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Storm-induced sediment gravity flows at the head of the Eel submarine canyon, northern California margin

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[1] As part of the STRATAFORM program, a bottom-boundary layer (BBL) tripod was deployed at 120 m depth in the northern thalweg of the Eel Canyon during winter 2000. Increases of the near-bottom suspended-sediment concentrations (SSC) recorded at the canyon head were not directly related to the Eel River discharge, but were clearly linked to the occurrence of storms. BBL measurements revealed that during intensifications of the wave orbital velocity, sediment transport at the head of the canyon occurred as sediment gravity flows directed down-canyon. Observational evidence for near-bed sediment gravity-flow transport included an increase toward the bed of the down-canyon component of wave-averaged velocity and high estimated SSC. At higher sampling frequencies (1 Hz), the current components during these events fluctuated at the same periodicity as the pressure, reflecting a clear influence of the surface-wave activity on the generation and maintenance of the sediment gravity flows. The origin of such flows is not related to the formation of fluid muds on the shelf or to intense wave-current sediment resuspension around the canyon head region. Rather, liquefaction of sediment deposited at the head of the canyon (induced by wave-load excess pore water pressures during storms) combined with elevated slopes around the canyon head appear to be the mechanisms initiating sediment transport. The resulting fluidized-sediment layer can easily be eroded, entrained into the water column, and transported down-canyon as a sediment gravity flow. Results from this study reveal that storm-induced sediment gravity flows occur periodically in the Eel Canyon head, and suggest that this kind of sediment transport process can occur in other submarine canyons more frequently than previously expected. *INDEX TERMS:* 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; 4558 Oceanography: Physical: Sediment transport; 4211 Oceanography: General: Benthic boundary layers; *KEYWORDS:* sediment transport, sediment-gravity flow, submarine canyon

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1. Introduction

[2] Continental margins form the relatively narrow transition zones between the markedly different domains of landmasses and deep-ocean basins. They are the main regions of input and transfer of sediments to the oceans, and as such, they represent important zones of sediment flux [*Nittrouer and Wright*, 1994; *Evans et al.*, 1998]. Heads of submarine canyons are common on continental margins, occurring near river mouths and on other portions of continental slopes. It is well known that canyon heads are preferential conduits for transport of sediment from shelf environments to adjacent deep-marine basins [*Shepard and Dill*, 1966; *May et al.*, 1983], but the complex variables acting in the formation, maintenance, and infill of these sediment pathways through time and space are still not fully understood.

[3] Submarine erosion is of major importance in affecting canyon morphology, and conditions in submarine canyon heads are well suited for slumping and sliding [*May et al.*, 1983; *Pratson and Coakley*, 1996]. Sediment transport in canyon heads can occur by gravitational mass flow and by a variety of channeled currents that fluctuate up- and down-canyon, mainly at tidal frequencies [*Shepard et al.*, 1979]. These currents can be strong enough (~30 cm/s) to move fine-grained sediment down-canyon without invoking mass-failure. Occasional strong down-canyon surges at speeds of ~100 cm/s also have been observed in canyons [*Inman*, 1970; *Gennesseau et al.*, 1971; *Shepard et al.*, 1977], and have been interpreted as having a turbidity-current origin.

[4] Turbidity currents are gravity currents in which the excess density is due to suspended sediment held in

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suspension by fluid turbulence [*Middleton*, 1993]. This type of current, driven by gravity acting on dispersed sediment in the flow, was also called a "sediment gravity flow" by *Middleton and Hampton* [1973, 1976]. This is a general term that includes any flow by which sediment moves due to its contribution to the density of the fluid, without referral to range of concentrations, Reynolds numbers, duration, or grain size. The understanding of this type of flow has been hampered by the extreme difficulty of monitoring it in the sea. Direct observation of sediment gravity flows within submarine canyons remains a difficult goal, although field research during the last several decades has resulted in reasonable documentation of several initiation mechanisms. The principal mechanisms are the injection of high concentration sediment suspensions resulting from river discharge (i.e., hyperpycnal flows [*Mulder and Syvitski*, 1995; *Mulder et al.*, 1997]), storm surges [e.g., *Inman et al.*, 1976; *Shepard et al.*, 1977; *Mulder et al.*, 2001], and earthquake-triggered mass failures [e.g., *Schwing et al.*, 1990, *Garfield et al.*, 1994].

[5] Sediment gravity flows causing down-slope transport of mud suspended in seawater have also been documented on several shelves off rivers discharging high suspended-sediment concentrations: Zaire [*Eisma and Kalf*, 1984], Yellow [*Wright et al.*, 1988, 1990], Amazon [*Kineke et al.*, 1996; *Sternberg et al.*, 1996], and Eel [*Ogston et al.*, 2000; *Traykovski et al.*, 2000]. These flows can occur where sediment supply from rivers exceeds transport capacity and the bottom nepheloid layer can concentrate a large amount of sediment (>10 g/L). These phenomena, called "fluid muds," generally involve fine, flocculated material that results from feedback among turbulence, resuspension, and sediment-induced stratification [*Wright et al.*, 2001].

[6] On the Eel shelf, gravity flows of fluid mud trapped by flow convergence and resuspension in the wave boundary layer are an important mechanism for cross-shelf transport during and after flood events [*Ogston et al.*, 2000; *Traykovski et al.*, 2000]. This type of flow has been identified as a key sediment transporting agent for creating mid-shelf flood deposits on the Eel continental margin [*Wheatcroft and Borgeld*, 2000]. Transport was observed to coincide with a period of strong waves and river flooding, suggesting that wave energy plays a key role in both suspending and maintaining these thin gravity flows.

