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Emplacement of massive turbidites linked to extinction of turbulence in turbidity currents

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Submarine turbidity currents are controlled by gravity acting on suspended sediments that pull water downslope along with them[1]. In addition to suspended sediments, turbidity currents also transport sediments at the base of the flow[2], which causes the reorganization of basal sediments prior to the settling of suspended grains[3–6]. However, as turbidity currents reach areas with minimal slope, they cross a fall-velocity threshold beyond which the suspended sediments begin to stratify the flow. This process extinguishes the turbulence near the bed[7,8]. Here we use direct numerical simulation of turbidity currents to show that this extinction of turbulence eliminates the ability of the flow to re-entrain sediment and rework the sediment at the base of the flow. Our simulations indicate that deposits from flows without basal reworking should lack internal structures such as laminations. Under appropriate conditions, then, sustained delivery of fine sediments will therefore result in the emplacement of massive turbidites. We suggest that this mechanism can explain field observations of massive deposits[9] that were emplaced gradually by dilute but powerful turbidity currents. We also conclude that turbulence in submarine turbidity currents is more fragile than river systems, and more sensitive to damping by the stratification of suspended sediment in the flow.

Turbidites are often characterized in terms of complete or partial manifestations of the Bouma sequence[10]. Units T_a to T_e in Fig. 1a correspond to a single flow event, with flow waning from bottom to top. Intervals T_a and T_b, tend to be sand. Interval T_b has parallel laminations, indicating bedload reworking as sediment settles[3]. Interval T_a is 'massive', that is, lacking sedimentary structures. Massive deep-sea turbidites are prominent features of channelized and unchannelized submarine fans. They are enigmatic in that they show little or none of the internal structure used to interpret emplacement mechanisms.

Parallel laminations are seen in fluvial deposits as well as turbidites, and have been reproduced in the laboratory[3–6]. Their formation is due to the organization of sand grains into streaks according to size and orientation by bedload. Mechanisms for the emplacement of massive turbidites are more speculative. These units are common in the ancient rock record of deep-water deposits, as well as in deeper parts of modern continental margins. Individual event beds can be up to metres in thickness (Fig. 1b), and extend for tens to hundreds of kilometres in the downdip and lateral directions[11]. They lack fluvial analogues.

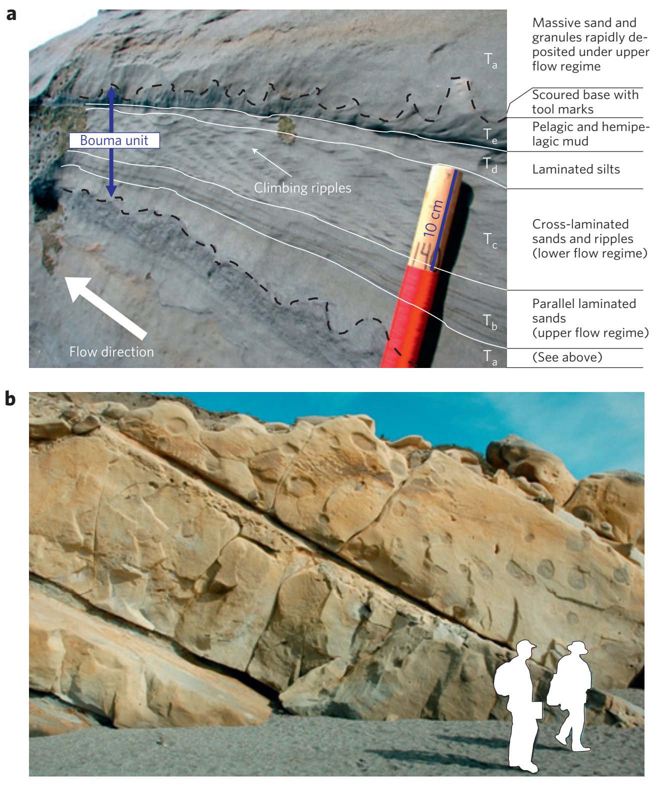

Figure 1 | Sedimentary deposits. a, Bouma sequence in an outcrop. Mount Messenger formation, New Zealand (courtesy of Zane Jobe). **b**, Three massive beds in an outcrop. German Rancho formation, USA (courtesy of Zoltan Sylvester).

