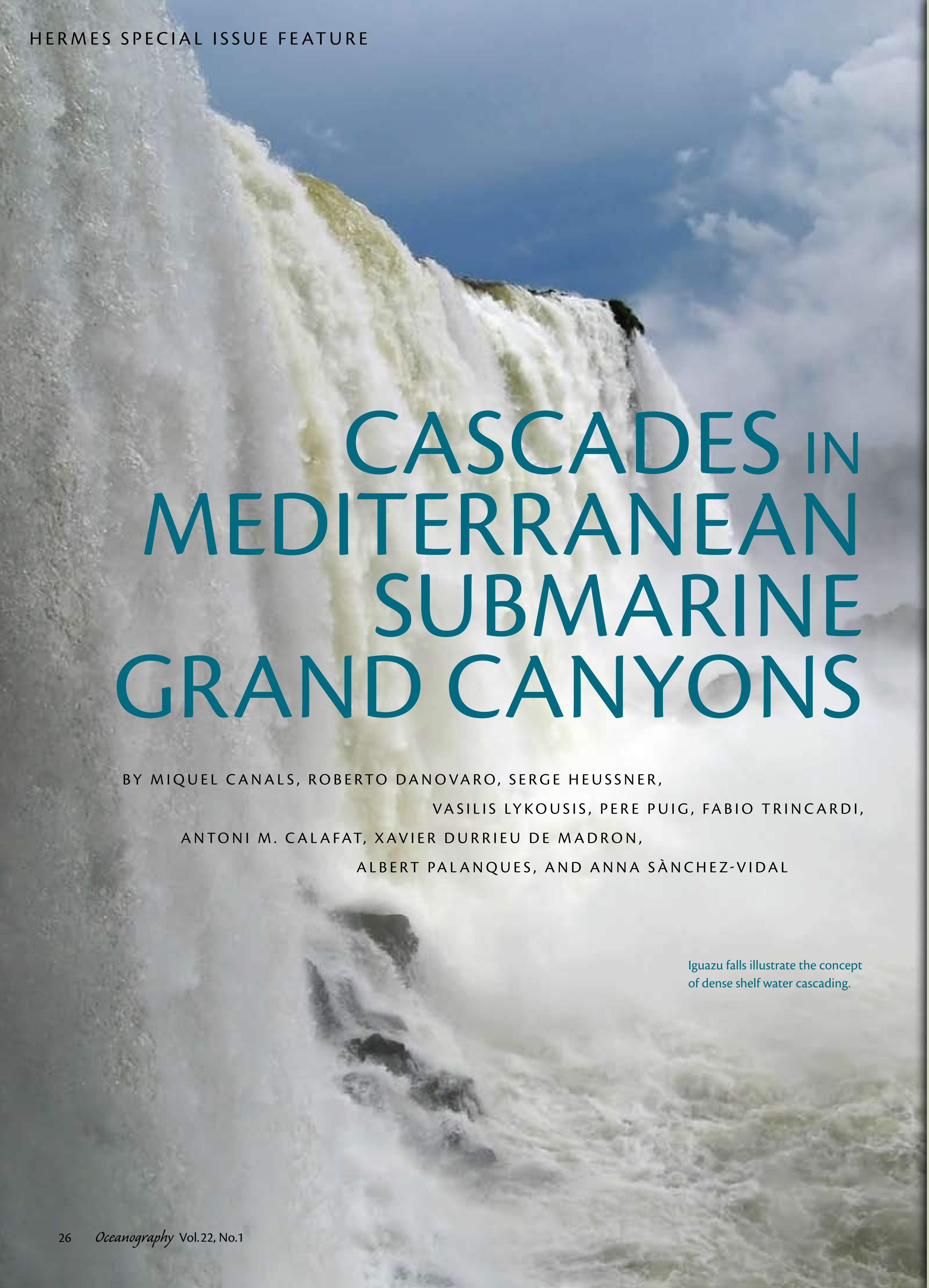
CASCADES IN MEDITERRANEAN SUBMARINE GRAND CANYONS

BY MIQUEL CANALS, ROBERTO DANOVARO, SERGE HEUSSNER, VASILIS LYKOUSIS, PERE PUIG, FABIO TRINCARDI, ANTONI M. CALAFAT, XAVIER DURRIEU DE MADRON, ALBERT PALANQUES, AND ANNA SÀNCHEZ-VIDAL



Iguazu falls illustrate the concept of dense shelf water cascading.

ABSTRACT. Continuous monitoring of water-column and near-bottom hydrosedimentary processes in the Mediterranean Sea over the last 15 years has resulted in a novel view of the functioning of this land-locked sea. Destratification of the water column and fast, dense, organic-matter-rich, and sediment-laden near-bottom currents occurring in late winter to early spring efficiently transfer matter and energy from the continental shelf and the upper ocean layers to the deep basin. These currents, known as dense shelf water cascading (DSWC), have been repeatedly measured by moored instrumentation during concurrent field experiments in the Gulf of Lion (northwestern Mediterranean Sea) and the Adriatic Sea (central Mediterranean). Physical oceanography observations made in the eastern Mediterranean in the early 1990s, together with observations of large-scale bed forms on the shelf floor, indicate that this phenomenon also occurs in the Aegean Sea (eastern Mediterranean) where it impacts the neighboring deep basins.

The source areas of DSWC are the northernmost shelves of the Mediterranean Sea. Due to their location and inland topography, they are more exposed to the cold, persistent, intense northerly winter winds that cool shelf (and offshore) waters enough to make them denser than underlying waters, thus triggering their sinking once a density threshold is reached. It has also been observed that low river discharge on these shelves favors late winter-early spring cascading as shelf waters become denser than they would be under high river discharge. While offshore convection cells bring only "blue water" to the deep basin, DSWC events carry huge amounts of organic and inorganic substances as they scour the shelf and slope seafloor while sinking. Cascades of DSW may last for several weeks, and cascading waters sink continually deeper until they find their density equilibrium level, which changes from year to year. It has been observed that particularly intense DSWC events that carry shelf waters to the deepest parts of the western Mediterranean basin occur at subdecadal frequency.

The influence of seafloor topography on the path followed by DSWC is best illustrated by submarine canyons. At specific locations, canyons are the main conduits for the cascading shelf waters, and from this developed the concept of "flushing submarine canyons." If the volume of cascading waters in a given event is too large, the canyons may be unable to accommodate it, and, therefore, those waters may escape from the canyons—especially where they are less entrenched. It has been also observed that DSW may cascade as sheet flows, sweeping continental slopes along tens of kilometers or more before spreading over the deep basin.

The findings reported in this paper are just the tip of the iceberg in terms of the consequences of DSWC on deep-water mass formation and on the deep ecosystem of the Mediterranean Sea. As cascades often occur simultaneously with spring phytoplankton blooms in the various Mediterranean regions, there is no doubt that their role as a natural mechanism for carbon sequestration from the shallow ocean layers will demand the attention of the scientific community in the coming years.

INTRODUCTION

Ecosystems in the Mediterranean, a land-locked sea, are strongly influenced by inputs from the landmasses surrounding it. Matter and energy fluxes from continental sources impact even the deepest Mediterranean basins. Continent-to-ocean transfers are mediated by continental shelves and slopes, where a number of complex hydrosedimentary and biogeochemical processes occur. The understanding of continent-to-ocean transfers is the main goal of "source to sink" (S2S) studies, a new multidisciplinary branch of marine science that has made noticeable progress in the last few years in various regions of the world's ocean, including the Mediterranean Sea. The aim of this paper is to present some of the most recent scientific findings on the drivers of the deep Mediterranean ecosystem, with a focus on submarine canyons and adjacent open slopes that are affected by cascades of dense shelf water (Figure 1).

According to *Wikipedia*, submarine canyons are "steep-sided valleys on the sea floor of the continental slope." This definition is correct in essence but fails to note that submarine canyons often deeply incise the continental shelf at their upper ends and that some of them extend far over the continental rise and abyssal plain in the form of deep-ocean channels at their lower ends. Canyons are thus highly efficient conduits for the transport of water, chemicals, and sedimentary particles from coastal areas to the deepest ocean basins. This "shallow to deep" channeling effect is reinforced in submarine canyons opening offshore large river mouths, where their heads can directly trap substantial amounts of riverine material.

Large submarine canyons with their heads located close to the shore are particularly well placed to funnel sinking waters that may form on the shelf. Dense shelf water cascading (DSWC), a type of current that is driven solely by a seawater density contrast, is a seasonal phenomenon that results from the formation of dense water by cooling and/or evaporation. Cascading occurs on both high- and low-latitude continental margins and can be locally favored by decreased river discharge, which reduces the buoyancy of the uppermost ocean layer (Canals et al., 2006).

Submarine canyon size is important as it controls the volume of cascading waters that can be accommodated inside the canyon. Canyon size is highly variable, ranging from deeply entrenched valleys hundreds of kilometers long to shallower valleys a few kilometers long. Like other landscape and seascape features, submarine canyons evolve, modifying their shapes and sizes over millennial time scales. When a canyon loses its sediment transport capacity, it normally degrades and sooner or later becomes buried. In contrast, if a canyon maintains or increases its sediment capturing ability and transport efficiency, it normally enlarges, both laterally and longitudinally, eventually forming a rather complex submarine drainage network.

