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LETTERS

Onset of submarine debris flow deposition far from original giant landslide

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Submarine landslides can generate sediment-laden flows whose scale is impressive. Individual flow deposits have been mapped that extend for 1,500 km offshore from northwest Africa[1–7]. These are the longest run-out sediment density flow deposits yet documented on Earth. This contribution analyses one of these deposits, which contains ten times the mass of sediment transported annually by all of the world's rivers[8]. Understanding how this type of submarine flow evolves is a significant problem, because they are extremely difficult to monitor directly[9]. Previous work has shown how progressive disintegration of landslide blocks can generate debris flow, the deposit of which extends downslope from the original landslide[10–13]. We provide evidence that submarine flows can produce giant debris flow deposits that start several hundred kilometres from the original landslide, encased within deposits of a more dilute flow type called turbidity current. Very little sediment was deposited across the intervening large expanse of sea floor, where the flow was locally very erosive. Sediment deposition was finally triggered by a remarkably small but abrupt decrease in sea-floor gradient from 0.05° to 0.01°. This debris flow was probably generated by flow transformation from the decelerating turbidity current. The alternative is that non-channelized debris flow left almost no trace of its passage across one hundred kilometres of flat (0.2° to 0.05°) sea floor. Our work shows that initially well-mixed and highly erosive submarine flows can produce extensive debris flow deposits beyond subtle slope breaks located far out in the deep ocean.

Giant submarine landslides can generate rapidly flowing mixtures of sediment and water. The seminal event for understanding such landslide-generated flows occurred offshore from the Grand Banks, Newfoundland, in 1929 (ref. 10). A large earthquake caused landslides across 100 km of continental slope. A series of submarine cables were then broken downslope from the landslides. These breaks recorded a flow, the frontal velocity of which was $19\,\mathrm{m\,s^{-1}}$ on a gradient of only 0.25°. The Grand Banks event showed that a single submarine landslide can generate two distinct types of sediment-laden flow[10], termed 'turbidity current' and 'debris flow'. Turbidity currents are fully turbulent and relatively dilute. We adopt the most common definition of turbidity currents, as flows in which sediment is supported primarily by fluid turbulence[14]. Debris flows have a higher sediment concentration that suppresses turbulence, such that other processes become more important than fluid turbulence for supporting sediment[14,15]. These processes include grain-to-grain collisions, reduced excess particle density, and yield strength of the sediment–water mixture[15]. Debris flows defined in this way are typically laminar, but can be weakly turbulent[15,16].

Previous studies, including those of the Grand Banks event, have shown that submarine debris flows can be generated by progressive disintegration of strata within an initial large submarine landslide[9–12]. Debris flows formed in this way extend downslope from the landslide, sometimes for several hundred kilometres, and contain intact blocks of original landslide material. This type of debris flow deposit is typically tens of metres thick[9,10,12]. Here we describe a different type of large-scale debris flow deposit, and propose a new mechanism to explain its origin. This debris-flow deposit is unusual because it starts several hundred kilometres from the original landslide, is less than two metres thick, lacks any intact blocks of landslide material, and is encased within a turbidity-current deposit formed during the same event.

Our study is based on an analysis of shallow sediment cores from the Agadir basin, and the Seine and Madeira abyssal plains, located offshore from northwest Africa[1–7] (Fig. 1). These cores contain a sequence of deposits spanning the last ~200 thousand years (kyr) (ref. 6). The majority of flows originated from two distinct sources: the Moroccan continental margin and the volcanic Canary Islands[3,6] (Fig. 1). Flow deposits were correlated between cores (Supplementary Fig. 1). This correlation framework is unusually detailed and extensive[6], and allows us to analyse how the deposit from each flow varies spatially.

