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Redistribution of multi-phase particulate organic carbon in a marine shelf and canyon system during an exceptional river flood: Effects of Typhoon Morakot on the Gaoping River–Canyon system

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ABSTRACT

Volumetrically, turbidity currents are the prime suppliers of sediment to the deep sea, and conveyors of organic carbon from the terrestrial biosphere and submarine shelf into marine depositional basins. They result from complex processes of erosion, transport and deposition that can be difficult to study in detail. Here we present data from the Gaoping submarine canyon system, off SW Taiwan, which was perturbed in 2009 by the addition of flood deposits following Typhoon Morakot and sampled by gravity coring less than 2 months after the event. We use the different origins of organic carbon, distinguished by their carbon and nitrogen concentrations and δ^{13}C and δ^{15}N isotopic composition, to compare and contrast standard and extreme sedimentological conditions. Using well-constrained end-members, the results were de-convolved into inputs of metamorphic and sedimentary fossil organic carbon eroded within the Gaoping River basin, terrestrial non-fossil carbon and marine organic matter. In the upper Gaoping Canyon, sedimentation is dominated by the highly-localised hyperpycnal input of river washload and submarine sediment slumps, each associated with extensive flooding following Typhoon Morakot, whilst the shelf experienced deposition and reworking of hemi-pelagic marine sediments. A terrestrial signal is also found in the core-top of a fine-grained shelf sample over 20 km from the Gaoping Canyon, in a region normally dominated by marine carbon deposition, showing that Morakot was an unusually large flood event. Conversely, sediment from just above the canyon thalweg contains 0.23 wt.% depth-averaged marine organic carbon (37% of the TOC content) implying that terrestrial OC-dominated turbidites are tightly constrained within the canyon. Hyperpycnal processes can lead to the rapid and efficient transport of both terrestrial and submarine sediments to more permanent burial locations.

1. Introduction

Erosion and export of solid matter by small mountain rivers are responsible for a disproportionate amount of sediment transport and particulate organic carbon transfer globally (e.g. Milliman and Syvitski, 1992). When this material reaches the ocean it tends to be deposited in large submarine fans or canyon systems, or transported into the deep ocean or subduction trenches. Organic matter can be trapped within the resulting sediments and potentially preserved on geological timescales (Galy et al., 2007; Kennedy and Wagner, 2011). Understanding the contribution of various forms of organic carbon to this sedimentary burial flux can enhance insight into the role of coupled terrestrial erosion and marine deposition in the global carbon cycle. In addition, the intimate association of organic matter with clastic sediment may also give new constraints on the sourcing and routing of sediment in submarine fans and canyon systems.

The combination of fast tectonic uplift (5–7 mm yr^{-1}; Teng, 1990) and frequent typhoons leads to export of a large amount of terrestrial sediment to the ocean from Taiwan (Dadson et al., 2003). As the island is situated near to the biologically productive tropical belt, large amounts of organic carbon from various sources are transferred together with this sediment, including recently produced material (OC$_{biosphere}$ – following the classification of Kao et al. (2014)) from soils, standing biomass and modern woody debris harvested from

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hillslopes and floodplains (West et al., 2011) and several types of ancient carbon (OC_{petro}), from lignite to graphite, eroded from exposed bedrock on the island (Dickens et al., 2004; Beyssac et al., 2007; Hilton et al., 2011). Work on Taiwanese rivers has shown that remobilisation of OC_{petro} from rock debris contained in landslide deposits within the fluvial channel network occurs throughout the year, but that large rainfall/flood events add $OC_{biosphere}$ to the suspended load (Hilton et al., 2008, 2012). Clastic sediment concentration in rivers draining the Taiwan mountains can increase by two orders of magnitude during storms, leading to an increase of fluid density and the formation of hyperpycnal plumes and turbidity currents where these rivers reach the ocean. Such density currents can quickly and efficiently transport sediments into marine basins (Dadson et al., 2005; Goldsmith et al., 2008; Masson et al., 2010; Liu et al., 2012). This, along with high submarine deposition rates for these conditions, can suppress marine remineralisation of organic matter and lead to the sequestration of terrestrial particulate organic carbon as well as marine carbon picked up in transit. Efficient (>70%) reburial of eroded fossil carbon has been observed in both hypopycnal and hyperpycnal systems off Taiwan (Kao et al., 2014), showing that terrestrial erosion and offshore transfer and burial can be a net export of carbon from the atmosphere, via the biosphere into the ocean. In contrast, deposition on a shallow marine shelf is likely to be only temporary, and organic carbon may be more prone to preservation on geological timescales if it can be transported further offshore, into a deeper basin. Organic carbon is prone to degradation in shelf sediments (Arndt et al., 2013), which will impact on the burial efficiency of the entire land–ocean sedimentary system, and therefore understanding the location and form of temporary deposits is important for quantifying POC from source to sink.

Whilst the mobilisation and fluvial transfer of particulate organic carbon to the coastline of rapidly eroding systems such as Taiwan have been observed and measured (Hilton et al., 2008, 2011), and the presence of terrestrially sourced carbon in deep marine deposits demonstrated (Weijers et al., 2009; Masson et al., 2010; Kao et al., 2014), less is known about the offshore transport of organic carbon linking source and sink. Studies of exhumed ancient turbidite systems allow for detailed lateral and vertical correlation (e.g. Amy and Talling, 2006), but the sediment and OC sourcing mechanisms and conditions are unknown. Here, we present a study of organic carbon contained in sediments of the Gaoping River in southwest Taiwan, and the marine shelf and canyon system into which it drains. These sediments were sampled within 2 months after passage of Typhoon Morakot in 2009 caused a flood with an estimated return time of 50–200 years (Chu et al., 2011) from a range of locations along the routing system. Opportunities to link identifiable extreme events and multiple offshore samples are extremely rare, and their content gives insight into the origin, marine transfer and offshore burial of particulate organic carbon (POC) during a large flood. Such events may be disproportionately important to burial fluxes over longer time scales. Additional samples collected earlier within the same system allow for some comparison with regular conditions.