[7] Through seabed observations in the STRATAFORM program, it was documented that a considerable amount of material was accumulating within the Eel Canyon [*Mullenbach and Nittrouer*, 2000]. As a result, the canyon head was instrumented with a BBL tripod and a mooring to identify the principal shelf-to-canyon sediment delivery mechanisms. Simultaneous data collected on the Eel shelf and within the Eel Canyon indicated that the increases of sediment concentration and fluxes in the canyon were not directly related to the Eel River discharge, but were linked to the occurrence of major storms that generate down-canyon sediment gravity flows [*Puig et al.*, 2003].

[8] This paper presents detailed results obtained by the BBL tripod deployed at the head of the Eel Canyon, and focuses on the potential mechanism that generates storm-induced sediment gravity flows in submarine canyon heads. These measurements represent a data set that can yield additional insight into the mechanics of sediment gravity flows, and provide observational evidence about a major process for sediment transfer from the Eel shelf to deeper parts of the margin.

2. Methods

2.1. Time Series

[9] During the STRATAFORM program, a BBL tripod was deployed in the northern thalweg of the Eel Canyon at 120 m depth (Figure 1). The tripod deployment began on 12 January 2000 and ended on 3 April 2000, covering most of the winter season and the entire 1999–2000 Eel River flood period.

[10] Instruments mounted in the tripod included two Marsh McBirney electromagnetic current meters (EMCM) and two Optical Backscatter Sensors (OBS, D&A Instruments) placed at 30 and 100 cm above the bottom (cmab), as well as a pressure sensor located at 140 cmab. These instruments were programmed to sample every hour and collect 470 measurements at 1 Hz (7.5 min of data per burst). The tripod also included a sonic altimeter placed at 117 cmab that hourly recorded distances between the bed and the instrument face. The altimeter had millimeter-scale resolution that was used to measure small-scale changes in seabed elevation. A CTD (Ocean Sensors 200) was installed at 146 cmab to measure water temperature and salinity every 30 min. Two additional temperature sensors (Hugren), set at a 5-min sampling interval, were placed at 30 and 100 cmab to measure the temperature gradient close to the seabed.

[11] The north and east current components measured by both EMCMs were transformed to along-canyon and across-canyon current components, respectively, taking 47° clockwise from North as the orientation of the canyon axis (negative down-canyon and northwestward). The OBS signals were not recorded due to an electronic malfunction, and absolute measurements of suspended-sediment concentration (SSC) were not available. However, the tripod was equipped with a downward-looking video system placed at 180 cmab that took clips of 7 s every 4 hours for seabed roughness observation. The qualitative analysis of the turbidity, using the opacity of the video images, provided temporal evolution of SSC during the entire deployment. Qualitative units ranged from 100 when the monitor screen was black, due to large amounts of suspended sediment in the water, to 5 when the image of the seabed was perfectly clear, during high visibility times. Additionally, an upward-looking 300-kHz acoustic Doppler current profiler (ADCP, RD Instruments) was mounted on the tripod and measured the current components (north, east, and vertical) every hour at 1-m bins, profiling from 115 m to 60 m water depth (i.e., from 5 to 60 mab). The mean backscatter signal measured by the four ADCP transducers was also used as an estimate of the SSC and provided information about the height above the seabed to which particles were suspended.

2.2. Forcing Conditions

[12] The Eel River water discharge during the study period was obtained from a USGS gauging station (11477000), located at Scotia, Canada, approximately 25 km upstream of the river mouth. Wind and wave conditions during the entire study period were recorded

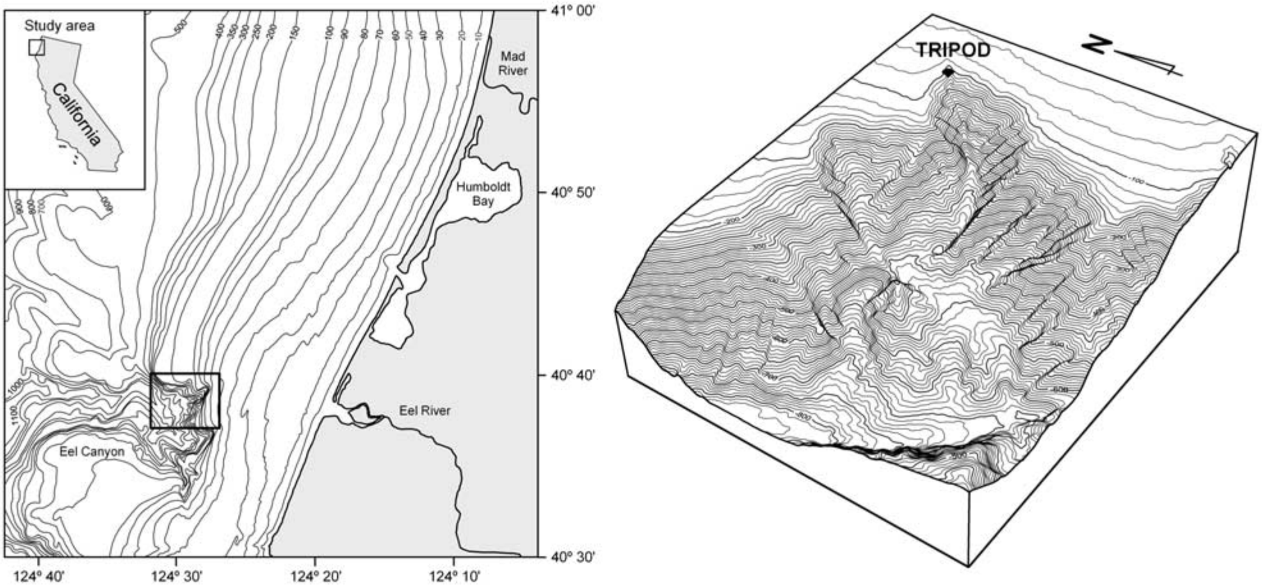

Figure 1. Bathymetric map of the Eel continental margin showing the location of the Eel Canyon head and high-resolution bathymetry for the northern thalweg and main axis of the Eel submarine canyon. The tripod was deployed in the bottom boundary layer at 120 m depth.

by a NOAA buoy (46030), located on Blunts Reef (40°25′22″N, 124°31′31″W) in 82 m water depth about 25 km south of the Eel Canyon. Wind speed and direction, significant wave height, and average wave period were obtained directly form the standard meteorological data file.

