaign ST0914a, May 2009 (courtesy of EC FP7 IP HERMIONE Project, grant agreement no. 226354). The interphase between water masses is shown, and possible depositional and erosional action related to that interface can be distinguished. *MOW* Mediterranean Outflow Water, *NACW* North Atlantic Central Water

therefore be the involvement of the physical oceanography community in the ongoing multidisciplinary research. Several key aspects arise:

- To gain a more detailed understanding of the circulation of deep water masses, including the flow of bottom currents around submarine obstacles, their flow behavior, variability, and their role in the construction of drifts and bedforms: local physical oceanographic studies would be essential for a better understanding of the processes, their simulation, and their modeling. There are no detailed local oceanographic data on bottom currents along the seafloor in most of the areas studied to date, especially where erosional contourite features are present.
- Deep-water processes related to flow phenomena such as internal waves, tides, benthic storms, eddies, and vortices are still poorly understood but are thought to be capable of generating depositional and erosional features in deep-water environments. Future research on contourites, using new and better techniques, should focus on a more detailed documentation and comprehension of these processes, their variability, imprint, and importance in the sedimentary/geological register.
- The detection and characterization of intermediate and deep nepheloid layers, which are often bound to water-mass interfaces (Fig. 9), and benthic boundary layers are currently under investigation and discussion. Nepheloid layers are frequently triggered and distributed by water-mass interfaces due to density contrasts and associated phenomena (internal waves, tides, etc.). The detection of such interfaces, and records of their variability in space and time, would be important targets for future multidisciplinary research in order to unravel the sedimentological, biological, and oceanographic processes associated with them.

Ancient and modern contourites

An integration of data on modern and ancient contourites, deposits, and features is needed for a comprehensive understanding of contourite formation. The resolution of architectural elements of CDSs studied in ancient rock records has long been an order of magnitude lower than for those observed in modern seas and oceans. Such data integration is expected to result in new insights into fundamental mechanisms and processes. Important aspects include:

- Careful revision of existing facies models, both for ancient and modern marine deposits, including their association with other deep-water sedimentary facies, their occurrence and recognition in modern and ancient depositional sequences (Fig. 10), and their understanding in terms of bottom-current processes and variability at both local and global circulation scales.
- It is now clear that the formation of sandy contourites is a distinct possibility, although it would be dependent on numerous factors: (1) the availability of sand-sized sediment; (2) bottom waters reaching sufficient velocities for the transportation of sand to the site of deposition; (3) favorable basin morphology; (4) prolonged time periods over which these processes operate. Elucidation of where contourite sands are likely to be deposited is required, along with robust facies and seismofacies models for their identification in outcrop and in the subsurface.
- Characterization of the depositional and erosional elements associated with individual contourite drifts, hiatuses, and with more complex contourite depositional systems, taking into consideration that such contourite products can be generated both instantaneously and in the course of steady processes. Higher-velocity

events in water mass circualtion are discontinuous and strongly related to benthic storms and large eddy formations.

- Comparisons between bottom-current and gravity flow processes and products, including their distinction from hemipelagic/pelagic sedimentation, will be of vital importance because many oceanic sedimentary deposits are the products of such processes. Several key topics arise: (1) The study of mixed turbidite/contourite systems and shallow-water contourite systems should be a specific target of future research, as very recently proposed by Faugères and Mulder (2011), because these systems are not well understood in terms of depositional processes, sedimentary facies, and geometry. (2) Relationships between deep-water circulation, gravity flows, and submarine slope stability: slope stability may be affected by fine-grained, low-permeability, high pore-water content contourites facilitating the formation of overpressurized gliding planes when rapidly loaded, or when their rigid biosiliceous microfabric collapses due to diagenetic alteration. (3) Detailed contourite drift analysis is an excellent sedimentological tool to decode global changes in paleocirculation and paleoclimate. The enhanced accumulation rates of contourite drifts, in comparison with condensed pelagic deposits, make them attractive for high-resolution paleoceanographic reconstructions serving to better understand the role of the oceans in the global climate system. The following paleoceanographic issues could be addressed in contourite research: ocean circulation during past climatic periods; ocean climate variability; abrupt climatic changes; climatic transitions; global warming and its potential impact on bottom-current circulation; numerical modeling of climate; and proxies for climatic reconstruction from contourite deposits. Approaches in this research need to be cautious, because the contourite sedimentary record is not continuous over time (sometimes discontinuities represent important hiatuses), and interpretations are generally based on the knowledge gained from modern processes and circulation models that do not necessarily apply in the past.