2. Regional setting

The Gaoping River is the second largest in Taiwan, draining an area of 3257 km^2 with a mean annual discharge of 8.5×10^9 m^3 (Huh et al., 2009b), giving an annual runoff of 2.60 m, and an average erosion rate of 4.5 mm yr^{-1} (Dadson et al., 2003). It erodes mostly Miocene-age sedimentary rocks and older metasediments in the mountains of the Central Range, before crossing the recent sediments of the Pingtung plain and entering the South China Sea at Kaohsiung. Here, material can move into the Gaoping Canyon, a sinuous incision of the shelf and slope off SW Taiwan, until it reaches the Manila Trench, 260 km offshore. The canyon head is located about 1 km from the river mouth, in a marine shelf with a width of 45 km. At the shelf edge, the canyon floor is located 500 m below the adjacent shallow marine bathymetry, incised into young ocean sediments. This ensemble is set within an accretionary prism formed due to subduction of South China Sea ocean floor in the Manila Trench. Long-shore currents off the Kaohsiung coast are generally weak and of variable direction (Liang et al., 2003), potentially bringing muds from either flank into the canyon.

In a region of high sea surface temperatures and relatively low salinity, fluvial sediment concentrations in excess of 36 g l^{-1} can lead to hyperpycnal behaviour of river discharge plumes (Dadson et al., 2005; Oppo and Sun, 2005; Chiang and Yu, 2008). This threshold could be lower due to saline incursion at the river mouth and suspended sediment concentrations of 21.72 g l^{-1} are known to have led to density currents in the Gaoping Canyon (Liu et al., 2012). Hyperpycnal conditions are most likely to occur during river flooding and/or coastal storms (Mulder et al., 2003; Goldsmith et al., 2008). When depositing sediment, this type of flow might lead to a turbidite sequence (Liu et al., 2009). At lower sediment concentrations, a hypopycnal plume may build at the river mouth. This turbid plume can spread at the ocean surface, causing fall out of suspended sediment and deposition over a wide area, with the plume behaviour dependent on discharge, buoyancy and surface currents. This process can lead to deposition of river load on the shelf as well as in the canyon. The Gaoping River is hypopycnal during regular discharge conditions and is only likely to be hyperpycnal for some hours to days during typhoon floods (Liu et al., 2013). Alternatively, larger volumes of sediment, including terrestrially sourced material, can be remobilised by slumping in the margins of the submarine canyon, and turbidity currents could ensue (Mulder and Cochonat, 1996).

On 7–10th August 2009 the Gaoping catchment was subjected to a major (estimated return time 50–200 years; Chu et al., 2011) flood following Typhoon Morakot. Although only a category 3 typhoon, Morakot had a particularly strong impact due to its halt over southern Taiwan and connection with a low pressure trough extending east from the Bay of Bengal. This trough fed heat and water vapour into the typhoon, leading to three days of rainfall with a recorded maximum of 2777 mm precipitation (Ge et al., 2010). Landslides affected about 130 km^2 of the Gaoping River basin, 3.9% of the catchment area (West et al., 2011), releasing an estimated 285 million tonnes of sediment. As a result, suspended sediment concentrations in the Kaoping River reached extremely high levels (60 g l^{-1}; Liu et al., 2012). As a result, hyperpycnal flows initiated at the river mouth and flowed through the Gaoping Canyon into the Manila trench (Kao et al., 2010; Su et al., 2012). Breakage of communication cables indicates that a turbidity current on 9th August travelled more than 150 km along the canyon in water depths up to 3700 m. A second submarine density flow initiated three days later in either the Gaoping Canyon or nearby Fangliao Canyon and led to cable breaks up to 375 km along the Gaoping Canyon–Manila Trench system (Carter et al., 2014).

This study considers the organic carbon content and composition of eight cores collected up to 35 km offshore Kaohsiung soon after Typhoon Morakot, from the Gaoping shelf and slope, in water depths of up to 1200 m. These cores were collected by the ship Ocean Researcher 1, during cruise 915 between 28 Sept. and 4 Oct., 2009, using a variety of methods including box, gravity and piston coring. Whilst it is possible for submarine sediment flows to be erosive and/or leave no trace, the upper sections of these cores are assumed to represent post-Morakot sediments. Fig. 1 shows the location of the core sites. Core sites K1 and K12A were proximal to the Gaoping River (2.5 km and 10 km offshore respectively), in or near the canyon thalweg. Cores K25B, K8, K8X and K15 were collected in an offshore-transect along the Gaoping Canyon. Core K11A was collected from incised shelf material on the flank of the Gaoping Canyon, 150 m above the thalweg, Core L9 was collected from the shelf, 20 km southeast of the canyon. Typical shelf sedimentation in this area occurs at an annual deposition rate of about 0.6 g cm^{-2} yr^{-1} (Huh et al., 2009a). These materials are complemented by 29 cores from an offshore sampling campaign in 2001, during more normal sedimentary conditions. These cores were arranged in a fan shape with an internal grid pattern, providing regular samples of an