Several mechanisms have been proposed for massive units. High-density turbidity currents were originally hypothesized to be surge-like currents with sediment concentrations ~20–30% by weight[12,13]. Near-bed grain hyperconcentration and hindered settling might significantly damp turbulence, causing sediment to be dumped out so as to prevent the formation of internal structures.

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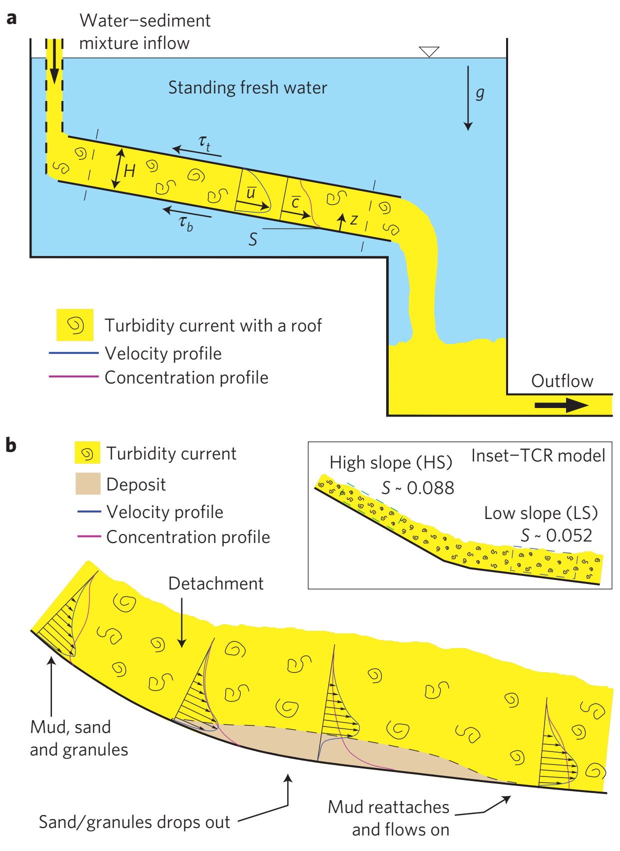

Figure 2 | Turbidity current modelling. a, Illustration of Turbidity Current with a Roof (TCR). The model considers flow purely driven by suspended sediment between parallel plates and neglecting ambient water entrainment. The TCR model captures stratification effects and allows for the development of equilibrium flows. **b**, Illustration of the 'separation bubble' leading to the gradual emplacement of a sandy massive turbidite. The material that drops out may include coarse mud as well. Inset: Illustration of the application of TCR to a declining bed slope.

A modified hypothesis invokes more incremental deposition from a sustained high-density turbidity current[14]. High-density turbidity currents in the laboratory, however, emplace parallel laminations[15].

Massive deposits might be emplaced by sandy debris flows[16]. Such flows would have no bedload and would freeze as they deposit without forming laminations. Experiments on sandy debris flows indicate that some mud must be present to allow runout on angles less than about 5 degrees (ref. 17).

Experiments have shown that relatively high deposition rates from sustained but relatively dilute fluvial suspensions can interfere with bedload reorganization and suppress parallel laminations[18]. This result might generalize to turbidity currents.

Each of these mechanisms may have a range of validity. The mechanism proposed here, however, need not invoke any of the additional factors of modified near-bed rheology due to hyperconcentration, debris flows or high deposition rates. As explained below, the proposed mechanism relies on flow density self-stratification, a phenomenon that is well-documented in rivers carrying suspended sediment[19]. It thus may have a wider range of validity than those previously proposed.

Stably stratified geophysical flows show profiles of density that decrease upwards. Stable stratification damps turbulence by suppressing mixing across the density gradient. River flows self-stratify as they suspend their own bed sediment[20]. Stable self-stratification in sand-bed rivers biases suspended sediment towards the bed, reduces depth-averaged concentrations and damps bed friction[19,21]. Fluvial self-stratification, however, is also self-limiting; were turbulence damping to cause all the suspended sediment to deposit, the flow would continue as gravity pulls the water itself.