The presence or absence of submarine canyons along a continental margin is relevant as it determines the paths and spreading conditions for cascading waters. Therefore, the geological history of margins should also be taken into account to understand the occurrence of submarine canyons. Various contrasting hypotheses have been formulated to explain the origin of submarine canyons. The "consensus" nowadays—if we can use such a term—is that each submarine canyon or set of submarine canyons has its own, independent evolutionary history. This statement was well expressed in the title of the seminal paper by Shepard (1981): "Submarine canyons: Multiple causes and long time

Miquel Canals *(miquelcanals@ub.edu) is Professor, Universitat de Barcelona, Facultat de Geologia, Departament d'Estratigrafia, Paleontologia i Geociències Marines, GRC Geociències Marines, Barcelona, Spain.* **Roberto Danovaro** *is Director, Department of Marine Sciences, Università Politecnica delle Marche, Ancona, Italy.* **Serge Heussner** *is Director of Research, Centre de formation et de recherche sur l'environnement marin (CEFREM), CNRS-Université de Perpignan Via Domitia, Perpignan, France.* **Vasilios Lykousis** *is Research Director in the Institute of Oceanography, Hellenic Centre for Marine Research, Anavissos, Greece.* **Pere Puig** *is Research Scientist, Institut de Ciències del Mar, Consejo Superior de Investigaciones Científicas (CSIC), Barcelona, Spain.* **Fabio Trincardi** *is Senior Research Scientist, Istituto di Scienze Marine-Consiglio Nazionale delle Ricerche (ISMAR-CNR), Bologna, Italy.* **Antoni M. Calafat** *is Senior Lecturer, Universitat de Barcelona, Facultat de Geologia, Departament d'Estratigrafia, Paleontologia i Geociències Marines, GRC Geociències Marines, Barcelona, Spain.* **Xavier Durrieu de Madron** *is Research Scientist, CEFREM, CNRS-Université de Perpignan, Perpignan, France.* **Albert Palanques** *is Research Professor, Institut de Ciències del Mar, CSIC, Barcelona, Spain.* **Anna Sànchez-Vidal** *is Postdoctoral Researcher, Universitat de Barcelona, Facultat de Geologia, Departament d'Estratigrafia, Paleontologia i Geociències Marines, GRC Geociències Marines, Barcelona, Spain.*

persistence." More information on the setting and origin of submarine canyons can be found in Canals et al. (2004) within the *Oceanography* special issue on "Strata Formation on European Margins: A Tribute to EC-NA Cooperation in Marine Geology," published in December 2004.

Areas of seafloor between successive submarine canyons cut into the continental slope are known as interfluves or "open slopes" and could also be affected by cascading waters that spill over the shelf break or escape from canyons. Depending on the distance from one canyon to the next and on the depth range of adjacent submarine canyons, open slopes will be wider or narrower and cover a smaller or larger bathymetric range. Open slopes in margin segments with active canyons tend to be naturally eroded by canyon enlargement processes, while open slopes in margin segments where canyon infill dominates tend to naturally merge with filling canyons to form long, continuous open slopes. Investigating both submarine canyons and nearby open slopes is the right strategy, as open slopes constitute—at least theoretically—a reference framework for submarine canyons, and vice versa.

> "INVESTIGATING BOTH SUBMARINE CANYONS AND NEARBY OPEN SLOPES IS THE RIGHT STRATEGY, AS OPEN SLOPES CONSTITUTE—AT LEAST THEORETICALLY—A REFERENCE FRAMEWORK FOR SUBMARINE CANYONS, AND VICE VERSA."

MATTER AND ENERGY TRANSFER ACROSS SUBMARINE CANYONS AND OPEN SLOPES

It has long been believed within the scientific community that submarine canyons are preferential conduits for the transfer of matter and energy from coastal areas and continental shelves to the deep ocean. However, it is only recently, over the last two decades, that both long-term and high-frequency in situ measurements (see Box 1) have provided a wealth of data illustrating the efficient and seasonally modulated export of sedimentary particles along Mediterranean margins, preferentially through submarine canyons (see, for instance, Heussner et al., 1996, 2006).

In simple terms, gravitational effects enhance trapping and downslope transport of particles within canyons compared to adjacent open slopes. To some extent, this is the same reason that water flows down along river valley axes

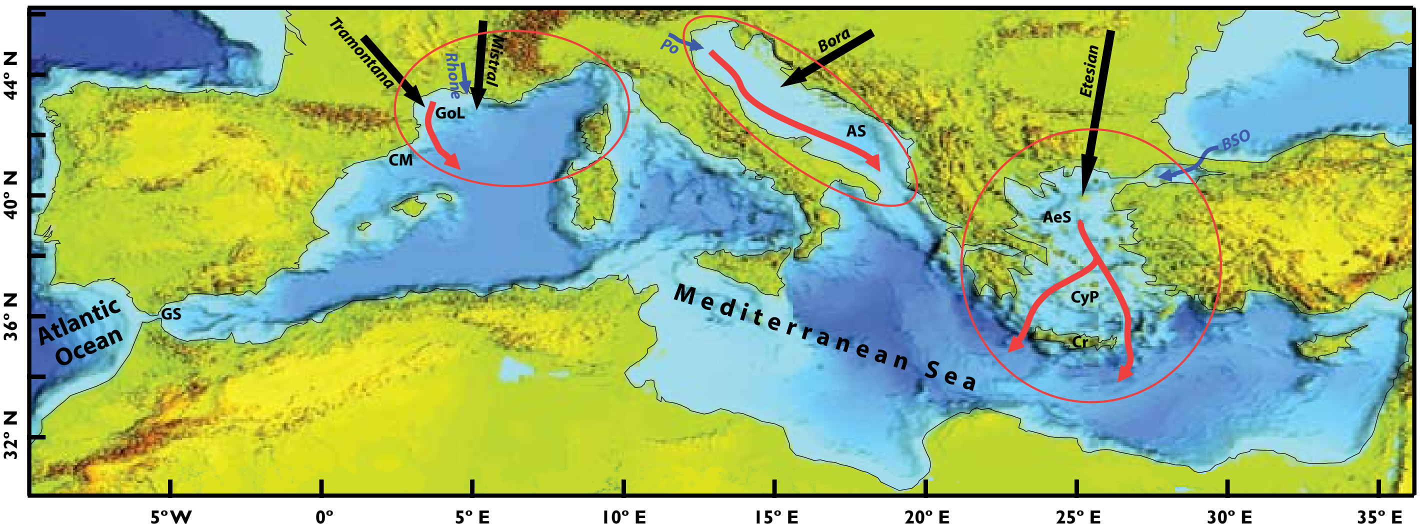


Figure 1. General map of the Mediterranean Sea and surrounding landmasses illustrating where dense shelf water (DSW) forms and the contributing factors. Red circles: Areas of dense water formation, both offshore (convection) and on the shelf (cascading). Black arrows: Northern winds. Blue arrows: Main rivers discharging freshwater on the shelves where DSW water episodically forms; the Black Sea low-salinity outflow is also indicated by a blue arrow. Red arrows: DSW paths. AeS: Aegean Sea; AS: Adriatic Sea; BSO: Black Sea Outflow; CM: Catalan Margin; Cr: Creta Island; CyP: Cyclades Plateau; GoL: Gulf of Lion; GS: Gibraltar Strait. *Drawing by J.L. Casamor*

BOX 1. MOORING TECHNOLOGY

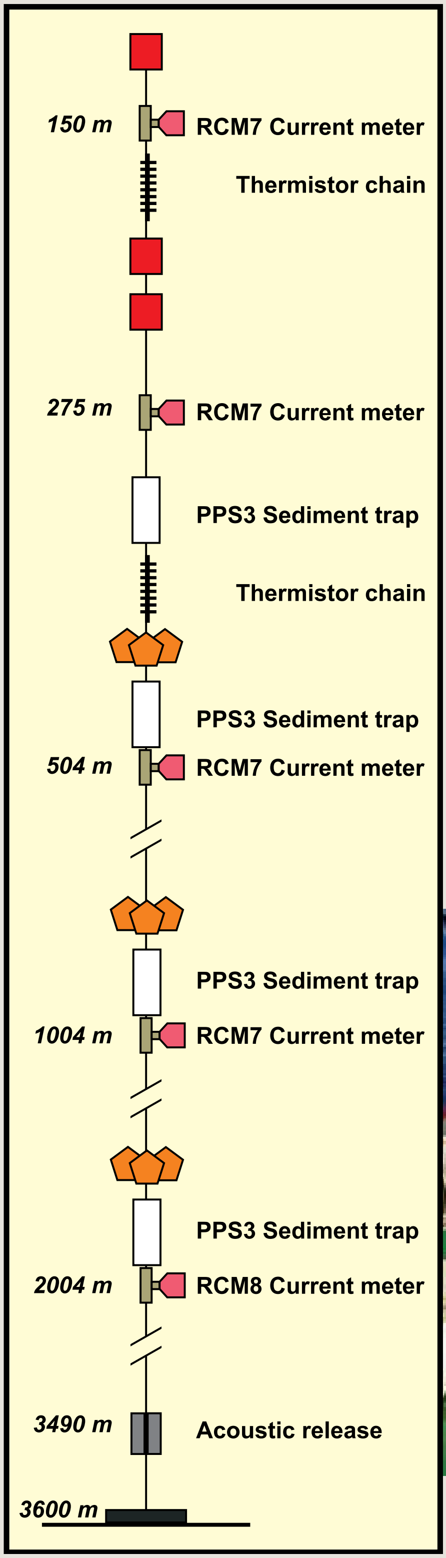


Figure B-1. Configuration of a deep-water mooring array. Unlabeled objects are flotation elements.

Since the 1970s, marine instruments that can remain submerged and operational for extended periods of time, and include control and data-logging capacity, have been developed to allow marine scientists to observe ocean conditions in many locations. These instruments, generally installed on subsurface moorings, can record data internally and be recalled to the surface by acoustic signals, providing continuous oceanographic measurements during extended deployments.

Following this approach, an important component of the methodology used to conduct studies of water and sediment dispersal in the Mediterranean Sea has consisted of continuous and simultaneous measurements (current speed and direction, temperature, conductivity, turbidity, downward particle fluxes) collected by various underwater oceanographic sensors and sampling devices installed on networks of moored arrays deployed at specific study sites, from canyon heads down to deep basins. Generally, these moorings are equipped with standard commercial instrumentation (i.e., single-point current meters with external sensors and sediment traps) arranged in pairs and deployed near the bottom, and possibly also at intermediate depths. Each mooring has an anchor weight and multiple floats to support it and keep the instruments in place, and an acoustic release that assures its recovery. An extensive network of moorings, along with data provided from coastal observatories and meteorological stations, has recently been used to characterize the occurrence of dense shelf water cascades in the Mediterranean and to quantify water and particle fluxes associated with this phenomenon.