Flow deposits typically comprise sand overlain by mud. The first type of sand contains a small fraction of interstitial mud (sediment $<32\,\mu\mathrm{m}$ is $<7\%$), becomes finer upwards, and has ubiquitous planar lamination or ripple cross-lamination (Fig. 2 and Supplementary Fig. 3). There is a gradual transition from this type of sand into overlying mud. These features indicate deposition from a low-sediment-concentration suspension inferred to be a turbidity current[6,14]. The second type of sand interval occurs in only one flow deposit, which we call bed 5 (refs 6, 17). This type of sand has four distinct features: it is ungraded, there are no laminations, it contains a much higher percentage of mud (sediment $<32\,\mu\mathrm{m}$ is $>30\%$), and it is separated from overlying mud by an abrupt change in grain size (Fig. 2; Supplementary Fig. 3). These four features indicate sand deposition en masse from a higher-concentration mud-rich sediment mixture[18] inferred to be a cohesive debris flow[11,17].

A turbidite (the deposit formed by a turbidity current) wholly encases the debrite (the deposit formed by a debris flow) within bed 5, indicating that both were deposited during the same flow event. Background oceanic sedimentation deposited hemipelagic sediment between other flow deposits (Supplementary Fig. 1), but hemipelagic sediment is absent between the turbidite and the debrite in bed 5.

The flow that deposited bed 5 contained $\sim 125\,\mathrm{km}^3$ of sediment[6] (22.5×10^{13} kg of sediment, assuming a density of $1{,}800\,\mathrm{kg\,m^{-3}}$). Some submarine density flows originate from flood discharges from rivers[14]. However, even during very large historical floods, rivers supplied only 10^9 to 10^{11} kg of sediment to the ocean[19]. The annual flux of sediment from all of the world's rivers to the oceans[13] is $\sim 2 \times 10^{13}$ kg. The large volume of bed 5 indicates flow initiation by a submarine landslide.

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Debrite and turbidite intervals within bed 5 have similar compositions rich in shallow-water shelf sediment[6] (Supplementary Fig. 3). This sediment composition, together with spatial trends in grain size, indicates that the original landslide occurred on the Moroccan continental margin near the Agadir canyon[2–6]. Seismic reflection profiles show that shallow landslides and debris flows are widespread along the flanks of this canyon, although the landslide that generated bed 5 cannot be identified using available data. The debrite in bed 5 is found in the centre of the Agadir basin, several hundred kilometres from the nearest plausible location for this landslide.

The event responsible for bed 5 probably caused significant erosion in the lower Agadir canyon, although preceding flows could also have contributed to this erosion. Our cores suggest that up to 4 m of hemipelagic sediment was eroded in locations 200–300 m above the canyon floor (Supplementary Fig. 2). Bed 5 directly overlies these erosional surfaces, where it comprises only a few centimetres of fine turbidite sand or mud. A spectacular field of ∼10-m-deep scours occurs at the canyon mouth[7] (Supplementary Fig. 2). This scour field was probably eroded primarily by the flow responsible for bed 5, because this flow was the coarsest-grained and presumably the most powerful flow in the last 200 kyr (ref. 6).

Beyond the canyon mouth there is a ∼100-km-long area of open sea floor that we term the 'exit ramp' (Figs 1 and 2). The flow deposited very little sediment on the exit ramp and locally eroded up to one metre of underlying material (Supplementary Fig. 1a). An abrupt change in gradient from 0.05° to 0.01° separates the exit ramp from the Agadir basin plain. This remarkably small change in gradient coincides with the start of debrite deposition, which extends for a further ∼250 km (Fig. 2). The debrite is underlain by turbidite sand in the distal Agadir basin, presumably because the turbidity current outran the debris flow. The turbidity current spread more widely than the debris flow (Supplementary Figs 4 and 5) and continued into the Madeira abyssal plain[2–6].