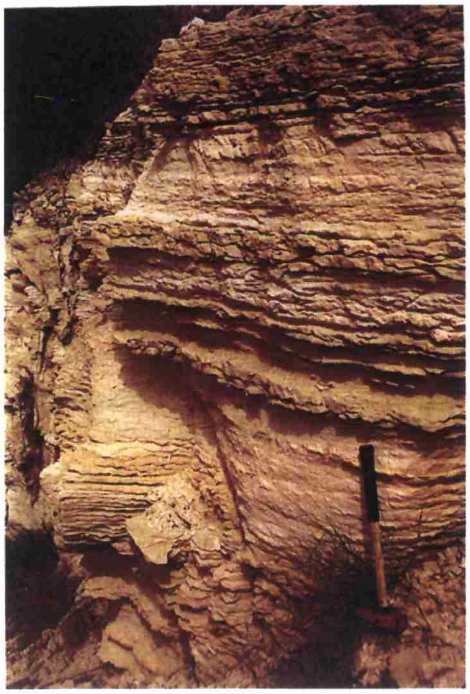


Fig. 10 Ancient contourite outcrops of the Lefkara Formation, Cyprus (extracted from Stow et al. 2002)

Contourites, geohabitats, and economic relevance

- Determination of how the nature of bottom-water flow drives deep-water ecosystems, especially the seabed fauna on an interbasin scale, and benthic communities associated with hard grounds such as cold-water coral ecosystems: future *Deep-water Circulation: Processes & Products* congresses need to involve the benthic biology community in contourite research.
- Assessment of the economic relevance of contourite deposits in terms of fisheries, mineral (Fe-Mn nodules, crusts) and energy (oil, gas, shallow gas, hydrates, etc.) resources: although hydrocarbon exploration plays an important role in this domain, the major issues and playgrounds must be identified and defined by basic research. This applies, in particular, to the unequivocal sedimentological characterization of contourites. Contourite sand sheets or reworking of unconfined, pre-existent sand-rich deposits are the best prospect because they represent laterally extensive sand bodies with good connectivity, especially where clean deep-sea sands are formed by high-velocity flows. Fine-grained contourites play an important role as permeability barriers (seals) in conventional oil-rich accumulations, but also in unconventional settings such as characterized by shale gas and gas hydrates; their identification and mapping would thus have a strong economic impact. A strengthened collaboration between academia and oil companies is essential in future contourite research.

Reviewers

The guest editors and authors are grateful to the following 55 reviewers (in alphabetic order) who contributed to the high scientific quality of this special issue by numerous constructive comments and useful suggestions:

F. Bache (GNS Science, Ocean Exploration, Lower Hutt, New Zealand), A. Barnolas (Instituto Geologico y Minero de España, Madrid, Spain), R. Bøe (Geological Survey of Norway, Trondheim, Norway), R. Brackenridge (Edinburgh Collaborative of Subsurface Science and Engineering (ECOSSE), Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh, UK), M. Bruno (Applied Physics, University of Cadiz, Spain), C. Campbell (Bedford Institute of Oceanography, Geological Survey of Canada, Dartmouth, Canada), D. Casas (Instituto Geológico y Minero de España, Madrid, Spain), C.M. Chiessi (Center for Earth System Science, National Institute for Space Research, Sao Paulo, Brazil), J.M. de Gibert Atienza (Departament d'Estratigrafia, Paleontologia i Geociències Marines, Universidad de Barcelona, Spain), M.T. Delafontaine (Senckenberg Institute, Wilhelmshaven, Germany), G. Ercilla (Departamento de Geología Marina, Instituto de Ciencias del Mar, CMIMA-CSIC, Barcelona, Spain), C. Escutia (Instituto Andaluz de Ciencias de la Tierra, Granada, Spain), J.-C. Faugères (Département de Géologie et Océanographie, Université Bordeaux 1, Talence, France), B.W. Flemming (Senckenberg Institute, Wilhelmshaven, Germany), S. García-Gil (Geociencias Marinas, Facultad de Ciencias del Mar, Universidad de Vigo, Spain), M. García (Scott Polar Research Institute, University of Cambridge, UK), J. Gil (Área de Estratigrafía, Departamento de Geología, Universidad de Alcalá, Madrid, Spain), E. Gonthier (Département de Géologie et Océanographie, Université de Bordeaux 1, Talence, France), P. Giresse (Centre de Formation et de Recherche sur les Environnements Méditerranéens (CEFREM), Université de Perpignan, France), F.J. Hernández-Molina (Facultad de Ciencias del Mar, Universidad de Vigo, Spain), J. Howe (Scottish Association for Marine Science & UHI Millennium Institute-Dunstaffnage Marine Laboratory, Oban, UK), V.A.I. Huvenne (National Oceanography Centre, Southampton, UK), M. Ito (Earth Sciences, University of Chiba, Japan), P. Knutz (Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark), A. Koschinsky (School of Engineering and Science, Jacobs University, Bremen, Germany), J.S. Laberg (Department of Geology, University of Trømsø, Norway), S.M. Lebreiro (IGME-Geological and Mining Institute, Unit Global Change, Madrid, Spain), E. Llave (Instituto Geológico y Minero de España, Madrid, Spain), F.J. Lobo (Instituto Andaluz de Ciencias de la Tierra (IACT, CSIC), Facultad de Ciencias, Granada, Spain), L. Löwemark (Department of Geology and Geochemistry, Stockholm University, Sweden), J. Lutjeharms (Department of Oceanography, University of Cape Town, South Africa), J. Martin-Chivelet (Departamento Estratigrafía, Facultad de Ciencias Geológicas, Universidad Complutense, Madrid, Spain), E. Martorelli (Istituto di Geologia Ambientale e Geoingegneria (IGAG)-CNR, Rome, Italy), A. Mena (Xeociencias Mariñas e Ordenación do Territorio, Facultad de Ciencias do Mar, Universidad de Vigo, Spain), T. Nakajima (National Institute of Advanced Industrial Science and Technology (AIST), Geological Survey of Japan, Tsukuba, Japan), T. Nielsen (Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark), D.J.W. Piper (Bedford Institute of Oceanography, Geological Survey of Canada, Dartmouth, Canada), L. Pomar (Universitat de les Illes Balears, Ciencies de la Terra, Palma de Mallorca, Spain), M. Rebesco (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Sgonico, Italy), M. Rogerson (Department of Geography, University of Hull, UK), M. Roveri (Dipartimento di Scienze della Terra, Università degli Studi di Parma, Italy), R.A. Scasso (Departamento de Ciencias Geológicas, Universidad de Buenos Aires, Argentina), N. Serra (Institute of Oceanography, University of Hamburg, Germany), G. Shanmugam (Department of Earth and Environmental Sciences, University of Texas, Arlington, TX, USA), M. Sprovieri (Istituto per l'Ambiente Marino Costiero (CNR), Capo Granitola, Italy), D.A.V. Stow (Edinburgh Collaborative of Subsurface Science and Engineering (ECOSSE), Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh, UK), S. Toucanne (IFREMER, Géosciences Marines, Plouzané, France), F. Trincardi (ISMAR-CNR, Bologna, Italy), G. Uenzelmann-Neben (Alfred-Wegener-Institut (AWI), Bremerhaven, Germany), D. Van Rooij (Renard Centre of Marine Geology, Ghent University, Belgium), J.-T. Vázquez (Instituto Español de Oceanografía, Centro Oceanográfico de Málaga, Spain), J.A. Vera (Departamento de Estratigrafía y Paleontología, Universidad de Granada, Spain), A. Viana (Petrobras SA, Rio de Janeiro, Brazil), R. Violante (Argentina Hydrographic Survey, Buenos Aires, Argentina), A. Voelker (Unidade de Geologia Marinha, LNEG, Amadora, Portugal).

