LETTERS

Flushing submarine canyons

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The continental slope is a steep, narrow fringe separating the coastal zone from the deep ocean. During low sea-level stands, slides and dense, sediment-laden flows erode the outer continental shelf and the continental slope, leading to the formation of submarine canyons that funnel large volumes of sediment and organic matter from shallow regions to the deep ocean[1]. During high sea-level stands, such as at present, these canyons still experience occasional sediment gravity flows[2–5], which are usually thought to be triggered by sediment failure or river flooding. Here we present observations from a submarine canyon on the Gulf of Lions margin, in the northwest Mediterranean Sea, that demonstrate that these flows can also be triggered by dense shelf water cascading (DSWC)—a type of current that is driven solely by seawater density contrast. Our results show that DSWC can transport large amounts of water and sediment, reshape submarine canyon floors and rapidly affect the deep-sea environment. This cascading is seasonal, resulting from the formation of dense water by cooling and/or evaporation, and occurs on both high- and low-latitude continental margins[6–8]. DSWC may therefore transport large amounts of sediment and organic matter to the deep ocean. Furthermore, changes in the frequency and intensity of DSWC driven by future climate change may have a significant impact on the supply of organic matter to deep-sea ecosystems and on the amount of carbon stored on continental margins and in ocean basins.

An intricate network of submarine canyons with heads cut in the 130-m-deep crescent-shaped shelf is the most outstanding seafloor feature of the Gulf of Lions. Water is transported in a cyclonic direction by a thermo-haline along-slope current and a wind-driven mean coastal circulation. Constrained by the slope current offshore and the coast inshore, most shelf water is funnelled towards the narrowing southwestern shelf end where it hits the Cap de Creus promontory and is thereby deviated towards the nearby canyon (Fig. 1a).

Winter heat losses and evaporation induced by cold and dry northerly winds cause cooling and mixing of the Gulf of Lions' coastal and off-shelf waters. Once denser than surrounding waters, shelf water sinks, overflows the shelf edge, and cascades downslope until it reaches its equilibrium depth. Winter DSWC appears to be a major export mechanism with a strong inter-annual variability (Supplementary Fig. 1a). Cascading rapidly advects dense shelf water hundreds of metres deep over the slope where it merges with dense water formed off-shelf[9]. Since the early 1950s, winter hydrological surveys traced shelf water tongues within Lacaze-Duthiers canyon (LDC), next to Cap de Creus canyon (CCC)[10], with equilibrium depths between 170 and 800 m. Continuous monitoring of temperature and current since 1993 in LDC showed that shelf water sunk down to 500 m almost every winter[10]. During the 1998–99 and 2004–05 abnormally cold and windy winters, further characterized by lower (~22 km^3) than average (~30 km^3) northern freshwater inputs limiting the gain of buoyancy, it passed 1,000 m and was associated with exceptionally large sediment transfer (Supplementary Fig. 1).

In winter 2003–04, when seven canyon heads in the Gulf of Lions were monitored simultaneously (Fig. 1), the down-canyon cumulative sediment transport in CCC (with fluxes up to 3 $t\,m^{-2}$ for the 3-day-long strongest flushing outburst in late February) was one to two orders of magnitude higher than in all other canyons (Supplementary Fig. 2). We therefore focused our winter 2004–05 observations on this canyon (Fig. 1b). A major DSWC episode occurred from late February to late March 2005. DSWC outbursts were characterized by significant temperature decreases, and by