[13] Wave-orbital velocities (u_b) at the tripod site (120 m depth) were calculated according to $u_b = u_{rms}\sqrt{2}$, where u_{rms} is the root-mean square wave orbital velocity, which is calculated from the variance of the near-bottom orbital velocity recorded in each burst [*Madsen et al.*, 1993]. Information about the occurrence of earthquakes in the study area during the canyon tripod deployment was obtained from the USGS National Earthquake Information Center.

3. Results

[14] Near-bottom currents measured at the head of the Eel Canyon were distinctly oriented along the canyon axis, and fluctuated up- and down-canyon mainly at semidiurnal tidal frequencies (see work by *Puig et al.* [2003] for further details). Burst-averaged maximum current speeds at 100 cmab were 40.8 and 59.6 cm/s, directed up- and down-canyon, respectively, whereas at 30 cmab they were slightly lower and reached maximum speeds of 37.6 and 48.3 cm/s, up- and down-canyon, respectively.

[15] The temporal evolution of estimates for near-bottom SSC obtained from the opacity of the video images and from the ADCP backscatter signal reflected numerous high-turbidity events that were correlated to storm events, but not to the Eel River discharge (Figure 2). Increases of the wave orbital velocity during storms clearly coincided with high values of SSC, suggesting that surface-wave activity impacted sediment transport through the canyon. Wave-orbital velocities at 120 m depth within the canyon reached values between 20 and 30 cm/s during the most energetic storms. These storm events occurred in late January and early March, before and after the most significant Eel River flood of 2000 (Figure 2d). During the late January storm, the winds were blowing from the southeast, whereas during the early March storm the winds were mainly from the northwest (Figure 2c). Superimposed on the sediment transport events observed during storms, the temporal fluctuation of the altimeter record showed ~5-cm seabed erosion during the first part of the deployment, ~10-cm sediment deposition coinciding with the Eel River flood season, and ~6-cm erosion at the end of the deployment (Figure 2g).

[16] Detailed data analysis during late January and early March storms revealed that when camera opacity values reached 100 units (''black screen'') for several hours, burst-averaged currents at 30 cmab were much higher (~15 cm/s) than at 100 cmab and were directed down-canyon (Figure 3). These inverse near-bottom current profiles (i.e., profiles revealing an increase toward the bed in the down-canyon component of wave-averaged velocity), combined with high estimates of SSC, clearly demonstrate the presence of storm-induced sediment gravity flows at the head of the Eel Canyon, which potentially export large amounts of sediment toward deeper parts of the margin. The ADCP backscatter signal during those events increased considerably, indicating that high estimates of SSC reached many meters above the seabed. Water temperature and salinity measurements at the time of the observed sediment gravity flows did not show significant anomalies, and the temperature gradient close to the seabed was not modified.

[17] Maximum shear stresses at the tripod site were estimated using the combined wave-and-current boundary layer model from *Grant and Madsen* [1986]. A constant angle between waves and currents was used, assuming that the waves were directed onshore, and knowing that the near-bottom currents at the time of the sediment gravity flows were directed down-canyon. Because images from the downward-looking camera did not show any type of bed forms or rough