Turbidity currents do not share this resilience, as illustrated by direct numerical simulations of the Navier–Stokes equations governing sediment-laden flow[7]. A sufficiently high near-bed concentration gradient causes turbulence to be extinguished there. Sediment can thus settle out on the bed with little or no resuspension or reworking by bedload, so emplacing a massive deposit.

Turbidity currents do not have an equilibrium flow, such as that of rivers, because of ambient water entrainment[22]. This makes their modelling difficult. The formalism of 'Turbidity Current with a Roof'[7] (TCR) overcomes this by considering a flow driven purely by suspended sediment, but confined between two parallel plates (Fig. 2a). In the figure, H is channel height, z is the upward normal coordinate, $\bar{u}$ and $\bar{c}$ are respectively the flow velocity and volume concentration of suspended sediment averaged over turbulence (AOT), and τ_b and τ_t denote bottom and top shear stresses AOT.

Sediment resuspension from the rough, granular bed is modelled by the artifice of 'laminar' particle diffusion. Flow extinction is realized when the sediment is sequestered in a thin, near-bed zone where the particles are held up solely by laminar diffusivity. This configuration allows equilibrium flow and captures stratification effects.

Let S be the channel slope, C the layer-averaged volume suspended sediment concentration AOT (assumed to be $\ll 1$, that is dilute), V_s the sediment fall velocity (single size), g the gravitational acceleration, ρ the water density, ρ_s the sediment density, $R = (\rho_s/\rho) - 1$ ($\cong$1.65 for quartz) and ν the kinematic viscosity of water. Three dimensionless parameters govern turbulence: the shear Richardson number Ri_τ, the shear Reynolds number Re_τ and the dimensionless fall velocity $\tilde{V}$ given by

$$\mathrm{Ri}_\tau = \frac{RgCH}{2\,u_{*n}^2}$$

$$\mathrm{Re}_\tau = \frac{u_{*n}\,H}{2\,\nu}$$

$$\tilde{V} = \frac{V_s}{u_{*n}}$$

where $u_{*n} =$ is the nominal shear velocity given in terms of u_{*b} and u_{*t}, the shear velocities at the bottom and top walls, by

$$u_{*b}^2 = \frac{\tau_b}{\rho}$$

$$u_{*t}^2 = \frac{\tau_t}{\rho}$$

$$u_{*n}^2 = \frac{1}{2}\left(u_{*b}^2 + u_{*t}^2\right)$$

Here Re_τ characterizes turbulence in the absence of stratification ($\tilde{V} = 0$ in TCR). Ri_τ and $\tilde{V}$ mediate the degree of stratification and, thus, turbulence damping. For a given $\tilde{V}$, increasing Ri_τ damps turbulence and biases suspended sediment towards the bed; increasing $\tilde{V}$ for a given Ri_τ has the same effect. These trends also prevail for fluvial suspensions[8]. In the layer-averaged four-equation model of turbidity currents[22] damping is mediated by the product $\mathrm{Ri}_\tau\,\tilde{V}$.

The effect of increasing $\tilde{V}$ while holding $\mathrm{Ri}_\tau = 11.4$ in TCR is shown in ref. 7. $\tilde{V} = 0$ yields the expected unstratified turbulent logarithmic layer, which is maintained as $\tilde{V}$ increases to 0.022. Turbulence damping is reflected in an effective Karman constant that decreases with increasing $\tilde{V}$, in analogy to rivers[19].

Turbulence is abruptly extinguished in a substantial zone near the bed as $\tilde{V}$ increases beyond 0.022. Let u' and w' be