Simple calculations indicate that flow was at least weakly turbulent on the exit ramp. The debrite within bed 5 is unusually thin, suggesting that this debris flow had particularly low yield strength. A yield strength of approximately 1.3 Pa is estimated for motion of a ∼3-m-thick debris flow on a gradient of ∼0.01° (assuming Bingham plastic rheology and a flow density of <1,250 kg m^3)[20]. Debris flows with such low yield strength can support sand[21] but are predicted to become turbulent when their velocity exceeds ∼0.8 m s^{-1} (ref. 20). This velocity is likely to be exceeded on gradients steeper than ∼0.02°, assuming a friction coefficient[22] of ∼0.004. Similar benthic foraminiferal assemblages in the turbidite and the debrite also suggest that the flow was originally well-mixed, and therefore at least weakly turbulent (Supplementary Discussion).

Two mechanisms for debris flow formation are evaluated. In the first model, the debris flow originates by means of a complete disintegration of the original landslide, but deposited no sediment for ∼200 km across the canyon mouth and exit ramp (Fig. 3c). This debris flow could have been weakly turbulent[19], but turbulence was not the primary sediment support mechanism[17,18]. In the second model, debris flow originates from a decelerating turbidity current generated by the initial landslide (Fig. 3b). The models differ mainly in whether turbulence is the primary mechanism for sediment support during flow bypass across the lower canyon and exit ramp. We cannot determine unequivocally which support mechanism was most important in this part of the flow. Lack of debris-flow deposits and evidence for fast-flow velocities (giant scours and minimal deposition, for example) indicate that sediment was probably supported primarily by turbulence.

We propose that debris-flow deposition was probably triggered by rapid deceleration of this initial (weakly or strongly turbulent) sediment