Maintaining this type of mooring is difficult, because mooring deployments are tied to the duration of the research effort (typically three-year projects), which must include funds and ship time for their installation, refurbishment, and maintenance. This factor usually limits the length of the time series and provides only isolated snapshots of information (classically, annual records) that do not permit identification of interannual fluctuations of deep-sea oceanographic processes. In the Northwest Mediterranean, two programs break this general rule: the Centre de Formation et de Recherche sur l'Environnement Marin (CEFREM) long-term mooring deployments in the Planier and Lacaze-Duthiers submarine canyons, initiated in 1993 (see Heussner et al., 2006, for details), and the Dynamique des Flux de Matière en Mediterranée (DYFAMED, part of the French-Joint Global Ocean Flux Study [JGOFS]) site in the Ligurian Sea, initiated in 1988 (see http://www.obs-vlfr.fr/sodyf/home.htm for details). After years of continuous data collection, these long-term observatories are yielding new scientific insights that reflect the existence of important interannual/decadal oceanographic variability often correlated with large-scale meteorological parameters and/or with event-driven processes, such as the intense, dense shelf-water cascades described in this paper.

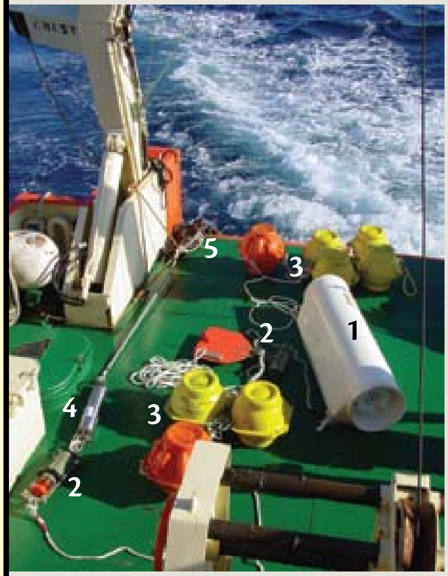


Figure B-2. Instruments ready for deployment as part of a mooring array include (1) a particle trap, (2) current meters, (3) flotation balls, (4) an acoustic release, and (5) weight.

(i.e., the topographic gradient determines flow direction and transport). However, in the ocean, the density contrast between particle-laden waters and surrounding clearer waters is much smaller than that between riverine freshwater and the surrounding air, for instance. Other processes, such as geostrophic circulation, can therefore interfere with particle transport and accumulation in the ocean. It should also be noted that sediment-laden waters can be either denser or lighter than surrounding waters (e.g., they are lighter off river mouths where they form river-influenced surface plumes; see, for instance, Arnau et al., 2004). Consequently, these particle-laden layers, often called "nepheloid layers," occupy a position in the water column according to their relative density. When they immediately overlie the seafloor, they are called "benthic nepheloid layers." All types of nepheloid layers—superficial, intermediate, and benthic—can spread over open slopes and submarine canyons, though the benthic nepheloid layers and sometimes the intermediate types tend to be more developed in submarine canyons (Durrieu de Madron et al., 1990, 1992; Durrieu de Madron, 1994).

Particles exported beyond the continental shelf to the deeper environment originate from various sources. Allochthonous sources include aeolian dust (e.g., from North African deserts), sediments and pollutants transported by rivers, particles carried in suspension from afar by mesoscale ocean currents, and sewer discharge and ship tank cleaning. Autochthonous sources include biological production, erosion and resuspension of seafloor materials by waves and currents, landslides, and anthropogenic activities such as anchoring, dredging and, especially, trawling (Palanques et al., 2001, 2006; Ferré et al., 2008). In historical times, human activities both on land and at sea have had strong indirect and direct impacts on particle concentrations in ocean waters, either by increasing the particle load released to the sea (e.g., because of agricultural development or deforestation that has increased erosion of river basins, thus adding to particle discharge at river mouths) or by decreasing it (e.g., because of river damming). Direct disturbance of the seafloor by trawlers and other activities certainly adds significant volumes of particles that remain in suspension for variable periods, depending on the intensity of the activity itself, the grain size and density of the particles, and the energy level of each specific area.

The study of matter and energy transfer across continental margins, which includes particle transfer, is not only of scientific relevance but also of the utmost interest for environmental, economic, and societal reasons. Only by understanding particle transfer in the ocean will we be able to understand how deep ecosystems are fueled, and to determine their capacity to capture and store carbon. Improving our understanding of natural carbon storage and quantifying it is one of the greatest challenges our society faces in view of ongoing global warming. Investigating particle fluxes is also important to better understand the transfer and fate of pollutant loads to the deep ocean, which affect living resources, including commercial species. It is also of interest to know how, where, and under what conditions hydrocarbon reservoirs formed in the past, which may allow better search strategies to be developed—a key issue in view of the increasing worldwide pressure on energy resources.

THE NORTHWEST MEDITERRANEAN SEA

The Catalan and Gulf of Lion margin in the Northwest Mediterranean Sea is the most densely canyoned margin segment in the entire Mediterranean basin (Figure 1). It includes > 100-km-long submarine canyons with their heads close to shore and their mouths opening into the deep basin at depths generally in excess of 2000 m (see Figures 1 and 4 in Amblas et al., 2004). Some of the most prominent canyons are, from east to west and from north to south, Petit Rhône, Sète, Lacaze-Duthiers, Cap de Creus, La Fonera, and Blanes. Of these, Petit Rhône, La Fonera, and Blanes open off large (Rhône) to medium (Ter) or small (Tordera) river mouths at present, while many others were also connected to paleo-river mouths during periods of low sea level, for instance, during the Last Glacial Maximum, 21,000 years BP (Canals et al., 2004).

A long-term monitoring experiment to study downward particle fluxes and currents was initiated in 1993 on the continental slope of the Gulf of Lion and continues today as part of the HERMES project. The objectives are to describe the spatial, seasonal, and interannual variability of flux intensity and settling-particle composition, and to analyze the role of diverse forcing factors in the control of particle exchange across the margin. To that end, for the first two years, an array of mooring lines with sediment traps and current meters (see Box 1) was deployed. With respect to general along-slope circulation, this array had extensive spatial coverage in canyons at the eastern entrance, in the middle and western exit of the gulf, at head and mid-canyon depths, and on adjacent open slopes. From late 1995 onward, this design was reduced to two arrays of instruments at the eastern entrance and western exit of the gulf. Monthly fluxes and hourly temperatures and currents were recorded at 500 m (30 meters above bottom, mab) in the canyon heads and at 1000-m (530 and 30 mab) and 500-m (30 mab) nominal depths at mid-canyon and open slope sites (Heussner et al., 2006). In addition, a high-frequency flux (HFF) experiment, including a set of nine mooring lines deployed on a 10 x 20 mile grid at depths from 300 to 1650 m, was performed during spring 1997 on the eastern continental slope of the Gulf of Lion. This experiment was designed to capture fluxes related to the annual spring phytoplankton bloom in the area in order to measure short temporal and small spatial flux variations. The final aim of this HFF experiment was to understand the importance of coupled hydrological and biological processes in the cycling of carbon in the water column (Flexas et al., 2002; Van Wambeke et al., 2002). The mooring work was complemented by a large number of oceanographic cruises using several research vessels.

Results from the first 10 years (1993–2003) show that particle fluxes in the 10^1–10^4 mg m^{-2} d^{-1} range increase along slope (particularly evident in the near bottom traps) from northeast to southwest (Lacaze-Duthiers Canyon), indicating an increased shelf export of particulate matter in the western part of the system (Heussner et al., 2006). These results were further confirmed in winter 2003–2004, when seven canyon heads in the Gulf of Lion were monitored simultaneously. In situ measurements showed that the cumulative down-canyon sediment transport in the westernmost Cap de Creus Canyon (with cumulative