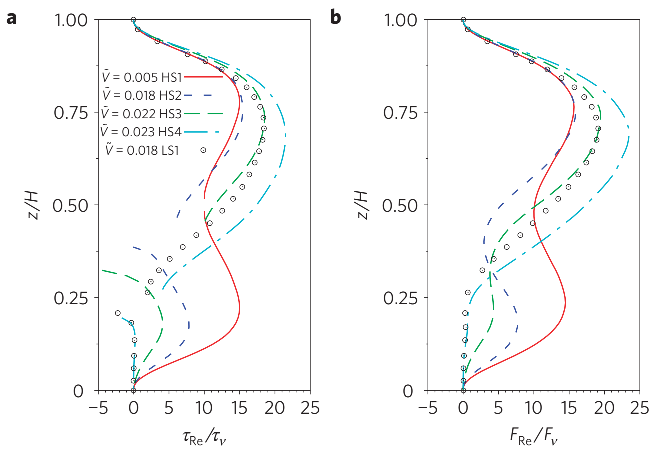

Figure 3 | Reynolds flux profiles in the TCR model. a, Vertical profile of $\tau_{\mathrm{Re}}/\tau_\nu$. **b**, Vertical profile of F_{Re}/F_ν. HS refers to results for the high slope model and LS refers to results for the low slope model (see inset in Fig. 2b).

the local fluctuating components of streamwise and upward normal velocity, and c' be the local fluctuating component of volume suspended sediment concentration. The turbulent Reynolds stress τ_{Re} and turbulent upward normal Reynolds flux of suspended sediment F_{Re} are:

$$\tau_{\mathrm{Re}} = -\rho\overline{u'w'}$$

$$F_{\mathrm{Re}} = \overline{c'w'}$$

The corresponding molecular forms are:

$$\tau_\nu = \rho\nu\frac{\mathrm{d}\bar{u}}{\mathrm{d}z}$$

$$F_\nu = -\kappa\frac{\mathrm{d}\bar{c}}{\mathrm{d}z}$$

Figure 3 shows $\tau_{\mathrm{Re}}/\tau_\nu$ and F_{Re}/F_ν versus z/H for $\tilde{V} = 0.005$, 0.018, 0.022 and 0.023 and $\mathrm{Ri}_\tau = 11.4$ (HS in Fig. 3). For $\tilde{V} = 0.023$, both ratios vanish within $0 \le z/H \le 0.175$. Values of $\tilde{V} > 0.022$ thus cause self-stratification that does not simply modify the flow, but rather completely changes it by extinguishing turbulence in a substantial near-bed zone. In Fig. 3, $\mathrm{Re}_\tau = 180$, a value that is orders of magnitude below field scale, but falls within the range of turbulence Reynolds similarity[7,23]. Results with $\mathrm{Re}_\tau = 180$, 400, $\mathrm{Ri}_\tau = 11.4$ under varying configurations for TCR show a slow increase in critical $\tilde{V}$ for turbulence suppression with increasing Re_τ, allowing possible extrapolation to field conditions.

The above result has profound implications for field-scale turbidity currents because subtle changes in slope, grain size and loss of confinement can disrupt the fragile equilibrium between the settling of sediment grains and their upward resuspension by near-bed turbulence. Channel slope declines downstream in submarine canyon-fan systems[24]. In TCR, the balance between the downstream pull of gravity and boundary resistance yields $\mathrm{Ri}_\tau = 1/S$. That is, $\mathrm{Ri}_\tau = 10$ for $S = 0.1$, for example at the head of Scripps Submarine Canyon[25], and $\mathrm{Ri}_\tau = 500$ for $S = 0.002$, for example at the distal end of the Amazon Submarine Channel[24]. Calculations for sand-bed rivers at bankfull flow, however, yield values of Ri_τ ranging from about 0.5 to 3 (Supplementary Text S1). Turbidity currents are thus far more fragile than rivers in regard to turbulence damping by self-stratification.

We explore the effect of declining slope by applying TCR (as documented in refs 7 and 8) to two equilibrium cases (see Fig. 2b inset): (1) high slope $S = 0.088$ ($\mathrm{Ri}_\tau = 11.4$, HS2), and (2) low slope $S = 0.052$ ($\mathrm{Ri}_\tau = 19.1$, LS1), both with $\tilde{V} = 0.018$ and $\mathrm{Re}_\tau = 180$. At the higher slope the flow is fully turbulent near the bed, but the turbulence there ($z/H \le 0.175$) is extinguished at the lower slope (see Fig. 3), creating conditions conducive to massive-turbidite emplacement.

Table 1 | Results of the field-scale application of the TCR example shown in Fig. 3.