Acknowledgements We thank Burg W. Flemming (Editor-in-Chief), Monique T. Delafontaine (Associate Editor), and Jubilyn Hilario (Journal Editorial Office Assistant) for their sustained support, corrections, suggestions and editorial work, all of which have greatly helped the authors to improve their papers and to meet the high quality criteria of Geo-Marine Letters. The Spanish *Comisión Interministerial de Ciencia y Tecnología* (CYCIT) supported this publication through the CTM2009-07702-E/MAR, CTM2008-06399-C04/MAR (CONTOURIBER), CTM2008-06386-C02/ANT, and CTM2009-14157-C02 (MONTERA) projects. The international congress on *Deep-water Circulation: Processes & Products*, held on 16–18 June 2010 in Baiona (Pontevedra, Spain), was organized by the following European institutions: University of Vigo (Spain), Heriot-Watt University (UK), Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS, Italy), Instituto Geológico y Minero de España (IGME, Spain), Renard Centre of Marine Geology, Ghent University (Belgium), Instituto Español de Oceanografía (IEO, Spain), Laboratorio Nacional de Energia e Geologia (LNEG, Portugal), Consejo Superior de Investigaciones Científicas (CSIC, Spain), and Edinburgh Collaborative of Subsurface Science and Engineering (ECOSSE, UK). Additional support and collaboration was received from the following organizations: University of Cadiz (UCA, Spain), National Oceanographic

Centre, Southampton (NOCS, UK), Instituto Hidrográfico de la Marina (IHM, Spain), Servicio de Hidrografía Naval (SHN, Argentina), British Antarctic Survey (BAS, UK), Alfred Wegener Institute (AWI, Germany), International Association of Sedimentologists (IAS), Consejería de Medio Ambiente y Desarrollo Sostenible (Xunta de Galicia, Spain), Centro Tecnológico del Mar-Fundación (CETMAR, Spain), Asociación de Oceanógrafos de Galicia and Sociedad Geológica de España (SGE, Spain). Finally, the congress itself was sponsored by Repsol, TGS-NOPEC, PETROBRAS, GAS NATURAL, The Partex Oil and Gas Group, SECEG SA (Sociedad Española de Comunicación del Estrecho de Gibraltar), Simrad, Esgemar SA, Geomytsa, Tecmarin, Edinburgh Collaborative of Subsurface Science and Engineering (ECOSSE, UK), Baiona Council, Turismo Rías Baixas (Diputación de Pontevedra), ORGANIZA+, Starplanning, Hotel Thalasso Atlantico, and Paradores de España.

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