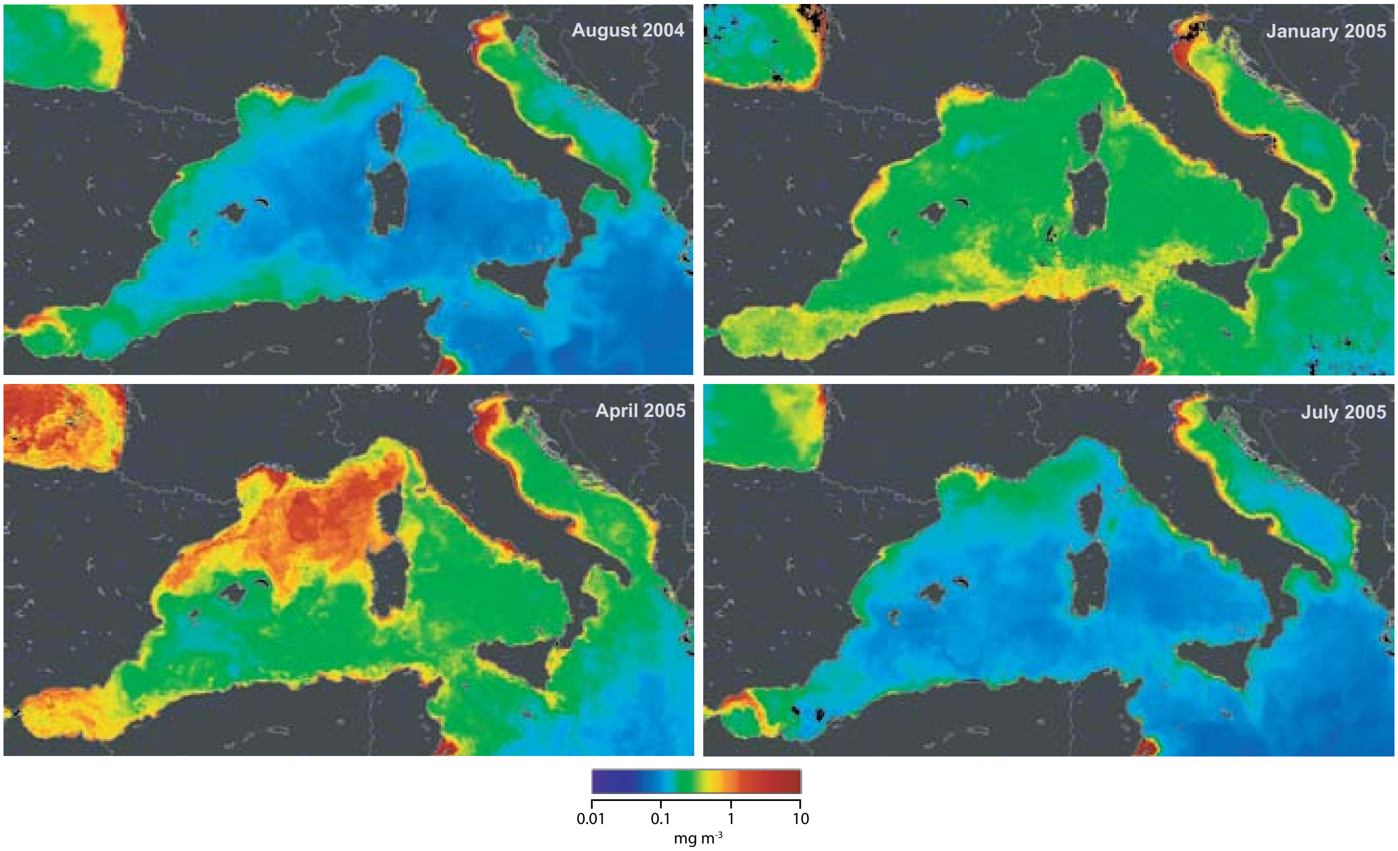


Figure 2. MODIS composites showing chlorophyll-*a* concentration in surface western Mediterranean and Adriatic waters through the annual cycle from August 2004 to July 2005 (high concentrations in red). The dense shelf water cascading (DSWC) event in the Gulf of Lion occurred from late February to late March 2005, coinciding with a spring phytoplankton bloom.

transport up to 3 t m^{-2} [t = metric tons] for the three-day-long strongest flushing outburst in late February) was one to two orders of magnitude higher than in all other canyons. The secondmost flux was in the neighboring Lacaze-Duthiers Canyon, also located at the western end of the gulf (Canals et al., 2006; Palanques et al., 2006).

During "normal" export situations, the bulk chemical composition (organic matter, carbonate, opal, and lithogenic fraction) remains rather stable, but periods of elevated fluxes tend toward values typical of continental shelf sediments. The contribution to the total flux of primary particles settling out of the overlying waters is limited, decreasing from around 50% for the lowest mass fluxes to less than 10% for the highest ones. Transfer thus appears to be essentially mediated by resuspended material (Heussner et al., 2006).

From the results collected during the multiyear experiment, it also became clear that downward particle fluxes and potential forcing parameters exhibit high seasonal variability, with higher values from late autumn to early spring (Figure 2). The most dramatic expression of seasonal variability and high flux occurs during DSWC, which, following the general pattern of shelf export, reaches its peak in the western Gulf of Lion (Figure 3). Water in the gulf is transported in a cyclonic direction by a thermohaline along-slope current and a wind-driven mean coastal circulation. Constrained by the slope current offshore and the coast inshore, most shelf water is funneled to the southwest along the narrowing shelf where it meets the Cap de Creus promontory and is thereby diverted toward the nearby canyon.

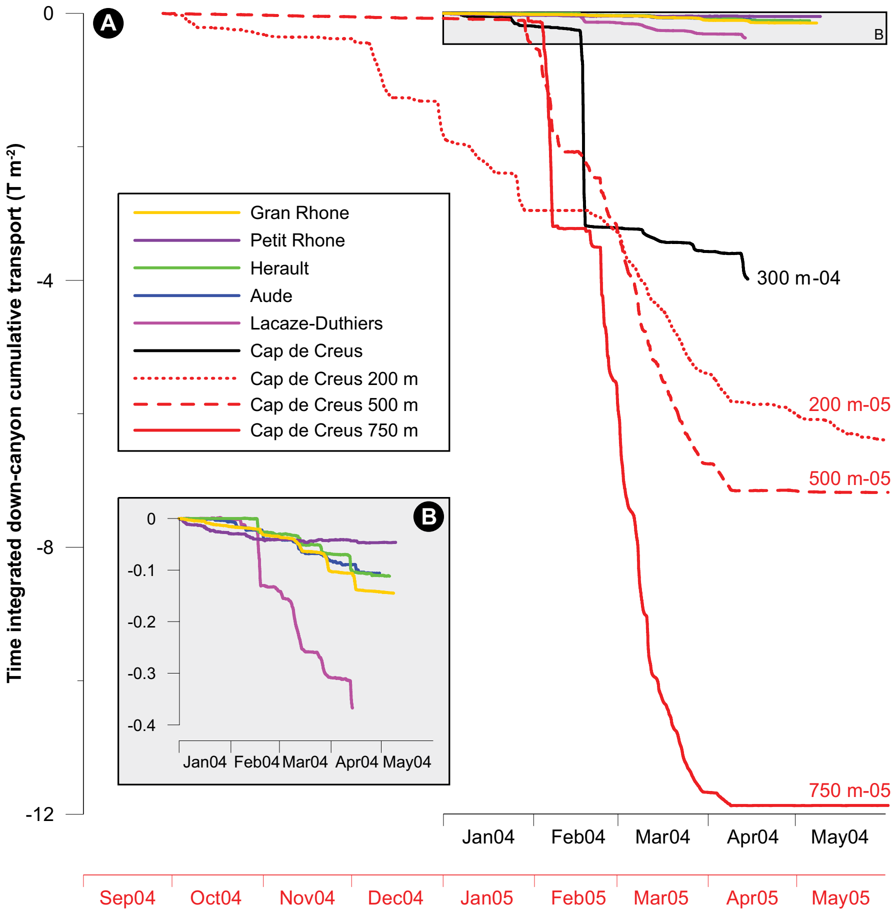


Figure 3. Time-integrated, along-canyon cumulative suspended sediment transport measured near the seabed during the cascading season. (A) The records from various water depths during the intense cascading event from late February to late March 2005 in the Cap de Creus Canyon, in red, superimposed on parallel records from canyon heads at 300-m water depth from six submarine canyons (each canyon represented by a different color) along an east-west transect in the Gulf of Lion during a mild cascading event from January to early May 2004. (B) Close-up of the January to early May 2004 records in all canyon heads but that of the Cap de Creus Canyon. Note that (A) and (B) have different vertical scales. The graphs show that in 2004 the dominant down-canyon suspended sediment transport in the Cap de Creus Canyon was two orders of magnitude higher than in all the other canyons except the Lacaze-Duthiers Canyon, where the difference was one order of magnitude. It also shows that cumulative fluxes in the Cap de Creus Canyon were three times higher in 2005 than in 2004. Canyons in the legend are ordered from east (Gran Rhône Canyon) to west (Cap de Creus Canyon) from top to bottom. Labels to the right of each Cap de Creus Canyon record indicate the water depth of the measurement and the year.

During winter months, cold and dry northerly winds cause cooling, heat loss, evaporation, and mixing of waters in the Gulf of Lion coastal and off-shelf areas. When shelf water eventually becomes denser than surrounding waters, it sinks, overflows the shelf edge, and cascades downslope until it reaches its equilibrium depth, which varies from year to year. Cascading rapidly advects dense shelf water hundreds of meters deep over the slope where it merges with dense water formed off-shelf. Continuous monitoring of temperature and currents since 1993 in Lacaze-Duthiers Canyon shows that shelf water sinks to depths of 500 m almost every winter. Cascading exhibits strong interannual variability, with intense and highly energetic events occurring at a quasi-decadal frequency, as shown by the long-term records collected in the area. In addition to cold wind intensity and persistency, buoyancy of surface waters also plays an important role as it determines the stratification of the upper ocean water masses and preconditions the formation of lighter or denser cascading waters. During the 1998–1999 and 2004–2005 abnormally cold and windy winters, also characterized by northern freshwater inputs significantly lower than average (~ 22 km^3 instead of ~ 30 km^3, mainly from the Rhône River), the buoyancy gain was reduced to a minimum. In these years, cascading water passed 1,000 m and was associated with unprecedented winter flux peaks (Canals et al., 2006).

The major DSWC episode lasted 40 days from late February to late March 2005 and consisted of a series of bursts characterized by significant temperature decreases, and by concomitant increases in down-canyon current speed, water density, and suspended sediment concentration (Figure 4). Although the size range of sediment grains collected before cascading was 2–4 μm with < 1% silt and sand, during the main cascading phase the mean grain size of the sediment caught by traps (see Box 1) deployed 30 mab in the canyon axis ranged from 31–62 μm with > 50% silt and sand (Canals et al., 2006; Puig et al., 2008). This finding indicates a highly turbulent and energetic flux that exported 12 million tons of sedimentary particles down canyon. This equals 40% of the mean annual solid discharge of all rivers opening into the Gulf of Lion!