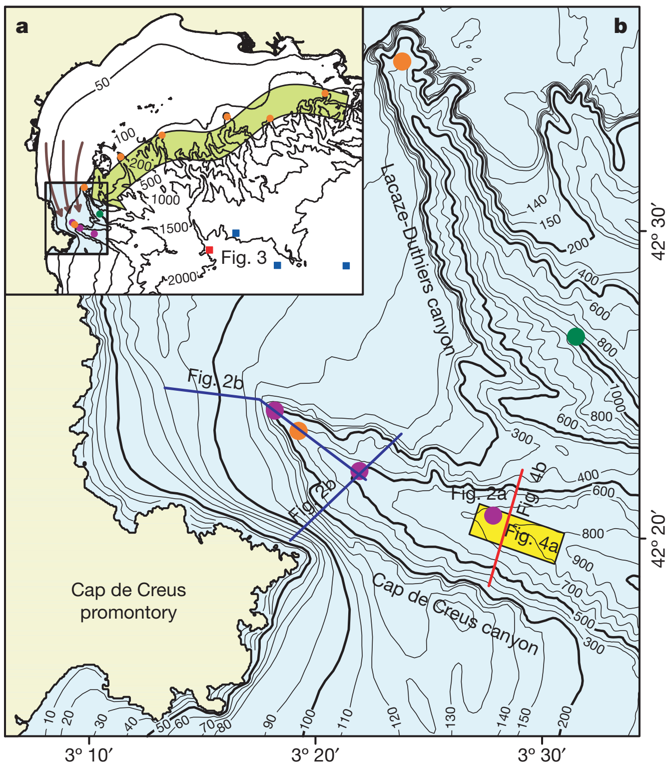

Figure 1 | Bathymetry maps and station location. a, Bathymetry map of the Gulf of Lions (GL). Mooring stations shown as follows. Orange dots, winter 2003–04 at 300 m; purple, winter 2004–05 at 200, 500 and 750 m; and green, long term mooring at 1,000 m. Deep hydrological stations at (red square) and off (blue squares) the mouth of the Cap de Creus Canyon (CCC) are also shown (see Fig. 3). Arrows indicate the direction of the mean coastal (brown) and slope circulation (green). **b,** Detailed bathymetry of the southwestern end of the GL. Time series shown in Fig. 2a correspond to the 750 m mooring (purple dot) inside CCC. Locations of the hydrological sections in Fig. 2b (blue lines), and of the side scan sonar sonograph (yellow box) and section b (red line) in Fig. 4 are also indicated.

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increases in down-canyon current speed, water density and suspended sediment concentration (SSC) (Fig. 2a and Supplementary Fig. 3). Current direction and hydrological characteristics during the cascading event highlighted the asymmetric path of the dense and turbid water tongue sweeping the southern canyon wall (Fig. 2b). While a new survey in April 2005 confirmed its disappearance from the upper and middle canyon reaches, a 2,141 m deep cast at the mouth of the canyon revealed the near bottom intrusion of colder, fresher and turbid dense shelf water below the deep water newly formed off-shelf (Fig. 3). The magnitude of the winter 2004–05 DSWC was comparable to the 1998–99 event and had a strong impact on the deepest water masses[11,12].

Silt and sand-sized bed loads associated with such extreme events erode canyon floors. We found a field of giant furrows—tens of kilometres long, with wavelengths up to 100 m and heights up to 10 m (Fig. 4)—covering most of the CCC floor down to 1,400 m. These megascale bedforms, carved on overconsolidated mud, are organized into sets with different directions and degrees of development. The field hangs >50 m over a >500-m-wide sand and gravel-filled axial incision ('thalweg') collecting particles transported along the furrows and the canyon axis upstream. Its location corresponds to the area directly affected by DSWC during the severe 2005 event, including parts of the southern canyon wall (Fig. 2b). *In situ* measurements, sonographic evidence (Fig. 4), and published criteria[13,14] confirm that erosion prevails in the furrowed area and that the furrow formation process is currently active, though intermittent.

Giant furrows are erosive features requiring highly energetic processes to develop[13,14]. The current shear stress generated during the 2005 cascading event was large enough (~0.7 N m^{-2}) to resuspend sand, which itself has the potential to erode fine-grained cohesive substrata to form furrows[13,14]. During the main cascading event, the mean grain size of the sediment caught by traps deployed 30 m above the bottom in the canyon axis ranged from 31 to 62 μm with >50% silt and sand. Sediment collected before cascading had a size of 2–4 μm with <1% silt and sand (Supplementary Fig. 4). Both sediments were, however, finer than those in the axial incision (0.5–8 mm coarse sand to gravel). SSC decreased dramatically at the end of cascading by exhaustion of easily resuspendable material, as shown by the 500 m and 750 m records (Fig. 2a and Supplementary Fig. 3). SSC was much lower at 200 m depth because of the preferential pathway for dense shelf water and suspended particles along the southern flank of the canyon (that is, away from the upper canyon axis where the mooring was located), which is in agreement with the development and directions of the giant furrow field. On the basis of these characteristics, the furrow field is interpreted as the seafloor imprint of severe DSWC events repeated through time.