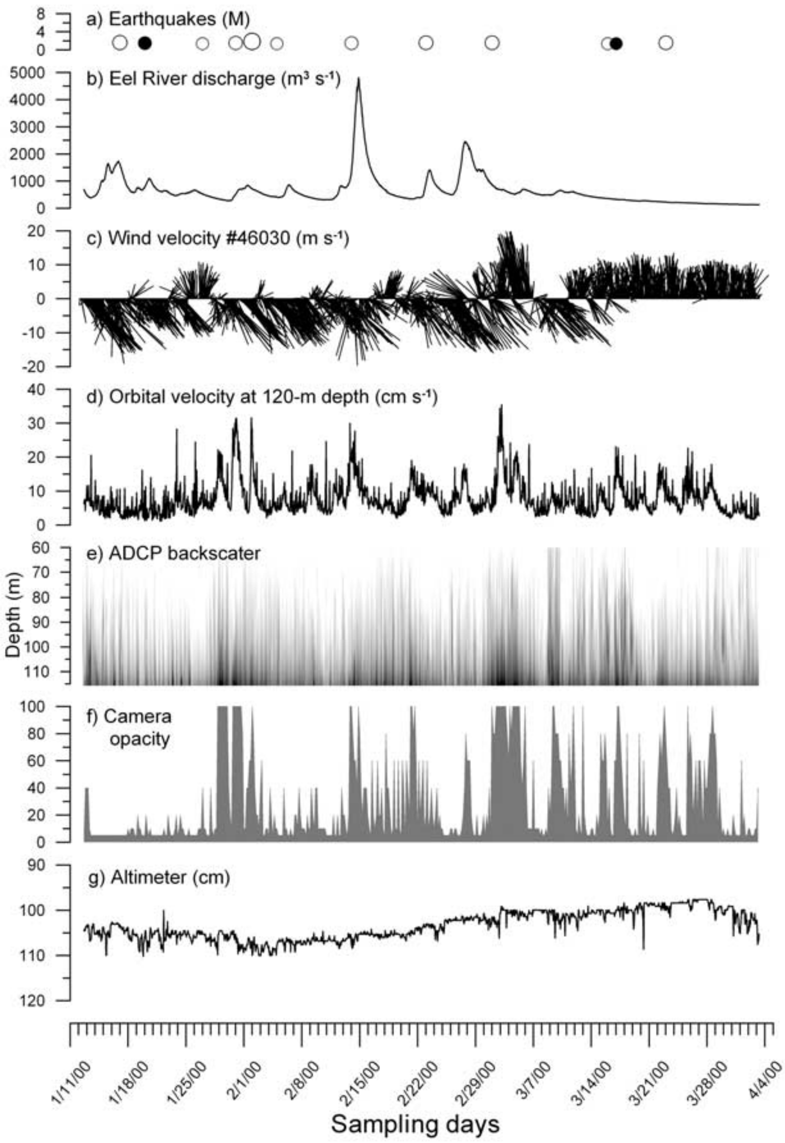

Figure 2. Temporal evolution of the Eel River discharge at Scotia, Canada, and wind velocity vectors recorded by NOAA buoy 46030, combined with time series of wave-orbital velocity (at 120 m depth 100 cmab), estimates of suspended-sediment concentration (ADCP backscatter and camera opacity), and seabed elevation measured relative to the BBL tripod. Note that increases of suspended-sediment concentration were linked to intensifications of the orbital velocity due to the wave activity, without showing correlation to the Eel River discharge. Circles at the top of the plot indicate the occurrence of earthquakes during the study period. The size of the circle scales with the earthquake magnitude (ranging from M 2.8 to 3.8), and the black circles indicate those earthquakes that occurred at the surface. The wind velocity vectors indicate the direction from which the wind blows.

morphology, a flat bottom was considered for the analysis. Combined wave-current shear stresses during the occurrence of sediment gravity flows were >0.1 Pa, reaching maximum values in late January and early March storms of 0.17 and 0.20 Pa, respectively (Figure 3d).

[18] Coinciding with the occurrence of a sediment gravity flow, the near-bottom current components recorded at the "burst" timescale (1 Hz) oscillate at the same periodicity as the pressure and were mainly oriented in the along-canyon direction (Figure 4). This up- and down-canyon current fluctuation at high frequencies denotes a clear influence of the surface-wave activity on the currents at 120 m depth, which may also contribute to maintenance of the sediment gravity flow while it is transported down-canyon.

[19] During the study period, 12 minor earthquakes ranging from M 2.8 to 3.8 were detected in the study area (Figure 2). Those earthquakes were mainly deeper than 15 km; only two of them occurred at the surface.

4. Discussion

4.1. Origin as Sediment Gravity Flows

[20] The occurrence of several storm-induced sediment gravity flows during winter 2000 would require the forma-