In addition, current measurements at 5 mab revealed speeds as high as 85 cm s^{-1}, approaching those of turbidity currents. High densities and speeds give rise to DSWC with a strong entrainment capacity for loose particles from unconsolidated seafloor sediments on the shelf, canyon, and slope. The 2005 cascading event remobilized loose sand filling the canyon axis, which behaved as a "river of sand," as demonstrated by the down-canyon sliding of an entire mooring initially deployed at 500-m water depth and anchored with a 400-kg train wheel. The current meter pressure sensor indicated that the mooring slid down-canyon in multiple steps from 500–600-m depth on January 29 after the first arrival of dense shelf water to this site. The strong

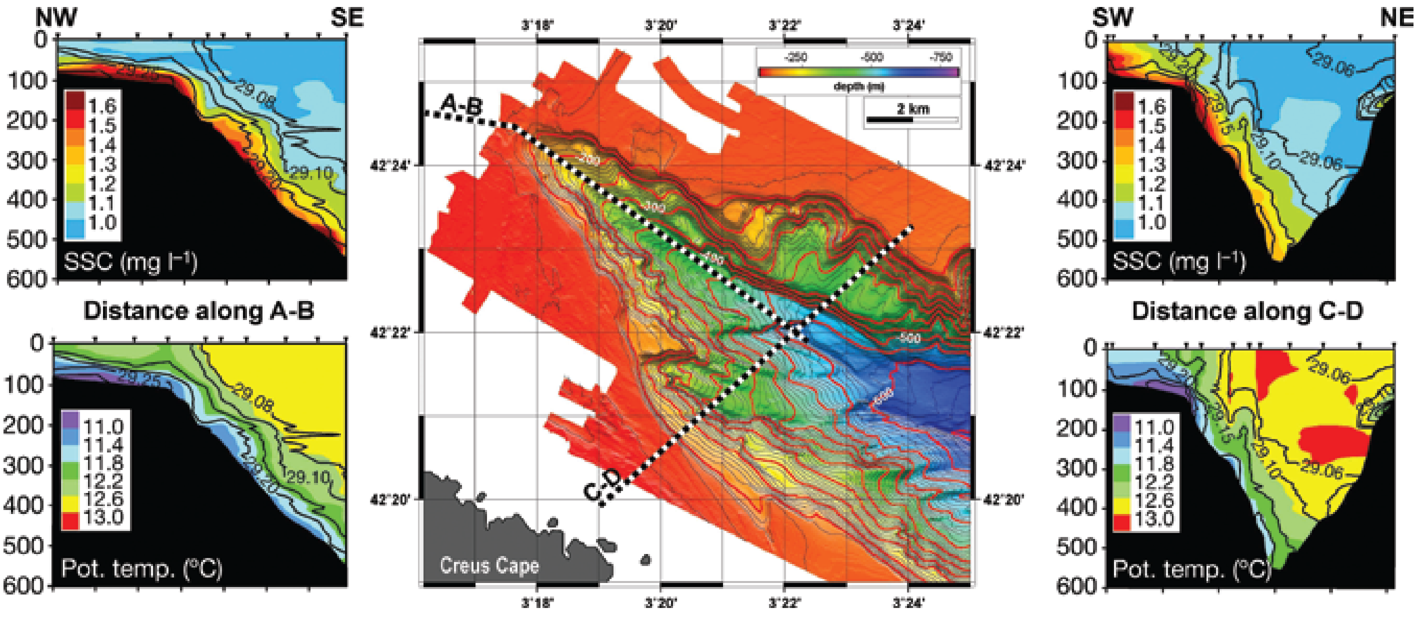


Figure 4. Potential temperature and suspended sediment concentration (SSC) sections with potential density anomalies (black contours) along and across the upper Cap de Creus Canyon for February 24–26, 2005. The DSWC plume flows down-canyon along its southern wall. Current meters measured down-canyon speeds ranging from 20–85 cm s^{-1} five meters above bottom at 750-m depth during the same period. See location of the sections in the central multibeam bathymetry map. *Modified from Canals et al., 2006*

currents presumably dislodged the anchor weight and dragged the mooring 3 km away from its original position. The fishermen who accidentally caught the displaced mooring noticed that the train wheel was very shiny, indicative of polishing as it was exposed to continuous sand blasting by strong cascading currents. A similar occurrence involved a mooring deployed at 200-m depth, which was moved down to 600-m depth within the main thalweg (deepest part of the canyon), more than 9 km away from its original position (Puig et al., 2008).

DSWC also controls off-shelf carbon fluxes and the functioning of deep ecosystems (Sanchez-Vidal et al., 2008). The DSWC season in the Gulf of Lion and elsewhere is often synchronous with high biological production levels in surface waters. Shelf waters showed high chlorophyll-*a* values (2–4 µg l^{-1}) in late February–early March 2005, indicative of a phytoplankton bloom. Water and organic carbon fluxes within the DSWC core in the Cap de Creus Canyon have been calculated for the whole of the February–March 2005 cascading period (40 days), using average mean flow speed (0.6 m s^{-1}), plume thickness (60 m), and canyon width (6,000 m). The volume of dense shelf water exported through the canyon totaled 750 km^3 (> 2/3 the water volume overlying the 70-km-wide Gulf of Lion shelf, which with ~ 12,300 km^2 is the largest in the entire Mediterranean Sea) (Canals et al., 2006). It is remarkable that this volume of water was exported down the canyon in only 40 days.

The total volume of dense shelf water exported from the Gulf of Lion shelf, mostly through Cap de Creus Canyon as reported above, and from the Catalan shelf, where it flowed mostly through La Fonera and Blanes canyons, reached 1200 and 1050 km^3, respectively (Ulses et al., 2008). This volume of water represents about seven times the mean annual discharge (330 km^3) of all rivers opening into the Mediterranean Sea (UNEP/MAP/MedPOL, 2003). The cascading of such a huge volume of shelf waters must have triggered a compensating movement of offshore waters at shallower depths that would have been pulled in over the large continental shelf of the gulf.

Using particulate (POC) and dissolved organic carbon (DOC) concentrations of 0.1 and 0.7 g m^{-3}, respectively, in surface waters of the Gulf of Lion, the organic carbon transport was estimated at 0.6 x 10^6 t (15,000 t d^{-1}) for the Cap de Creus Canyon alone during the 2005 cascading period. Normalizing this cascading transport estimate to the Gulf of Lion's shelf area yields a total organic carbon flux of 50 g C m^2 yr^{-1}. For the entire margin segment where DSWC occurs, a total organic carbon transport of 1.8 x 10^6 t (45,000 t d^{-1}) was estimated. These fluxes are much higher than the average export of carbon because of open-water winter convection in the nearby Ligurian Sea. Furthermore, the daily POC export during the late February–early March 2005 event is comparable to the upper range of cascade-driven fluxes estimated for North Atlantic margins; this is particularly notable when taking into account the oligotrophic character that dominates most of the Mediterranean Sea during most of the year.

Though submarine canyons, and the Cap de Creus Canyon in particular, are the main conduits for DSWC, it is notable that these waters also spill over the shelf edge south of each canyon, subsequently spreading over the continental slope and beyond. Part of the transported water probably escapes from canyons as they become less incised, mainly at the lower canyon reaches. Dense waters may also escape from canyons when the density contrast with the in situ water mass decreases to zero. The DSWC may then spread along the adjacent open slope following the isobaths. These off-canyon waters are then driven by the regional deep mesoscale circulation and by topographic gradients, thus covering large areas of the deep basin, especially after intense events.

Company et al. (2008) present interesting results demonstrating the relationship between intense cascading events and the fishery of the deep-sea shrimp *Aristeus antennatus*, one of the most valuable living resources for the regional fishing fleet. DSWC events can be compared to regenerative fires in forests. Initially, cascades cause the resource to disappear and the fishery to collapse, although it subsequently recovers and peaks three to five years after the event, following a period with significant increase of juveniles, as shown by the landing records in the ports of northern Catalonia. This pattern has been consistently observed for all DSWC events known to have occurred from 1977 to 2005 (Figure 5). Although it seems clear that the temporary disappearance of the shrimp is due to the strong currents accompanying DSWC, it is still unclear whether the subsequent enhanced recruitment and fishery peak is caused by the large transport of particulate organic matter to the deep basin leading to (1) a better-nourished adult population resulting in improved reproductive success, or (2) higher larval survival because of increased food availability. The long-lasting increase in near-bottom turbidity could make predator attacks on larvae and juveniles less successful, or predators could be negatively affected by the strong cascading currents. It is important to note that DSWC provides an alternative explanation to the temporary collapse of *Aristeus antennatus,* which was previously thought to be the result of overfishing.

There is also the question of how DSWC, a highly dynamic driver of canyon, open slope, and deep basin ecosystems, will respond to climate change. It is not totally clear whether the frequency and intensity of DSWC will increase or decrease in a warming world. Some predictive models using the IPCC A2 scenario indicate that in the coming century there will be less precipitation and river runoff, and higher temperatures in the Mediterranean region (Somot et al., 2006; Hermann et al., 2008). Although the first factor will reduce light waters and buoyancy at the sea surface, thus easing formation of dense shelf waters, higher temperatures and warmer surface waters will act in the opposite direction. These models suggest that the temperature effect will prevail and that DSWC to the deep basin in the Gulf of Lion will be virtually eliminated by 2100. If true, it means that less carbon will be removed from the ocean surface and exported to the deep ecosystem as organic matter, that enormous amounts of cold shelf water will cease to lower the accelerating warming trend of deep waters, and that the DSWC "manna" injection of fresh organic matter to the deep ecosystem will dramatically diminish or even stop. If these predictions prove to be correct, the catch of