Our observations showing that sediment mass transport affecting large portions of the seafloor can be simply triggered by DSWC add

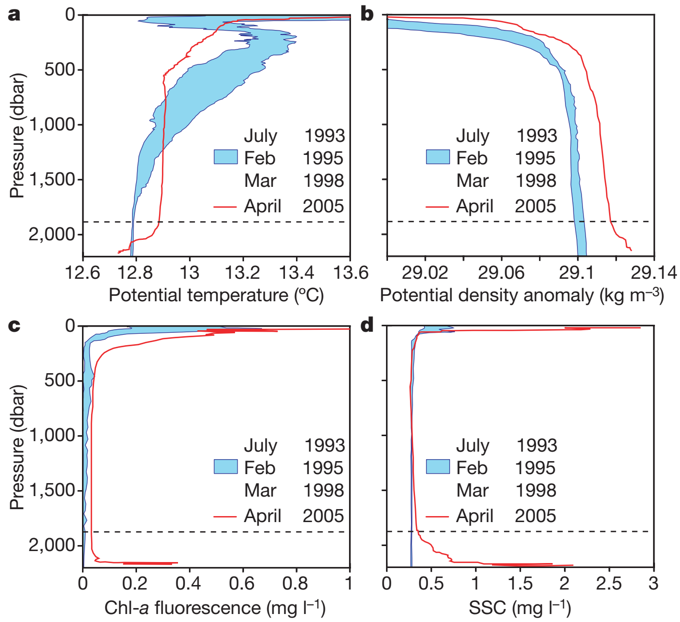

Figure 3 | Deep comparative profiles of key parameters at and off the CCC mouth. a, Potential temperature. **b,** Potential density anomaly. **c,** Fluorescence. **d,** Suspended sediment concentration. The anomalous April 2005 profiles (red) at the canyon mouth (2,141 m) are compared with the range of normal profiles (blue shadowed area) recorded deeper than 2,000 m off the canyon mouth in 1993, 1995 and 1998 (see Methods). The homogeneous water mass observed from 1993 to 1998 corresponds to the Deep Western Mediterranean Water. The April 2005 profiles revealed a large anomaly, with warmer water in the lower half of the water column, resulting from off-shelf dense water formation, overlying a near-bottom, abnormally cold water layer (below dotted line) that demonstrates the intrusion of very dense, chlorophyll-rich and turbid shelf water. See locations in Fig. 1.