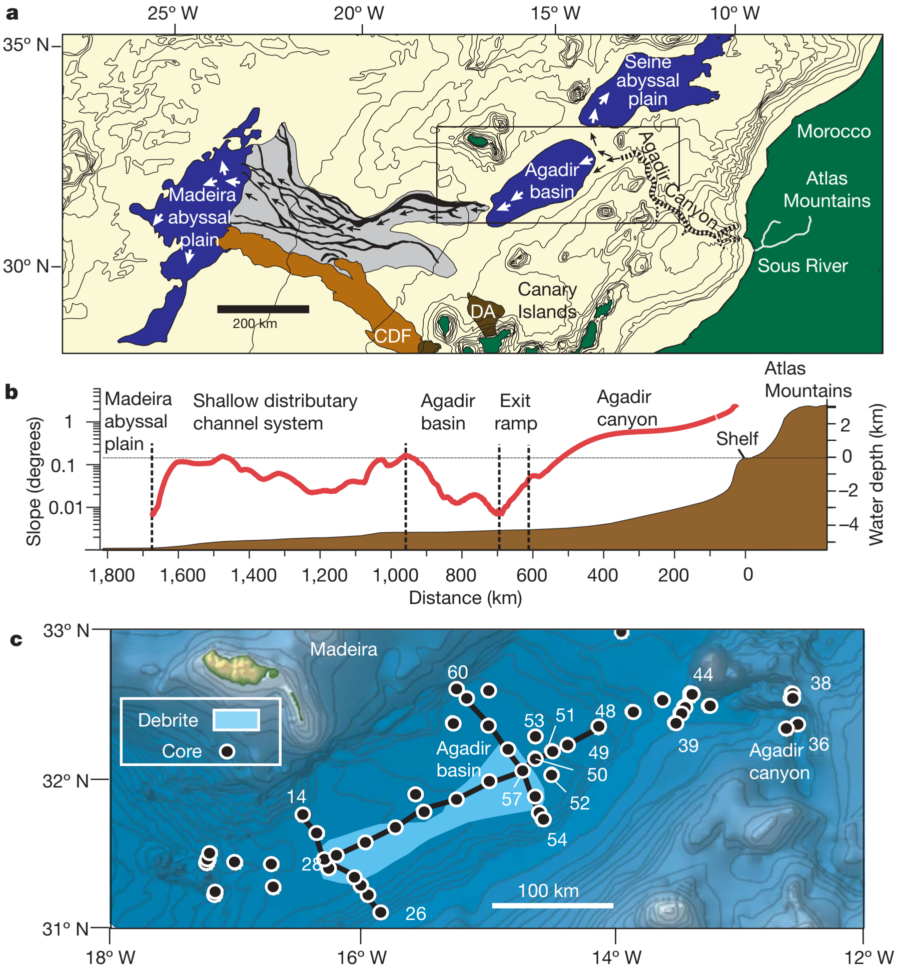

Figure 1 | Location of main features in study area offshore from northwest Africa. a, The Agadir canyon (stippled), Agadir basin, Seine and Madeira abyssal plains; channel network between Agadir basin and Madeira abyssal plain (grey shade); Canary debris flow (CDF; shaded brown); debris avalanches (DA) from Canary Islands[1–7]. The path of the flow that deposited bed 5 is shown by arrows. Box indicates area shown in **c.** Bathymetric contours spaced at 500 m intervals. **b**, Change in seafloor gradient (red line) plotted against distance along flow path. **c**, Location of cores (filled circles), debris-flow deposit (debrite), and the location of the cross-sections shown in Fig. 2 (28–48) and in Supplementary Figs 4 and 5 (the three bold black lines) in Agadir basin.

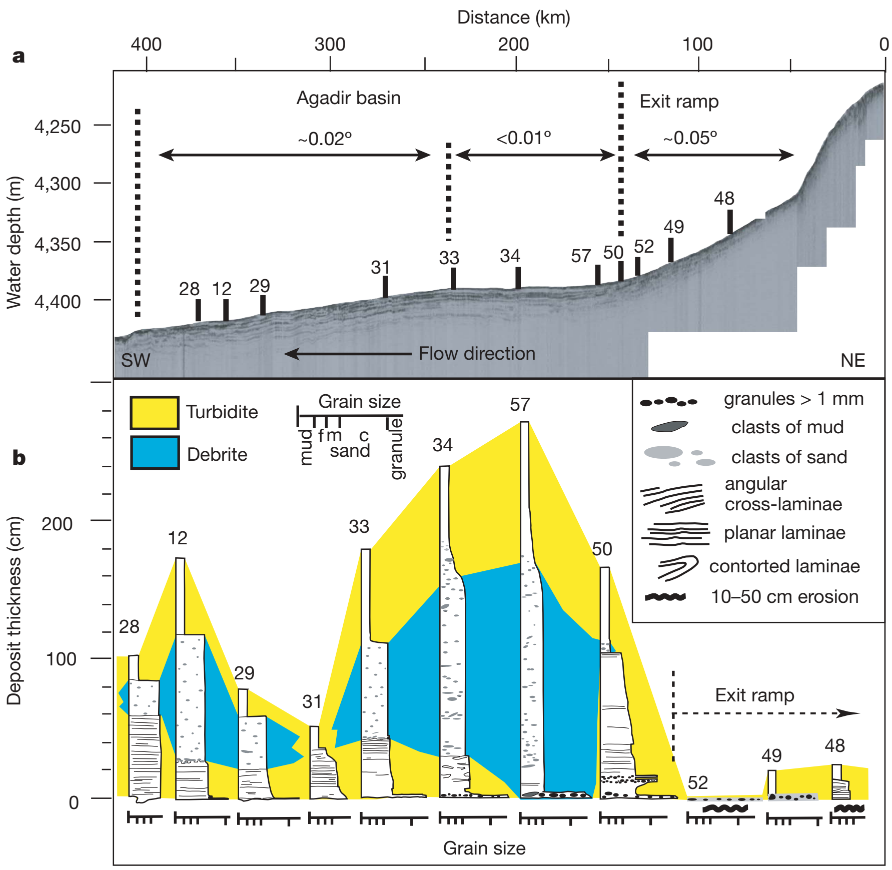

Figure 2 | Change in seafloor gradient and the shape of bed 5. a, High-resolution (3.5 kHz) seismic reflection profile along the exit ramp and axis of the Agadir basin. **b**, Sedimentary logs documenting the thickness, grain size and sedimentary structures within bed 5. Intervals deposited by turbidity current and debris flow are indicated. Numbered core locations are shown in Fig. 1c. Hemipelagic intervals occur above and below bed 5 (Supplementary Fig. 1). f, fine; m, medium; c, coarse.