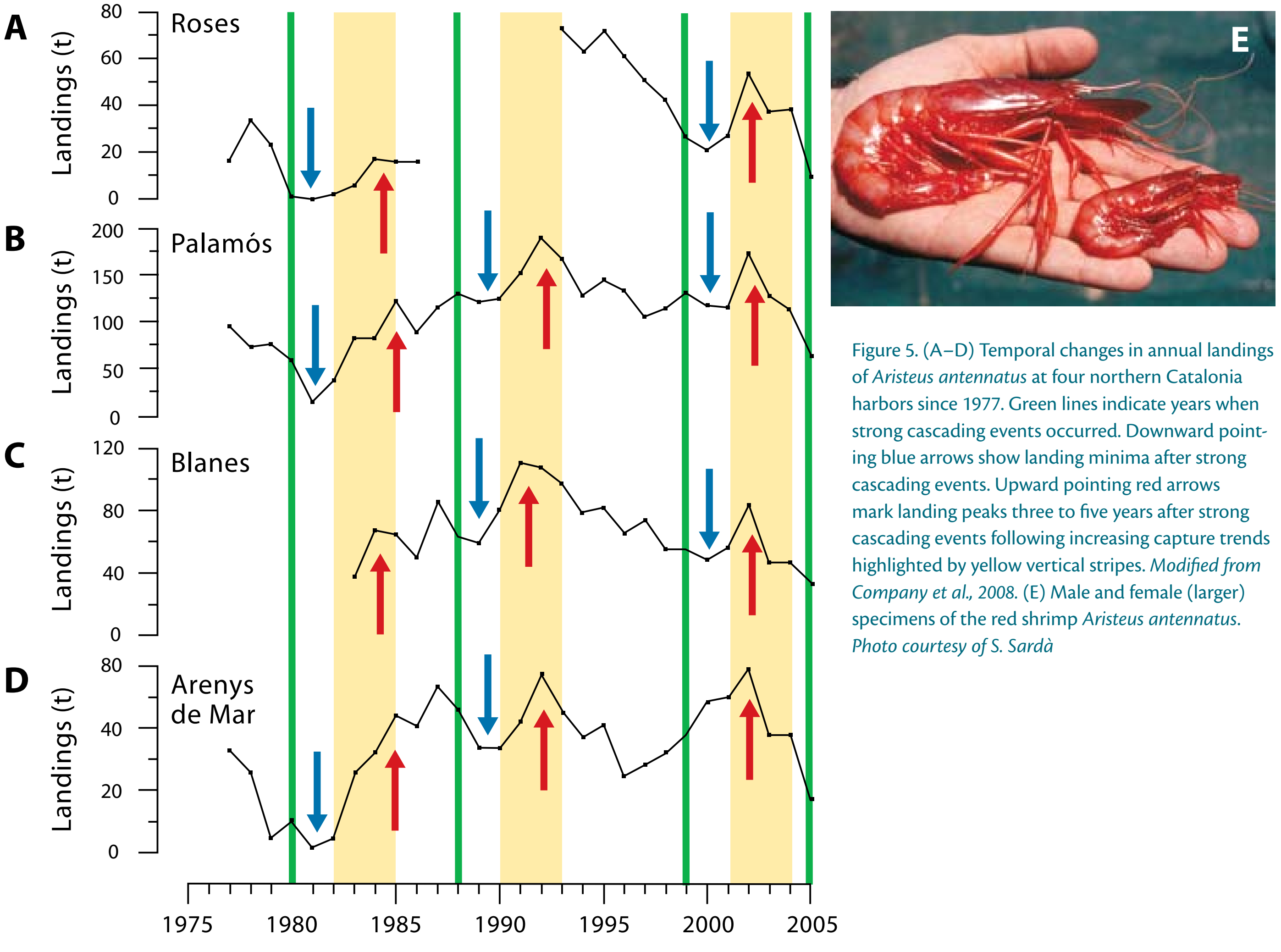


Figure 5. (A–D) Temporal changes in annual landings of *Aristeus antennatus* at four northern Catalonia harbors since 1977. Green lines indicate years when strong cascading events occurred. Downward pointing blue arrows show landing minima after strong cascading events. Upward pointing red arrows mark landing peaks three to five years after strong cascading events following increasing capture trends highlighted by yellow vertical stripes. *Modified from Company et al., 2008.* (E) Male and female (larger) specimens of the red shrimp *Aristeus antennatus. Photo courtesy of S. Sardà*

Aristeus antennatus fishery will possibly experience a true collapse, as the regenerative effect of DSWC is expected to decrease and eventually disappear.

THE ADRIATIC SEA

DSWC energetically impacts the seafloor of the Southwest Adriatic margin, generating near-bottom currents that erode and deposit large amounts of fine-grained sediment below a steep and markedly erosional upper slope. This water mass, named North Adriatic Dense Water (NAdDW), represents the densest water in the whole Mediterranean (T ~ 11°C, S ~ 38.5, σ_t ~ 29.5–29.6) (Zore-Armanda, 1963; Vilibic and Supic, 2005). It is generated on the broad, < 40-m-deep North Adriatic shelf through intense cooling and evaporation during January and February. The NAdDW flows southward along the Italian coast and reaches the shelf break over a prolonged interval (typically several weeks) about two months later (i.e., end of March to the beginning of April) (Zoccolotti and Salusti, 1987). The South Adriatic basin is also intruded by Levantine Intermediate Water (LIW), a salty water mass formed through evaporation in the eastern Mediterranean (T ~ 14°C, S ~ 38.7, σ_t ~ 29.1) (Zore-Armanda, 1963), which enters the south Adriatic through the Otranto Strait and flows southward along the western Adriatic, impacting the upper slope between 200 and 600 m (Cushman-Roisin et al., 2001; Figures 6 and 7). On the western side of the Adriatic basin, the slope is therefore impacted by two water masses, NAdDW and LIW, that both have a southward component of flow but which act on different time scales. The NAdDW is active every year for a short interval and, depending on the meteorological conditions in any one year, may or may not reach a density that enables it to sink all the way to the basin floor at 1200 m. The LIW, less energetic but more steady through the year, impacts the upper slope. Compared to the Gulf of Lion, the dense Adriatic water mass that forms only during winter takes a much longer time to reach the slope because

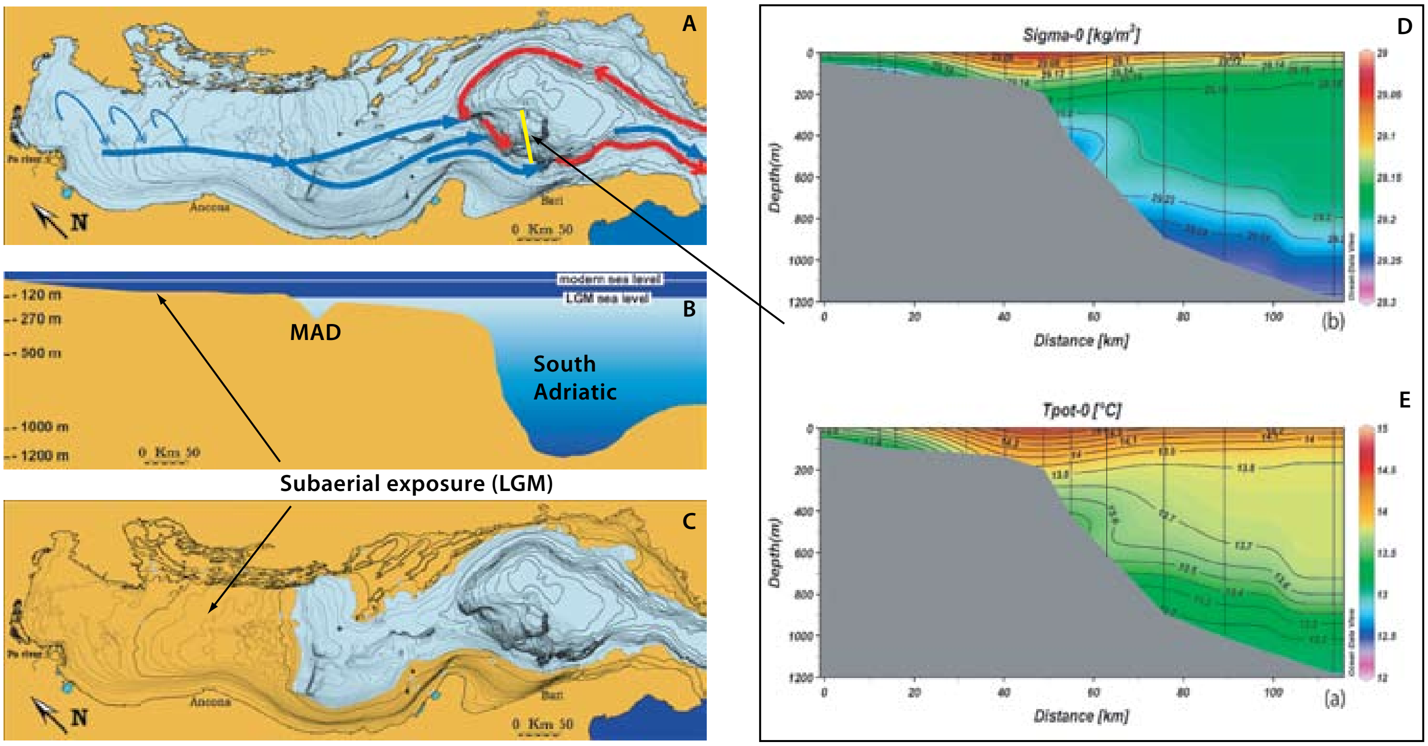


Figure 6. (A) Schematic reconstruction of regional intermediate- and bottom-water circulation patterns in the Adriatic basin. Thin blue arrows: Area of dense shelf water formation. Thick blue arrows: North Adriatic Dense Water flow. Red arrows: Levantine Intermediate Water flow. (B–C) Emergence of the Adriatic shelf during the Last Glacial Maximum in cross section and in plan view. (D–E) Hydrological sections across the Bari margin showing the near-bottom location of the densest and coldest water mass.