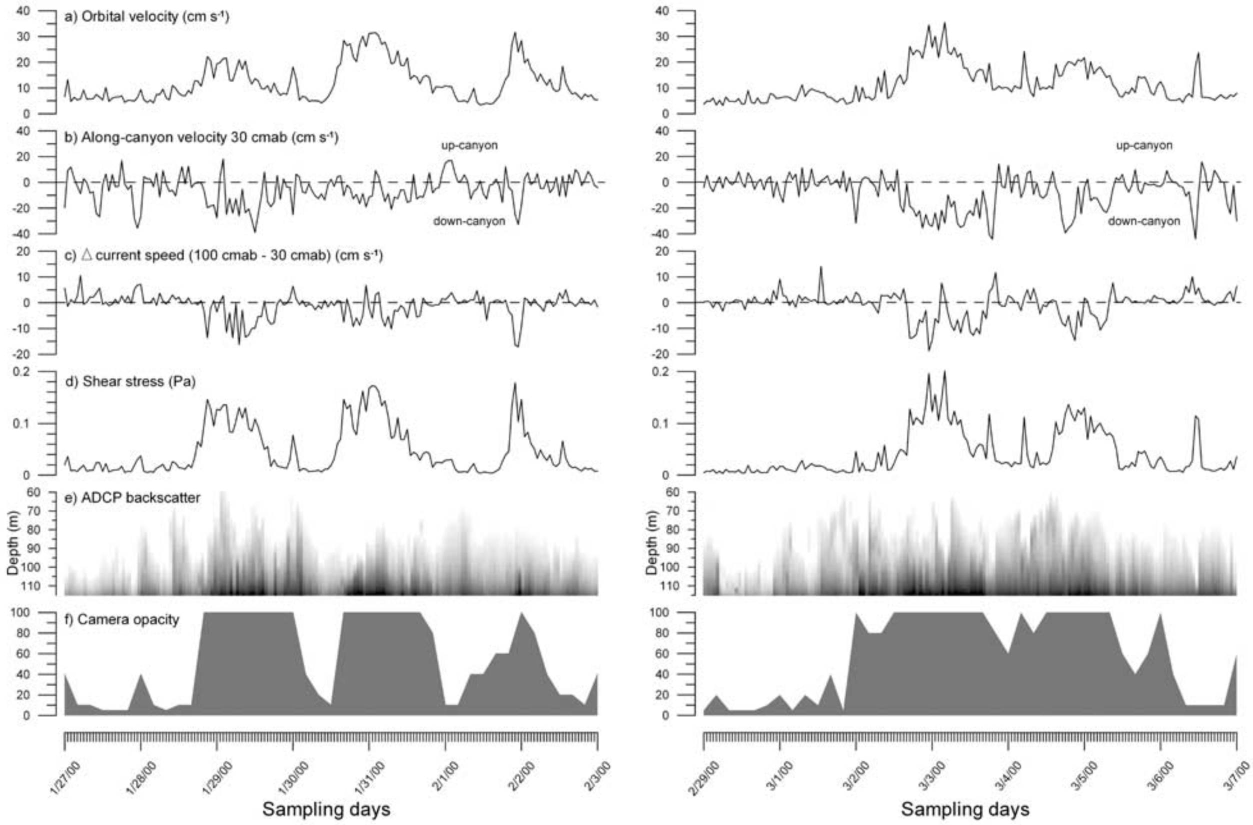

Figure 3. Detail of the measurements at the Eel Canyon head during (left) late January storm and (right) early March storm, showing the occurrence of several sediment gravity flows (three in late January and two in early March). Note that during these events, increases of the orbital velocity coincide with the higher estimates of suspended-sediment concentration, and that currents at 30 cmab are much greater than currents at 100 cmab and are directed down-canyon. The calculated wave-current shear stresses during these events are slightly above 0.1 Pa.

tion of high-concentration near-bottom suspensions or fluid muds up-canyon from the tripod location, originating from the adjacent shelf or within the canyon thalweg. *Traykovski et al.* [2000] discussed the role of wave-dominated bottom stresses in generating and transporting fluid mud on the Eel shelf during periods of high sediment input (floods in the Eel River) and large wave-orbital velocities (storms on the shelf). These fluid-mud layers appear to be trapped in, and scale in thickness with, the wave boundary layer and seem to flow downslope until they run out of wave energy. This occurs in a depth of 90–110 m of water (on the outer shelf) where the wave boundary layer during storms is less than 5 cm [*Traykovski et al.*, 2000].

[21] *Ogston et al.* [2000], after comparing measurements obtained from three instrumented tripods deployed simultaneously on the Eel shelf, suggested that the generation of these high-concentration bottom layers occurs in shallow water beneath the river plume and that they move seaward from a coast-parallel line source. Although the fluid-mud flows could be directed toward the Eel Canyon region and may be the origin of the sediment gravity flows observed in the canyon head, measurements from one of these events demonstrated that on the shelf it takes about 12 hours to move fluid mud from 60 to 65 m water depth [*Ogston et al.*, 2000]. In this situation a seaward-moving high-concentration bottom layer would arrive at the outer shelf many hours after being generated by the wave action in shallower locations.

[22] Data from the canyon tripod indicates that the sediment gravity flows (identified by the difference between current speed at 30 and 100 cmab) occur almost simultaneously with the increase in orbital velocity (Figure 3), and that they do not coincide with the occurrence of a major Eel River flood event (Figure 2). In addition, boundary layer measurements obtained on the Eel shelf during winter 2000 showed that SSC recorded at 60 m depth only reached maximum concentrations at 30 cmab of $\sim$1 g/L during late January and early March storms, when the sediment gravity flows were observed in the canyon head [*Puig et al.*, 2003], suggesting that the formation of fluid-mud concentrations on the shelf was unlikely at that time. This indicates that the observed sediment gravity flows are not related to the formation of fluid-mud flows on the shelf, and that they appear to be generated by other mechanisms occurring in the same canyon-head region.

4.2. Episodic Mass Failure

[23] Instability of sedimentary deposits on continental margins can be an important mechanism for sediment transport and redeposition [*Evans et al.*, 1998]. Slope fail-

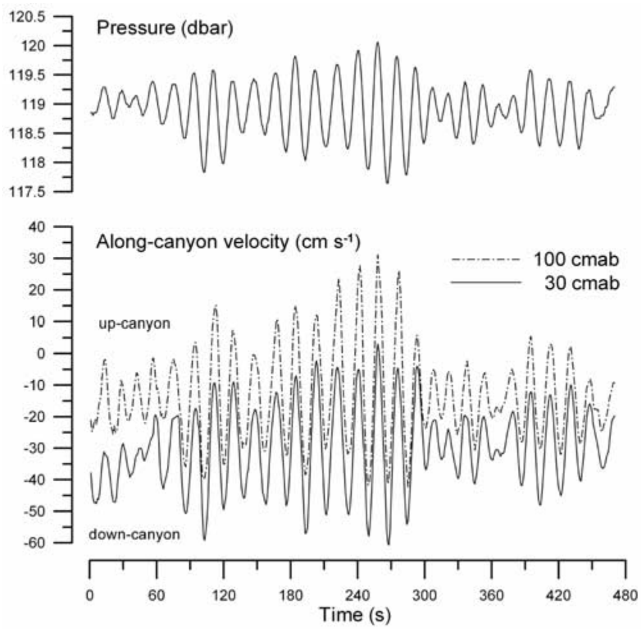

Figure 4. Detail of the temporal evolution of the pressure and the along-canyon current components from a sampling burst (470 s), coinciding with the occurrence of a sediment gravity flow during a late January storm (0700 on 29 January 2000). Note that the 30-cmab current velocities are persistently down-canyon, 15–20 cm/s greater than those at 100 cmab, and that the current components fluctuate at the same periodicity as the pressure (17 s).

ures occur where the relative magnitudes of the environmental forces that tend to deform and weaken sedimentary deposits exceed the strength properties of the sediment that tend to resist such deformation. Bottom slope, seismicity, and storm-wave environment impact the driving forces, whereas sediment-depositional patterns and sediment-stress history control the resisting strengths [*Lee and Edwards*, 1986].