suspension (Fig. 3). Rapid flow deceleration increased the gradient Richardson number significantly and thus reduced turbulent mixing. Sand settled more rapidly from the flow once turbulent mixing was suppressed[23]. Turbidity currents have a zone of minimum turbulence near their velocity maximum, which could have helped to trap sediment near the bed[23]. A denser sediment suspension thus formed near the sea floor, overlain by an abrupt decrease in sediment concentration, or lutocline[1,24,25]. During the latter stages of this process, cohesive mud

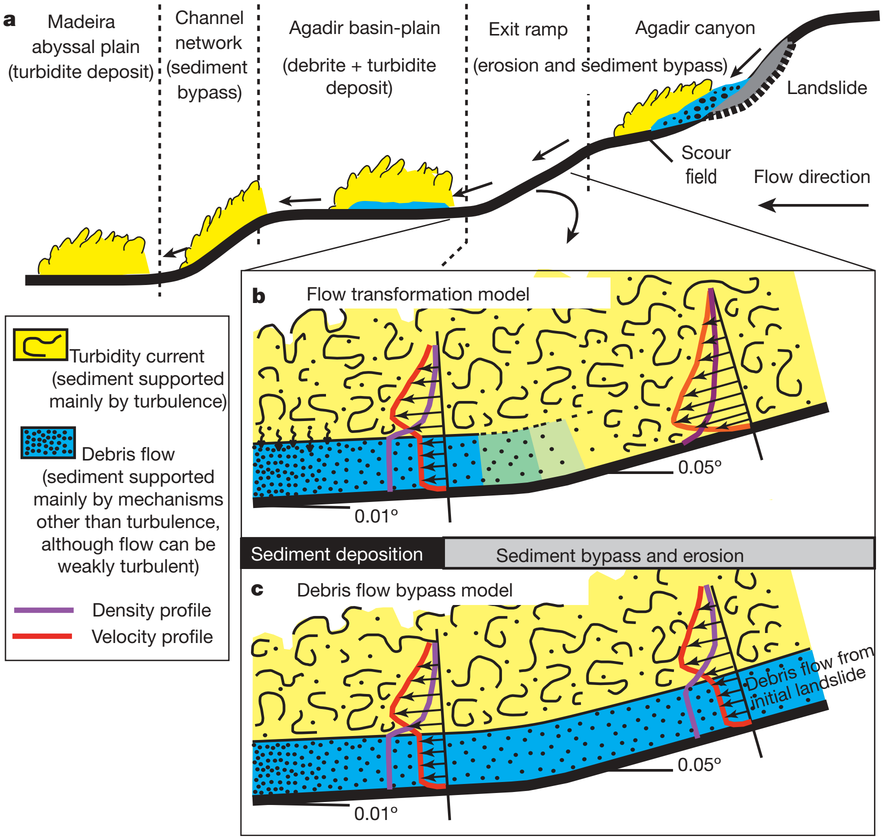

Figure 3 | Evolution of flow event that deposited bed 5 showing two alternative mechanisms for generating the debris flow. a, Evolution of entire flow event from Agadir canyon to Madeira abyssal plain. **b**, Debris flow forms owing to flow transformation from turbidity current beyond break in slope. The event comprises only well-mixed turbidity current in the lower Agadir canyon and exit ramp. **c**, Debris flow forms by disintegration of initial landslide in upper canyon. The debris flow is present in the lower canyon and exit ramp but leaves no deposit (bypasses). We note that the turbidity current is actually much thicker than debris flow in both models. Greenish shaded areas indicate gradual transition from turbidity current to debris flow.

within the suspension developed sufficient yield strength to damp turbulence further[23]. Eventually, as turbulence was fully suppressed, yield strength replaced turbulence as the mechanism that supported sand within the flow[23]. En masse settling then generated the ungraded, structureless, mud-rich and sharp-topped debrite sand[18].