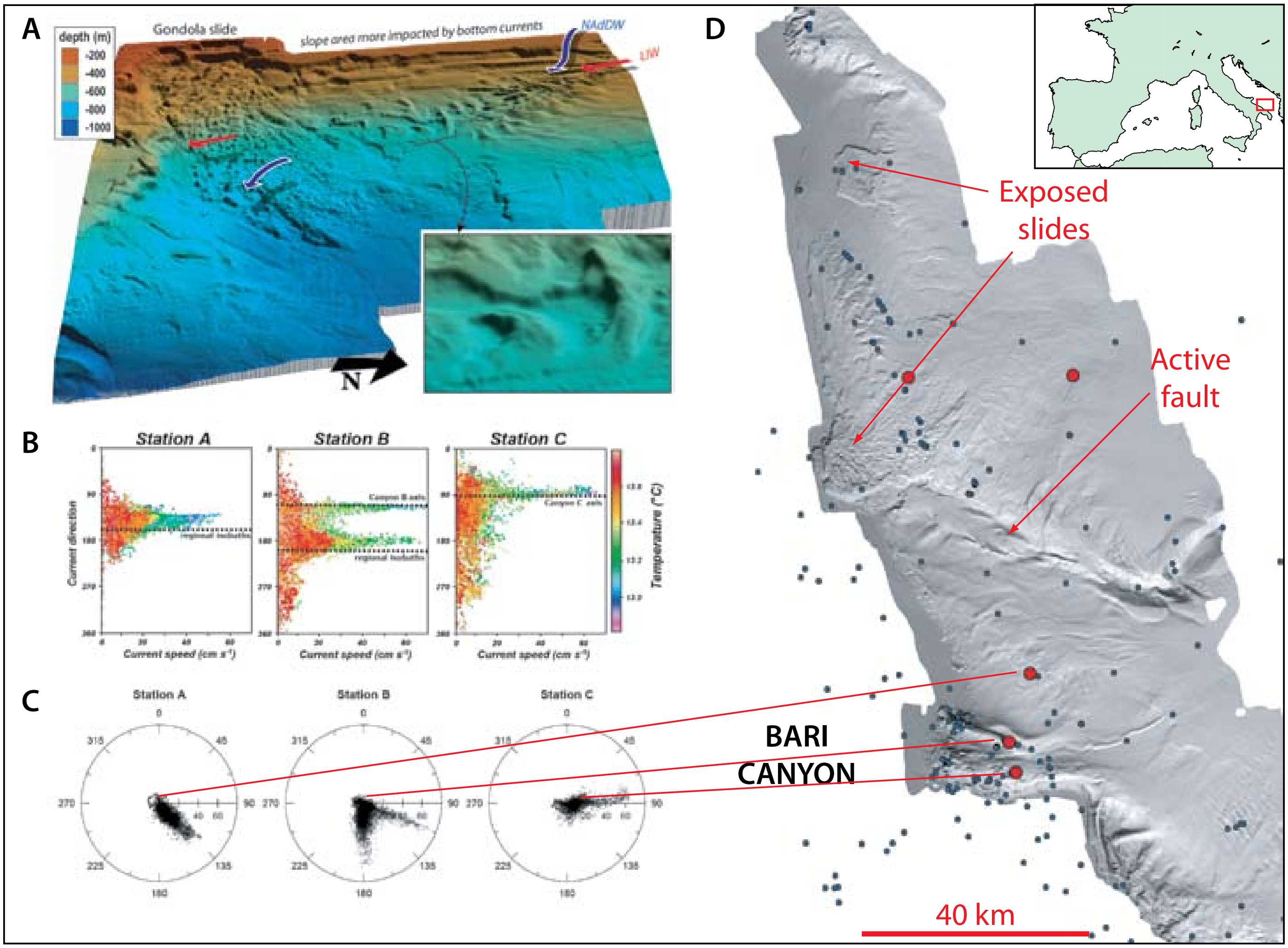


Figure 7. (A) Three-dimensional views of part of the Southwest Adriatic margin showing how the action of North Adriatic Dense Water (NAdDW) and Levantine Intermediate Water (LIW) on the seabed creates a variety of large-scale bed forms. (B–C) Plots illustrating that the highest current speeds always correspond to the lowest water temperatures when there is cascading. The ability of the Bari Canyon to trap and divert dense, cold-water currents along the canyon axis can also be appreciated by comparing the three plots. (D) General three-dimensional view of the Southwest Adriatic margin showing its topographic complexity and geodynamics. Red dots are the locations of near-bottom current measuring stations and blue dots are sediment sampling sites. The Gondola slide in (A) corresponds to the exposed slide at the middle left side of the image.

of the elongate, northwest-southeast-oriented shallow Adriatic shelf.

Two different pre-conditioning situations can favor the formation of the NAdDW: (1) intrusion of the salty LIW all the way to the northern Adriatic shelf, resulting in saltier, and therefore denser, water at the start of the winter, or (2) the particularly intense cooling of the surface water related to the prolonged impact of the cold Bora catabatic winds (catabatic winds move downslope because of cooling, especially at night) reaching the area from the northeast. In both cases, the highest rates of NAdDW production reflect low Po River runoff during the summer (Vilibic, 2003). A plot of several years of wind measurements over the area shows significant interannual variability in the number of wind days and in the intensity of the wind, suggesting significant variations in the density and volume of NAdDW produced from year to year (Bignami et al., 2007).

A one-year time series of temperature, bottom-current speed, and total mass flux (TMF) at about 650-m water depth within and outside the southern Bari Canyon (Turchetto et al., 2007) documented an increase in bottom-current speed between March and April. The episodes of increased bottom-current speed appear consistently related to the lowest water temperatures and the highest TMF, tracking the off-shelf cascading NAdDW (Figure 7). Additional but short-term bottom current data collected further north on the open slope, probably near the end of a cascading phase, showed current speeds reaching ca. 35 cm s^{-1}. In both cases, the current speed is not steady during a cascading event and the intervals (typically hours) of increased bottom current speed are characterized by a more down-slope direction compared both to lower-energy phases of the cascading process and to the rest of the year (Turchetto et al., 2007; Trincardi et al., 2007b). In addition, analysis of sediment trap samples (deployed with the current meters) shows that episodes of DSWC are characterized by enhanced terrestrial organic carbon content relative to the rest of the year (Tesi et al., 2008).

The Southwest Adriatic north-south stretch of outer shelf and open slope that is variably impacted by cascading NAdDW is about 100-km long and includes the cascade-flushed Bari Canyon, located where the continental shelf narrows substantially and the slope changes direction from roughly north-south to more northwest-southeast (Bignami et al., 2007, and references therein; Turchetto et al., 2007; Trincardi et al., 2007a). Crossing the Southwest Adriatic slope, the NAdDW partially entrains the surrounding LIW before sinking toward the bottom of the basin and contributing to the Adriatic Dense Water (ADW)[1] outflow (Manca et al., 2002).

Swath bathymetry and side-scan sonar (TOBI) images of the Southwest Adriatic margin, and a dense grid of chirp sonar profiles, define an area of extreme seafloor complexity characterized by sediment waves, erosional scours, longitudinal furrows, and giant comet-shaped marks (Verdicchio and Trincardi, 2006). These distinctive bottom-current features are not randomly distributed but appear genetically linked and have a consistent down-current arrangement. The pattern of these distinctive features indicates that the cold NAdDW plunges off-shelf oblique to the slope, possibly also interacting with the steady-state flow of the slope-parallel LIW (Trincardi et al., 2007b).

By cascading across the slope, the dense water impinges on the seafloor and interacts with the complex margin morphology related to active faults and exposed slide scars, large slide blocks, and a variety of mass-transport deposits (Minisini et al., 2006). It also generates patchy fields of large-scale mud waves that are spatially associated with a variety of erosional bed forms, such as moats, furrows, and comet marks.

A branch of the cascading NAdDW is confined and accelerated in the Bari Canyon system where it produces strong currents capable of reaching downslope velocities greater than 60 cm s^{-1}, eroding the canyon thalweg and entraining large amounts of fine-grained sediment. At the canyon exit, in water depth greater than 900 m, the current becomes less confined, spreads laterally, and generates an 80-km^2 field of mud waves. These bed forms migrate up current and have up to 50-m amplitudes and wavelengths of about 1 km. Furrow fields form both on the open slope and against the northern side of morphological highs associated with significant changes in slope orientation or the presence of slope ridges and seamounts (such as the 400-m-high Dauno seamount located at the base of the slope). All of these morphological features act as barriers, forcing the dense water flow to veer and—possibly—accelerate and become more erosive (Verdicchio et al., 2007).

Five distinct fields of mud waves occur in variable water depth along the margin, from the upper slope down to the basin floor. All of these fields are located downslope of large erosional areas but occupy slope sectors characterized by dissimilar morphologies. These fields of mud waves, locally with characteristic bidirectional crests, develop away from the main current path and represent a less-energetic record of the impact of the cascading process on the slope. Furrows are spatially and genetically associated with the mud waves, and develop particularly on their downslope (and down-flow) limbs, where current flows reach their maximum strength (Verdicchio and Trincardi, 2006). Data regarding the distribution, morphology, orientation, and stratigraphy of these patchy fields of mud waves are interpreted to record the long-term (millennial-scale) average of the seasonally variable direction and intensity of the cascading NAdDW currents,

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[1] ADW (T ~ 13°C, S ~ 38.6, σ_t ~ 29.2) is the main water mass that forms in the South Adriatic; it represents the most important component of the Eastern Mediterranean Deep Water (EMDW). The ADW results from an open-ocean formation process preconditioned by a permanent cyclonic gyre, similar to processes also observed in the Gulf of Lion and the Rhodes Gyre. ADW formation is also influenced by the inflowing LIW, together with the very cold and dense NAdDW reaching the South Adriatic.

evidencing their preferential pathways across the slope.

Sediment cores and seismic correlation suggest that the modern oceanographic regime became active some time after the onset of the last glacial-interglacial transition and that all the bed forms described above (both erosional and depositional) are primarily active during interglacial periods, both the modern interglacial as well as the previous interglacials, when climatic forcing also allowed formation of NAdDW on the shallow north Adriatic shelf. Such an oceanographic regime was shut down during glacial times when most of the North Adriatic shelf was subaerially exposed, thus preventing the process of surface water cooling and dense water formation (Figure 6; Verdicchio et al., 2007).

THE AEGEAN SEA

Due to a complex, long-term geodynamic evolution and active neotectonics, the Aegean Sea displays a complicated physiography in terms of seabed morphology and land-sea configuration. The seafloor topography of the North Aegean is characterized by a series of deep trenches and troughs with depths reaching 1500 m, separated by shallow sills and shelves. An extended shallow sill, the Cyclades plateau, which is shallower than 200 m, separates the Central from the South Aegean Sea (Figure 8) (Lykousis et al., 2002).

The combination of the influx from North Aegean rivers and the inflow of low-salinity Black Sea Water (BSW) through the Dardanelles, together with air-sea interactions, creates an intricate hydrological system that acts on water-mass hydrology, circulation, and biological, chemical, and sedimentological processes in the Aegean Sea. The variability of the system, most pronounced along north-south trends, and the spatial variability of trophic conditions create a unique area for the study of biogeochemical fluxes.