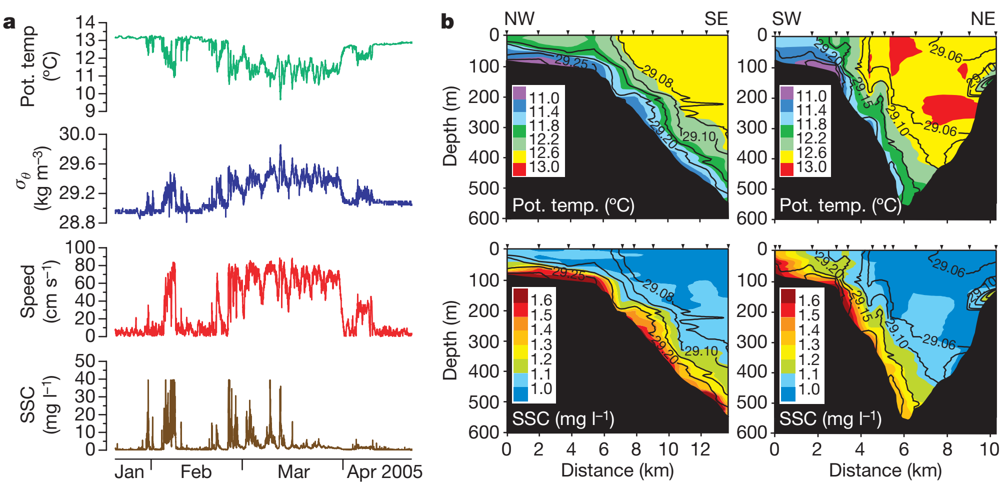

Figure 2 | Time series and sections of key parameters in the CCC. a, Potential temperature, potential density anomaly, current speed and suspended sediment concentration records at 750 m depth during the cascading period of winter 2004–05. DSWC events correspond to temperature drops concomitant with density increases. **b,** Potential temperature and suspended sediment concentration sections with potential density anomalies (black contours) along and across the canyon head on 24–26 February 2005. The DSWC plume flows down-canyon along its southern wall. Current meter measurements 5 m above bottom at 750 m depth during the same period recorded down-canyon speeds ranging from 20 to 85 cm s^{-1}. See locations in Fig. 1.

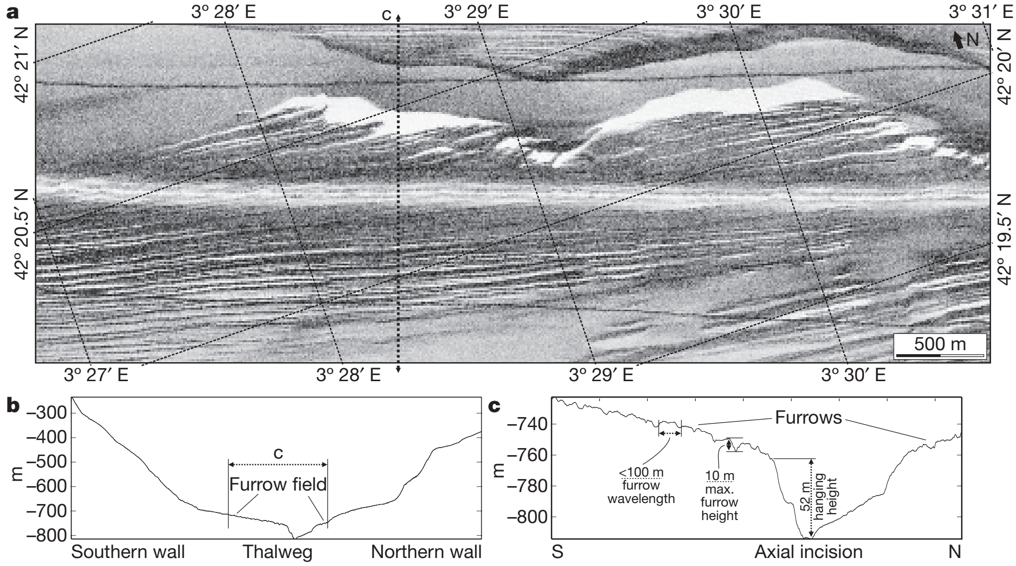

Figure 4 | Acoustic image of the CCC floor. a, Side scan sonar high-resolution sonograph of giant furrows on overconsolidated mud. Cohesions up to 40 kPa were measured *in situ* on the same mud type at the inner flank of a nearby canyon. The light grey zone in the lower part of the sonograph suggests that the furrows are locally smoothened or draped by softer sediment. The lighter band along the middle of the sonograph is an acquisition artefact. **b**, Illustrative section across canyon. **c**, Section across furrow field derived from multibeam bathymetry data showing furrow height (up to 10 m) and wavelength (up to 100 m), and field hanging height (52 m) over the axial incision. See locations in Fig. 1.