D (μm)	V_s (cm s^{-1})	u_{*n} (m s^{-1})	H_h (m)	H_l (m)
80	0.51	0.29	12	20
100	0.75	0.43	26	43
150	1.44	0.82	95	160
200	2.21	1.27	225	376

For field-scale interpretation, we consider sediment sizes $D = 80$, 100, 150 and 200 μm, and $C = 0.01$ (ref. 24). Values of u_{*n} and the flow thicknesses H_h and H_l at the higher and lower slopes are obtained from the specified values of $\tilde{V}$, Ri_τ and C (see Table 1).

H_h and H_l, which increase with increasing grain size, fall in a realistic range for field-scale turbidity currents[24,26]. The lower slope yields higher flow thicknesses, which are conducive to near-bed turbulence extinction in field-scale flows.

Turbidity currents transport a range of sizes, including sand, mud and granules. Leveed submarine channels often have sand-rich beds bounded by high, mud-rich levees[27]. Mud can be expected to travel as washload during powerful flow events. The finer mud is available to sustain the turbidity current even as sand, granules and coarser mud deposit. For example, the fall velocity of 200 μm sand is about 27 times higher than 30 μm mud.

We consider the scenario of Fig. 2b. At higher slopes, a powerful, sustained, dilute turbidity current carries mud, sand and granules. As slopes drop downdip, suspended sand stratifies the flow and kills near-bed turbulence. The sand, granules and coarse mud gradually deposit without bedload reworking, creating a massive deposit. If the flow upstream is sustained with temporally constant grain size distribution, the deposit will lack grading as well as laminations. The same conditions emplace floating granules that otherwise might suggest a debrite.

As the sand gradually rains out, the flow is depleted of the element that caused self-stratification. A fully turbulent, muddy turbidity current can reattach downdip. The zone of near-bed turbulent extinction is expressed as the 'separation bubble' of Fig. 2b, where the massive deposit is emplaced. Loss of lateral confinement, for example at the mouths of channels, can also induce turbulence extinction (Supplementary Text S2).

Let U be the layer-averaged flow velocity and $\bar{c}_b$ the near-bed sand concentration. The flux of sand onto the bed in the absence of resuspension is $V_s\bar{c}_b$. The distance L_s the flow would traverse to deplete itself of sand is:

$$L_s = \frac{UH}{r_o V_s}$$

$$r_o = \frac{\bar{c}_b}{C}$$

The variables here are evaluated just upstream of separation. For $U = 3\,\mathrm{m\,s^{-1}}$, $H = 100$ m (ref. 24), $V_s = 1.4\,\mathrm{cm\,s^{-1}}$ (150 μm sand) and $r_o = 2$ (refs 18,28) we obtain $L_s = 10.4$ km. The time for the emplacement of a deposit of height H_d is:

$$T_s = \frac{(1-\lambda)H_d}{C r_o V_s}$$

Here $\lambda = 0.3$ is the deposit porosity. For the estimates presented before and for a deposit height of $H_d \approx 1$ m we obtain $T_s \approx 26$ min.

In an ancient sand interval this thickness would be reduced slightly owing to compaction.

An extensive submarine deposit has been mapped off northwestern Africa[9]. The bed slope declines from 0.05° to 0.01° near the transition from Agadir Canyon to Agadir Basin. One part of the deposit immediately downstream of a break in slope extends ∼100 km, has a characteristic thickness $H_d \approx 1$ m, is ungraded and has no laminations. The characteristic sediment size is medium sand, but the deposit also contains measurable amounts of mud. This deposit[9] is plausibly characterized in terms of a sandy debrite. We suggest here that it is also plausible that the deposit is a turbidite emplaced by collapse of the near-bed turbulence of a more dilute turbidity current mediated by the decline in slope.

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Author contributions

M.I.C., A.C., C.P., S.B., D.M., T.A.H. and G.P. proposed the research. M.I.C. and S.B. developed the code and performed the numerical simulations. M.I.C., S.B. and G.P. analysed the results and wrote the text. M.I.C. and A.C. prepared the figures. All authors participated in the interpretation of results, read and commented on the manuscript.

Additional information

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