[24] Turbidity currents triggered by large earthquakes can be recognized from their synchronous development in several different sediment drainage systems [*Normark and Piper*, 1991]. Numerous synchronous Holocene turbidite events (i.e., recorded by turbidite deposits) have been found in canyon mouths and downstream channels of Cascadia Basin, from Vancouver Island to Cape Mendocino [*Nelson and Goldfinger*, 1999, 2000]. The number of Holocene turbidite events progressively increases toward the Mendocino Triple Junction at the southern end of Cascadia Basin, which suggests that they were seismically triggered. In the channel of the Eel Fan, 50 turbidite events, or approximately one every 200 years, have occurred throughout the Holocene, although the absence of recent events suggests that they probably represent earthquakes greater than M 7.2 [*Nelson and Goldfinger*, 1999]. Seismicity in the study area during the tripod deployment was very weak (M 2.8–3.8). Most of the earthquakes were deep (>15 km), and the two earthquakes that occurred at the surface did not cause any sediment gravity flows in the canyon head (Figure 2).

[25] Sediment failure in submarine canyon heads also may be induced by storm waves [*Lee and Edwards*, 1986]. In Scripps Canyon head, mostly between 15 m and 60 m depths, a layer of sediment several meters thick was removed during a discrete flushing event caused by storm surge [*Inman et al.*, 1976; *Shepard et al.*, 1977]. Similarly, storm-induced flushing of the sediment deposited in the Monterey Canyon head may occur annually during the first onshore storm of the fall/winter season [*Okey*, 1997; *Xu et al.*, 2002]. In the Capbreton Canyon, *Mulder et al.* [2001] found a turbidite deposit associated with a sediment failure at the canyon head caused by a violent storm (10-year return period) that hit the Bay of Biscay in December 1999. Usually, this type of event has been associated with extremely large storms and a recurrence period of several years. However, the sediment gravity flows observed in the Eel Canyon head during winter 2000 occurred several times through the same stormy period, coinciding with increases of wave energy, each lasting for several hours as the wave orbital velocity maintained high values (Figure 3). This behavior suggests that these gravity-driven processes are not caused by a single catastrophic event, but rather by a more continuous mechanism that can occur several times throughout a given stormy period and rapidly supply sediment particles to the water column.

4.3. Sediment Resuspension

[26] Wave-current resuspension of outer-shelf sediment deposited around and within the canyon head, combined with focused sediment transport toward the axis of the canyon, could be a plausible mechanism for creating the high SSC necessary to generate a sediment gravity flow. Shear stresses at the tripod site were estimated using the combined wave-and-current boundary layer model from *Grant and Madsen* [1986] to estimate if surface sediment deposited around the canyon head could be resuspended during the two major storms that generated sediment gravity flows. Maximum wave-current shear stresses at the tripod site during the occurrence of sediment gravity flows were 0.17 and 0.20 Pa during late January and early March storms, respectively. Critical shear stresses for fine-grained cohesive sediments are difficult to determine, and they have to be obtained by means of erosion devices [*Gust and Müller*, 1997; *Whitehouse et al.*, 2000]. Experimental analysis using an erosion chamber was performed on a sediment core immediately following collection in April 2000 in the Eel Canyon head (96 m water depth). Results from this analysis revealed that resuspension of aggregates at the sediment surface occurred at a shear stress of 0.07 Pa, and that the critical shear stress for fine-grained (d_{50} = 9 μm) underlying sediments was 0.27 Pa [*Thomsen et al.*, 2002]. These measurements are characteristic of a single location at a particular time, therefore representing only a glimpse of the seabed. However, they indicate that aside from an easily erodible surface layer, the critical shear stress observed is higher than the maximum combined shear stresses reached during the two major storms that initiated the observed sediment gravity flows (0.1–0.2 Pa). This suggests that wave-current resuspension in the vicinity of the canyon head could occur, but that significant erosion could not be generated. Assuming that the production of sediment gravity flows from multiple storms in close succession would require some erosion of underlying sediments, it is unlikely that spatial or temporal variability of erosive capability is sufficient to produce the flows observed.

[27] The rapid formation the sediment gravity flows, immediately after the increase of the wave-orbital velocity, also suggests that such flows could not be initiated from wave-current resuspension alone. Entrainment of sediment into suspension needs a certain amount of time (hours) to fill the boundary layer with SSC great enough to generate fluid-mud suspension and develop a sediment gravity flow, even if bottom shear stresses are much higher than critical values for surface sediment resuspension. To test whether sediment resuspension in the canyon head region could generate such flows, the erosion rate E during the most energetic storms can be calculated using the *Smith and McLean* [1977] relationship,

$$E = 0.65\frac{0.0024(\tau_s/\tau_c - 1)}{1 + 0.0024(\tau_s/\tau_c - 1)}, \tag{1}$$

where E is the dimensionless entrainment rate, the applied shear stress is τ_s = 0.2 Pa, the largest shear stress during the storm events, and τ_c = 0.07 Pa, the critical shear stress from the surface sediment. The erosion rate is related to the dimensionless entrainment rate according to

$$\mathrm{E} = v_s E, \tag{2}$$

where v_s is the particle settling velocity observed by *Sternberg et al.* [1999] on the Eel shelf (i.e., 1 mm/s).