This transformation was probably triggered by deceleration near the slope break at the base of the exit ramp, because thick debrite starts just beyond this point. Flow transformation could have initiated on the exit ramp (as recorded by thin granule layers with mud matrix in cores 52 and 48; Fig. 3), or across a wider expanse of the Agadir basin. Seafloor erosion in the lower canyon probably increased sediment concentration, and 'primed' this particular flow to transform. This would explain why other large-volume flow deposits[6] do not contain debrites near the same slope break (Supplementary Fig. 1).

The origin of sandy debris flows is important not just for understanding how sediment is delivered to the deep ocean by huge flows, but also has potential implications for hydrocarbon exploration. This is because some of the world's largest oil and gas reserves[26–28] occur within ancient rock sequences that contain similar debrites, deposited during the same event as surrounding turbidites[17]. Mud-rich debrite sandstone is a barrier to subsurface flow of oil and gas within more permeable turbidite sandstone. It is necessary to predict the extent and shape of these debrite sandstones to recover hydrocarbon reserves efficiently. Our work shows that extensive debrites can form down flow from abrupt slope breaks and areas of significant seafloor erosion. The 'linked' debrite forms the centre of the deposit and is encased within turbidite sandstone and mudstone.

We also demonstrate that voluminous submarine flows can leave behind remarkably little sediment on low slopes (0.2 to 0.05° in our case). This result also has important implications for assessment of submarine geohazards. Exploration for oil and gas now commonly targets 'deep-water' oceanic settings on the continental slope[26–28]. Large-volume density flows are potentially catastrophic for seafloor installations involved in oil and gas recovery[26,27], whose value may be several hundred million dollars[28]. These installations are typically sited on slopes $>0.05^\circ$. Cores collected next to the installations for geotechnical purposes are often used for subsequent geohazard analysis. Our work suggests that such cores could contain a subtle record of very large volume flows. The clearest record of these flows is found by coring low-gradient basin plains, downslope from installations. The frequency of large-scale flows and their parent landslides could be greatly underestimated if cores from only higher-gradient settings next to installations are used.

METHODS SUMMARY

Individual flow deposits were correlated between cores using sand-fraction composition, the ratio of coccolith species within mud, magnetic susceptibility, colour, thickness, and relative position of layers within the core[3,6] (for example, Supplementary Fig. 1). Ratios of coccolith nannofossil species within hemipelagic mud were used to date the flows[2–6], together with an oxygen isotope stratigraphy. We analyse the deposit of a particular flow (bed 5) that occurred ~60 kyr ago[6]. Coccolith and benthic foraminifera mixtures are documented within bed 5. Coccolith nannofossils record the relative age of sediment incorporated into the flow[2,4–6]. Older coccoliths originate from more deeply buried sediment layers. Benthic foraminiferal microfossil assemblages record the water depth from which these sand-sized particles originated[29,30].

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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 P.J.T. wrote the manuscript, incorporating comments from all co-authors. R.B.W. led the research project and was chief scientist on cruise CD166. B.T.C. was co-chief scientist during cruise CD166. P.J.T., D.G.M., M.F., A.M.A., S.D.-T., A.G. and C.Z. participated in data collection during this cruise. P.J.T., R.B.W. and D.G.M. visually described cores. M.F. completed grain size analyses. R.S. analysed benthic foraminifera assemblages. A.M.A. processed bathymetric and shallow seismic data. S.D.-T., assisted by C.Z., quantified sediment composition and imaged sedimentary structures. S.B., P.P.E.W. and A.G. analysed coccolith assemblages. L.A.A. contributed to data interpretation. R.B.W., P.J.T. and B.T.C. obtained industry funding.

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