an unprecedented dimension to current understanding of sediment gravity flows in the deep sea[15]. According to accepted views, river floods and sediment failures initiate most sediment gravity flows including turbidity currents (whose movement is sustained by the upward turbulence of the water–sediment mixture and grain-to-grain interactions), resulting in sediment-laden plumes denser than the surrounding waters because of higher particle concentrations. In the case of DSWC, the water itself is dense enough to sink and rapidly move downwards along the bottom. A $\sim 0.2\ \mathrm{kg\,m^{-3}}$ horizontal density contrast between the cascade and the ambient water (Fig. 2b) in February 2005 was sufficient to initiate intense downslope water flow without additional sediment load. Whereas computation of theoretical velocities[16] resulted in speeds exceeding $1\ \mathrm{m\,s^{-1}}$, measurements at 5 m above the bottom revealed speeds as high as $85\ \mathrm{cm\,s^{-1}}$, equalling those of turbidity currents[17]. Its own density and high speed endow DSWC with a strong dragging capacity on loose particles and underconsolidated seafloor sediments.

Beyond sediment transport, DSWC controls off-shelf carbon fluxes and the functioning of deep ecosystems. High concentrations of phytoplankton in cascading waters compared to surrounding waters have been observed elsewhere[18–20]. The DSWC season in the Gulf of Lions is generally synchronous with high biological production levels in surface waters; the shelf waters showed high chlorophyll-*a* values ($2–4\ \mu\mathrm{g\,l^{-1}}$) in late February–early March 2005, indicative of a phytoplankton bloom. Water and organic carbon fluxes within the DSWC core have been calculated for the whole cascading period (40 days), using average mean flow speed ($0.6\ \mathrm{m\,s^{-1}}$), plume thickness (60 m) and width (6,000 m). Exported shelf water reached $750\ \mathrm{km^3}$ (>2/3 the water volume overlying the Gulf of Lions shelf). With particulate organic carbon (POC) and dissolved organic carbon (DOC) concentrations of 0.1 and $0.7\ \mathrm{g\,m^{-3}}$ in surface waters of the Gulf of Lions, a total organic carbon transport of 0.6×10^6 t ($15{,}000\ \mathrm{t\,d^{-1}}$) can be estimated. Normalizing this cascading transport estimate to the Gulf of Lions' shelf area ($1.2 \times 10^{10}\ \mathrm{m^2}$) yields a total organic carbon flux of $50\ \mathrm{g\,C\,m^2\,yr^{-1}}$. This is higher than the average export of $16–25\ \mathrm{g\,C\,m^2\,yr^{-1}}$ due to open sea winter convection in the nearby Ligurian Sea[21]. Furthermore, our daily POC export ($1{,}875\ \mathrm{t\,d^{-1}}$) is comparable to the upper range of the cascading-driven fluxes estimated for North Atlantic margins[19-20].

In promoting such a massive carbon export from the shallowest reservoirs, DSWC contributes to its sequestration in deeper waters where it is less likely to return to the atmosphere. It also directly affects the functioning of the deep ecosystem by providing a fast way of fuelling highly nutritive, fresh organic matter to the deep, as attested by the increased near-bottom water fluorescence recorded at >2,000 m depth at the end of the cascading period (Fig. 3c). C/N ratios of sediment trap material caught in canyon heads from November 2003 to April 2004 reflected the shift from degraded organic matter (C/N = 9.5) during autumn stratified conditions to fresh organic matter (C/N = 6.5) during DSWC events (Supplementary Fig. 5).

As many continental margins where DSWC occurs[8,10] (Supplementary Fig. 6) are cut by deep canyons[22], flushing submarine canyons are likely to play a role of global importance in favouring the downslope movement of dense shelf water. Further data collection in DSWC canyoned margins worldwide should be given priority to better constrain global off-shelf sediment and carbon export and the full extent of DSWC impacts on the deep ecosystem.

A final critical point is the fate of DSWC in the coming decades. Modelling results for the Mediterranean Sea anticipate a major decrease of winter deep water formation in the Gulf of Lions[23] following the IPCC-A2 scenario for the twenty-first century as a consequence of a warmer and drier climate over the entire basin[24]. Deep water formation is also expected to decline in other areas of the world, particularly in high latitudes. In the Atlantic Ocean, the weakening of the thermohaline circulation is anticipated owing to the reduction in dense water formation in Nordic and Arctic regions[25]. Regionally, such alterations could significantly affect the shelf carbon pump[26] and the deep ecosystems whose functioning is linked to DSWC.