[28] Though quantitative concentration measurements were not made at the tripod site, the minimum concentration necessary to generate the downslope velocity observed can be estimated from the internal Froude number. Because the observed events were episodic, their dynamics will be controlled by the front of the flow. In this case, the internal Froude number must be close to one [*Parsons*, 1998]. That is,

$$\frac{U}{\sqrt{gRCh}} = 1, \tag{3}$$

where g is the acceleration of gravity (9.81 m/s^2), U is the mean downslope velocity at some height h, R is the submerged specific gravity of the sediment (1.6 for quartz), and C is the volumetric concentration. Therefore, solving C for U = 0.3 m/s at h = 0.3 m, we find that C = 0.019. This is consistent with unidirectional turbidity currents in the laboratory and in nature [*Parsons et al.*, 2002].

[29] If all of the sediment in suspension comes from the site of measurement, for surface sediment with a porosity of 0.65 [*Mullenbach*, 2002] and using an entrainment rate of 0.003 mm/s, it would take 5400 s to load the BBL with C = 0.019 from the seabed up to 0.3 m. Nearly 6 mm of erosion is necessary to produce this concentration. In reality, the concentration toward the bed will be higher and this effect will increase both the time required to reach C = 0.019 at 0.3 mab and the thickness of the eroded sediment layer. The estimated time lag and the depth of erosion associated with resuspension are inconsistent with the rapid formation of the observed sediment gravity flows, even without considering the heightened concentrations near the bed.

[30] One mechanism that could produce heightened concentrations within the canyon is sediment convergence. Sediment convergence has been suggested to be important for the formation of fluid muds on the continental shelf [*Ogston et al.*, 2000], and it may be common in submarine canyons (e.g., Quinault Canyon [*Thorbjarnarson et al.*, 1986]). However, the down-canyon flux observed at the tripod must be less than the entrainment flux generated in the contributing area. If we assume that within the thalweg the flow is uniform (consistent with high-resolution coring at the tripod site [*Lomnicky et al.*, 2003]), an estimate of the volumetric flux of sediment within the thalweg (Q_t) can be written as

$$Q_t = CUhw, \tag{4}$$

where C is the minimum volumetric concentration required to generate the sediment gravity flows, U and h are the velocity and the height of the current, respectively, and w is the width of the thalweg. Using the detailed bathymetry from the study area (Figure 5), the width of the thalweg w is 70 m. Again using U = 0.3 m/s and h = 0.3 m, and considering the contribution of flow above 0.3 m to be negligible (consistent with the measurements at 1 mab), the minimum down-canyon volumetric sediment flux within the thalweg is 0.12 m^3/s.

[31] During storm events, resuspended sediment inside the canyon will converge toward the axis of the thalweg and increase the bottom concentrations. The area up-canyon from the tripod site will have a direct impact on the observed flows. This area can be considered as the triangle described from 120 m water depth in the axis of the thalweg to the 95-m isobath (Figure 5), which is about 60,000 m^2. The milder slopes on the adjacent outer shelf will most likely produce much slower-moving gravity flows than within the canyon proper. As a result, these areas would not contribute to the nearly instantaneous flux observed within the canyon. The volumetric entrainment flux from the area of interest (Q_e) can be expressed as

$$Q_e = (1 - n)A\mathrm{E}, \tag{5}$$

which for a sediment porosity n = 0.65, A = 60,000 m^2 and E = 0.003 mm/s, becomes Q_e = 0.063 m^3/s, so $Q_t > Q_e$. Though the time required for all of the material from this area to be transported to the observation point is less than the sampling rate of the instruments (i.e., the farthest point in the triangle in Figure 5 requires 22 min of travel time between it and the observation point), resuspension alone is insufficient to produce the flux required to generate the observed sediment gravity flows, even when sediment convergence is considered. Therefore another transport mechanism must contribute to the rapid generation of sediment gravity flows within the canyon head during storms.

4.4. Fluidization by Waves

[32] The wave-orbital motions, in addition to generate shear stresses, also create a load fluctuation that, depending on the resistance of the seabed, can result in sediment fluidization or liquefaction [*Clukey et al.*, 1985; *Li and Mehta*, 1997; *De Witt and Kranemburg*, 1997]. In areas of high wave energy, liquefaction provides an alternative mechanism to resuspension from the seabed for creating

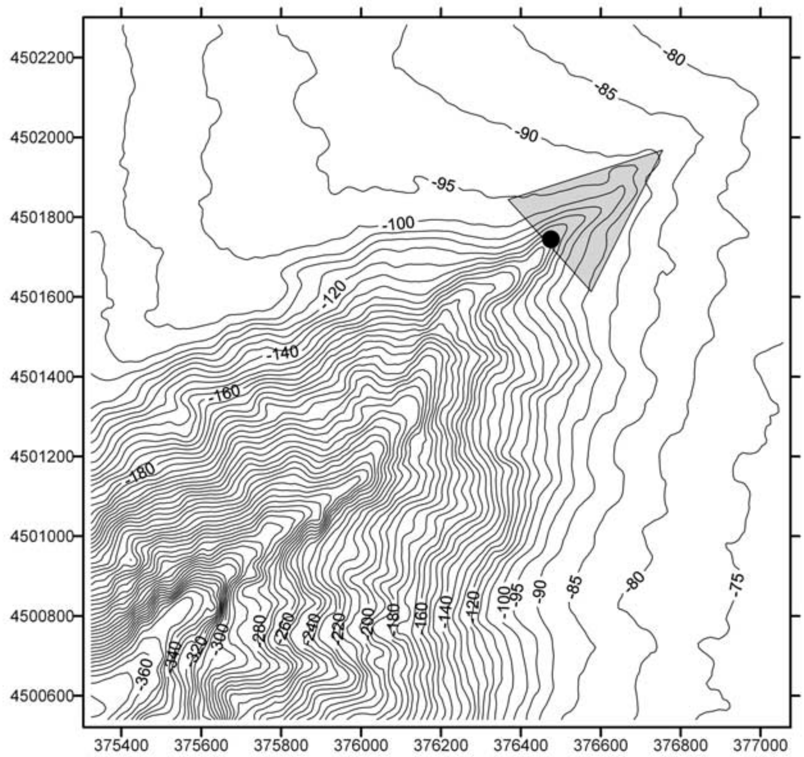

Figure 5. Detailed bathymetry from the upper-canyon section showing the location of the tripod (dot) and the area up-canyon from the tripod site considered for the volumetric entrainment flux analysis (triangle). Note that the map is in Universal Transverse Mercator coordinates.