Water circulation in the Aegean Sea follows, in general, a cyclonic pattern. However, the most active dynamic features of the Aegean are the mesoscale cyclonic and anticyclonic eddies (Theocharis et al., 1999). The inflow of BSW is the major source of brackish water for the North Aegean; the contribution of all the rivers discharging into the Aegean is less than the input of BSW by at least one order of magnitude. The flux of the BSW in the North Aegean varies from 100–1000 km^3 yr^{-1} (Ünlüata et al., 1990).

The South Aegean Sea, also known as the Cretan Sea, is the largest in volume and the deepest Aegean basin, reaching 2500-m depth. The Cretan Sea is connected to the Levantine basin and the Ionian Sea via the eastern and western Cretan straits through sills varying in depth from 150–1100 m. The hydrology and water mass dynamics of the South Aegean Sea are known from historical work and recently from analysis of data gathered within the framework of national, international,

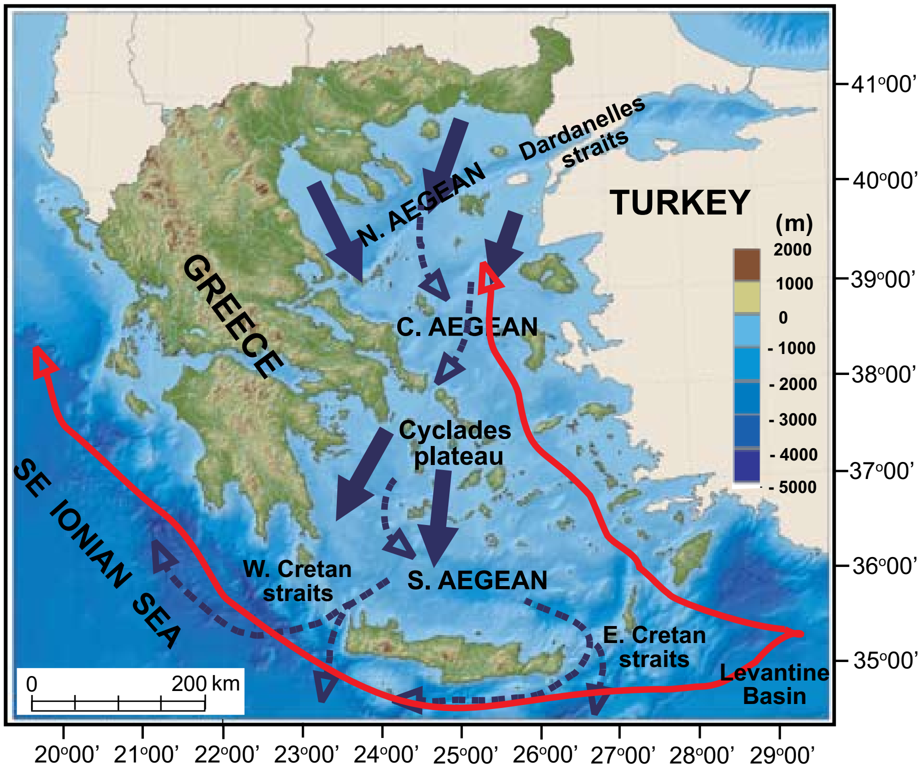

Figure 8. Three-dimensional view of the Aegean Sea region showing the location of places referred to in the main text and outlining the formation and circulation of dense shelf water (blue arrows) until it eventually cascades through the Cretan straits after sweeping the Cyclades plateau where resulting bed forms have been identified. Red arrows depict the flow of Levantine Intermediate Water.

and European programs (Theocharis and Georgopoulos, 1993; Theocharis et al., 1999). These investigations revealed the intense mesoscale variability that characterizes the circulation pattern in the South Aegean Sea and the Cretan straits. A succession of transient and/or recurrent cyclonic and anticyclonic eddies defines the water-mass distribution. Winter convection processes lead to intermediate and/or deep water-mass formation.

In the mid and late 1980s, the upper layer in the South Aegean was occupied by either (1) surface saline ($S \sim 39$) waters of Levantine origin (LSW), occurring during the warm period of the year within the upper 50 dbar layer, that enter the Southeast Aegean through the eastern Cretan straits, or (2) the less-saline ($S < 38.9$) surface BSW coming from the North Aegean and affecting mainly the Mirtoan and western Cretan seas. Moreover, most of the time there were intrusions through the Cretan straits of less-saline subsurface water of Atlantic origin, the so-called Modified Atlantic Water (MAW), coming from the Ionian Sea. Below the upper layer and down to the bottom, two denser (σ_t up to 29.16) water masses were distinguished: the LIW and the Deep Cretan water that contributes to the layers below the LIW in the eastern Mediterranean basin.

In the early 1990s, the structure of the deep Cretan Sea water column changed dramatically, as exceptionally dense ($\sigma_t > 29.2$), very saline ($S > 39$) water of local origin started filling the deep Cretan basin and overflowed through the sills of the Cretan Arc straits (Theocharis et al., 1999; Roether et al., 1996). Due to its high density, Cretan Deep Water displaced water from the deepest parts of the Levantine and Ionian basins in the eastern Mediterranean. Thus, the Aegean became the major contributor of warmer and more saline bottom water to the eastern Mediterranean.

> “UNDERSTANDING OF THE ENVIRONMENTAL, ECOLOGICAL, AND SOCIETAL IMPORTANCE OF DSWC AND THE ROLE THAT SUBMARINE CANYONS PLAY IS PROGRESSIVELY INCREASING, THANKS TO THE INTENSIVE RESEARCH WORK CARRIED OUT IN THE MEDITERRANEAN SEA.”

Immediately after cooling, the newly formed dense surface water sinks rapidly and flows southward directly above the seabed, thus flooding the deeper part of the Cretan basin. After filling the Cretan basin, the dense water overflows the Cretan straits and cascades through the canyons of the southwest flanks of the straits and spreads into the deep eastern Mediterranean, flooding the deep Ionian basin.

Side-scan sonar and 3.5-kHz profiler images showing numerous sandy bed forms on the north-northeast Cyclades plateau indicate the flow and cascading of dense water (Lykousis, 2001). The bed forms occur in depths of 80–130 m as: (a) dunes (wave length 10–35 m and height 1–2 m) composed of moderately well-sorted coarse sand, (b) large to very large sand waves (wavelength 50–300 m and height 1.5–6 m) usually developed in fine to medium sand, (c) mega-ripples (wavelength 3–5 m and height 0.2–0.4 m), (d) narrow sand ribbons, and (e) elongate sand patches. Short-period deployments of near-bed current meters recorded maximum values up to 10–15 cm s^{-1} with mean velocities of 6–7 cm s^{-1} and therefore failed to record the peak flow required to generate these bed forms. Such bed forms imply a strong, near-bed episodic southern flow on the order of 40–100 cm s^{-1} and, locally in the case of sand ribbons, up to 200 cm s^{-1}. Dense (deep) water that forms in the North and Central Aegean (including the Cyclades plateau) during exceptionally cold and dry winters subsequently sinks and flows over the seabed, causing these forms to develop (Lykousis, 2001).

The South Aegean clearly reflects the very oligotrophic character of the Aegean Sea. Downward matter fluxes are higher in the North relative to the South Aegean. Substantially higher values of near-bottom mass fluxes were measured in the deep basins of the North Aegean, implying significant deep lateral (advective) fluxes of particulate organic matter (POM). The North Aegean could be classified as “continental margin” ecosystem, while the South Aegean is a typical “oceanic margin” oligotrophic environment.

As a consequence, the Cretan Deep Water overflowing the Cretan straits and cascading toward the Ionian basin transports insignificant amounts of POM and nutrients but is rich in oxygen. However, episodic down-canyon POM fluxes have been observed by means of sediment traps deployed in the canyons of the Cretan straits (Kerherve et al., 1999).

Klein et al. (2003) used an intercalibrated set of eastern Mediterranean oxygen data collected from 1987 to 1999 to study the evolution of oxygen concentrations that accompanied the early 1990s changes in thermohaline circulation (dense deep water) of the eastern Mediterranean. They found that by the late 1990s the deep layers had considerably elevated oxygen concentrations compared to 1987 because of the cascade of oxygen-rich near surface waters into the deep layers during 1990–1995. These authors also proposed that this massive invasion of near-surface waters supplied large amounts of dissolved organic carbon with an unusually high fraction of labile material, which in turn enhanced oxygen consumption. Dissolved organic carbon and mesozooplankton ecology data provide supporting evidence. The enhanced oxygen consumption represents a further example of disturbance in the biogeochemistry of the eastern Mediterranean related to dense water cascading.

CONCLUDING REMARKS

Understanding of the environmental, ecological, and societal importance of DSWC and the role that submarine canyons play is progressively increasing, thanks to the intensive research work carried out in the Mediterranean Sea. Matter and energy transfer from shallow to deep are the main fuel supplies for deep-water ecosystems and are essential for their maintenance. Contrary to the classical view of vertical settling of particles, also known as "pelagic rain," new research results in the Mediterranean Sea have demonstrated that horizontal injection of particles plays a key role in sustaining deep ecosystems. Such injections often take the form of energetic cascades that last for weeks and occur with subdecadal frequency. In addition to the Northwest Mediterranean area, cascades of dense shelf water have been identified in the Adriatic Sea and deduced from bed-form assemblages in the Aegean Sea (Lykousis, 2001; Trincardi et al., 2007a,b). Therefore, DSWC could now be considered one of main drivers of the deep Mediterranean Sea. Because DSWC occurs in many ocean margins of the world (Ivanov et al., 2004), it is very likely that these findings have global implications. Finally, as an atmosphere-forced process, DSWC illustrates how the impact of climate change is transferred to the deep ocean. Clearly, further studies in other regions of the world ocean are needed to fully resolve the likely impacts of future climate change.

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