METHODS

Our observations result from a unique, dedicated experimental strategy combining adequate space and time (hourly to decadal) multidisciplinary monitoring of on-going processes and high resolution imaging of seafloor features.

Hydrography and organic carbon. Hydrography casts and water sampling were performed using a Seabird 9/11Plus CTD probe, equipped with a 25 cm optical path length Wetlab Cstar transmissometer, a Chelsea ECO/FL fluorometer and a Datasonics altimeter, mounted on a rosette holding Niskin bottles. Water samples were filtered up to filter saturation on pre-weighed 0.45 μm Nuclepore filters. Filters were dried at 40 °C and weighed to derive SSC. POC was analysed in a Leco CN 2000 on the solid residues from water samples filtered on pre-combusted (4 h, 450 °C) glass fibre Whatman GF/F filters (pore size 0.7 µm) and acidified under control with HCl 2 N to remove carbonates. DOC concentration was determined on Whatman GF/F filtered water samples and analysed with a High Temperature Catalytic Oxidation (HTCO) technique on a Shimadzu TOC-V CSH analyser following Cauwet's method[27]. Background hydrographic information provided in Fig. 3 was derived from the Discovery cruise station MA306 (24 July 1993), the Suivilion 12 cruise station L04 (15 February 1995), and the Fetch cruise station 118 (4 March 1998).

Instrumented moorings. Instrumented moorings deployed at 300 m depth inside canyons during winter 2003–04 (orange dots in Fig. 1) and at 500 m during winter 2004–05 (purple dot in Fig. 1) were equipped with a PPS3 Technicap sequential sediment trap (12 collecting cups) at 30 m above bottom and an Aanderaa RCM9/11 Doppler current meter at 5 m above bottom. 200 and 750 m deep moorings (purple dots in Fig. 1) in the CCC during winter 2004–05 were solely equipped with a near bottom current meter. Current meters were further equipped with temperature, conductivity, pressure and optical backscatter sensors. Sampling intervals were set to 1 week for traps and 20 minutes for current meters. In the LDC, a long term mooring (green dot in Fig. 1) deployed at 1,000 m depth has been in operation since 1993. It is equipped with two PPS3 traps and two Aanderaa RCM7/8 vector-averaging rotor current meters (with temperature and pressure sensors) at 30 m and 500 m above bottom. The long term sampling intervals were set to one month for traps and one hour for current meters.

Sediment samples and sonographs. Bottom sediment samples were collected with a 20 × 30 cm cross-section and 50 cm in height box corer along and across the axis of the CCC, adjacent to the mooring stations at ~200, 500 and 750 m water depth (see location in Fig. 1). Sediment samples were dispersed by a 0.05% sodium metaphosphate solution, wet sieved at 63 µm and analysed on a Sedigraph 5100 for grain-size distribution of the mud fraction. *In situ* undrained shear strength (cohesion) measurements on overconsolidated canyon floor muds were conducted with IFREMER's flexible penetrometer Penfeld. High resolution sonographs along the CCC axis were obtained in 2004 on board R/V *Professor Logachev* using a Mak-1M deep-towed 30 kHz side scan sonar (pulse length 1 ms, horizontal beam width 2°, vertical beam width 60°, TVG 40 dB). This system yielded a total swath range of up to 2 km while towed at a mean height of 100 m over the sea floor at a mean speed of 2.5 knots, with a variable resolution of about 7 to 1 m across and along track. Multibeam bathymetry data from which the section in Fig. 4c was drawn were acquired with an EM-300 Simrad system. Details on the collection and processing of CTD, current meter, sediment trap and side scan sonar data are provided as Supplementary Information.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions All authors contributed to the design and implementation of the experimental strategy. M.C. steered the integration and joint analysis of the data, interpreted side scan sonar data and wrote the final version of the paper in cooperation with S.H. P.P., X.D.d.M. and A.P. took the responsibility for time series, X.D.d.M. for hydrology data, and S.H. and J.F. for sediment trap data. All authors discussed the results and commented on the manuscript.

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