fluid-mud suspensions. During a given storm, infiltration pressures oscillate with wave pulses, while shear-induced excess pore water pressures increase progressively. Gradients in pore pressure can cause the pore fluid to flow relative to the soil skeleton, which may eventually lead to rupturing of the interparticle cohesive bonds, hence a loss of effective stress [*Mehta*, 1991]. When the initial bed matrix is disturbed by wave motion, the general manner in which liquefaction occurs depends on several factors, an important one being the degree of consolidation of the surface sediment.

[33] Submarine canyons serve as preferential traps and conduits for suspended sediment, which eventually may deposit on the seafloor, generating elevated sediment accumulation rates along the canyon axis [e.g., *Thorbjarnarson et al.*, 1986; *Schmidt et al.*, 2001]. A mud bed created from deposition of suspended sediment that has not been compacted by previous wave loading will liquefy almost immediately after wave load is placed on it [*Lindenberg et al.*, 1989; *Verbeek and Cornelisse*, 1997]. In addition, the presence of a large fraction of organic material in the sediment leads to the occurrence of an open sedimentary structure that fluidizes quite easily [*Mehta*, 1991]. This means that sediment wave-load liquefaction can easily occur in unconsolidated cohesive sediments with high water content and presence of organic matter such as the ones found in many submarine canyon heads, including Eel Canyon [*Mullenbach and Nittrouer*, 2000].

[34] Owing to the disintegration of the bed structure after liquefaction, the critical shear stress for sediment erosion decreases to almost zero [*Verbeek and Cornelisse*, 1997], and consequently, the volume of the transportable sediment under high wave stresses can increase considerably [*Clukey et al.*, 1985]. Laboratory studies of wave-induced sediment instability demonstrated that the wave shear stresses, when combined with gravity stresses, produced mass movement in the sediment column [*Mitchell et al.*, 1972; *Van Kessel and Kranenburg*, 1998]. Therefore, additional gravity shear stresses imposed by elevated slopes at the canyon head could help to initiate transport of a thin layer of wave-load-fluidized sediment and generate the sediment gravity flows observed.

4.5. Implications for the Sedimentary Record

[35] At "burst" timescale, the near-bottom current components measured during a sediment gravity flow oscillate at the same periodicity as the pressure (Figure 4), suggesting that the turbulence generated at the seabed by the surface waves is that responsible for keeping sediment in suspension. As soon as the wave energy diminishes, the estimates of SSC decreases drastically and the large down-canyon velocity near the bed, indicative of sediment gravity flows, ceases to exist (Figure 3c). This observation suggests that most of the sediment settles to the seafloor when the wave-current shear stresses are unable to support the sediment gravity flow. *Whitehouse et al.* [2000] found that there is a strong tendency for fluid mud to dewater and consolidate at low bed stresses (on the order of 0.1 Pa). This limit agrees with the timing for disintegration of the sediment gravity flows relative to the calculated wave-current shear stresses (Figure 3d). The rapid settling of sediment particles is also consistent with observations from the altimeter mounted on

the tripod, which reflected an erosional trend at the beginning and end of the deployment, but a net deposition of about 10 cm during the Eel River flood season, which was also the period dominated by sediment gravity flows (Figure 2). A similar depositional behavior was found by *Traykovski et al.* [2000] due to fluid-mud flows observed on the Eel continental shelf, where the decrease of the wave energy caused deposition of the near-bed high-concentration layer and contributed to the formation of the mid-shelf mud deposit. The processes observed in the Eel Canyon head could explain the thick layers (up to 19 cm) of recent sediment deposits (detectable ^{7}Be activity, high percentage of clay, and distinct physical sedimentary structures) formed annually inside the canyon [*Mullenbach and Nittrouer*, 2000; *Mullenbach et al.*, 2004]. The fact that the thickest deposits were consistently observed in the upper channel thalwegs (<500 m water depth) and not deeper [*Mullenbach et al.*, 2004] suggests that most of the sediment transported down-canyon settles to the seabed at depths just below where the wave energy is sufficient to maintain the sediment gravity flow, limiting the deposition to the upper canyon.

5. Conclusions

[36] Results from this field study have identified the presence of periodic storm-induced sediment gravity flows occurring at the head of the Eel submarine canyon. These flows are not related to river floods or intense resuspension of outer shelf sediments. Rather, they seem to be generated by development of excess pore water pressure during storms, which causes liquefaction of sediment deposited at the head of the canyon. The steep slopes around the canyon head may help to initiate down-canyon transport of a liquefied sediment layer and induce the rapid formation of a sediment gravity flow. This sediment transport process could explain the formation of thick recent sediment deposits found annually in the upper Eel Canyon. The results also suggest that the occurrence of storm-induced sediment gravity flows in submarine canyons could be more frequent than expected before, as most canyons have their heads at depths within the range of surface-wave activity. Thus, further BBL measurements within canyon heads will be necessary to fully understand contemporary off-shelf sediment transport and accumulation processes in submarine canyons.

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