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Direct sediment transfer from land to deep-sea: Insights into shallow multibeam bathymetry at La Réunion Island

N. Babonneau [a,*], C. Delacourt [a], R. Cancouët [a], E. Sisavath [b,c], P. Bachèlery [b,d], A. Mazuel [a], S.J. Jorry [c], A. Deschamps [a], J. Ammann [a], N. Villeneuve [b]

[a] UMR CNRS 6538 Domaines Océaniques, Université de Brest, UBO, Institut Universitaire Européen de la Mer, Place Copernic, 29280 Plouzané, France
[b] Laboratoire Géosciences Réunion, Université de La Réunion, UMR CNRS 7154, IPG Paris, 15 avenue René Cassin, BP 7151, 97715 Saint Denis messag Cedex 9, Réunion, France
[c] Ifremer, Géosciences Marines, Laboratoire Environnements Sédimentaires, BP 70, 29280 Plouzané, France
[d] Laboratoire Magmas et Volcans, UMR CNRS-IRD 6524, Observatoire de Physique du Globe de Clermont-Ferrand, Université Blaise Pascal, 5, rue Kessler, 63038 Clermont-Ferrand, France

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ABSTRACT

Submarine canyon heads are key areas for understanding the triggering factors of gravity currents responsible for the transfer of detrital sediment to the deep basins. This contribution offers a detailed picture of canyon heads off La Réunion Island, with high-resolution multibeam bathymetry in the water depth range of 4–220 m. The present feeding of the Cilaos turbidite system, one of the largest modern volcaniclastic systems in the world, is deduced from morphological and sedimentological interpretations of newly acquired data. The study highlights small-scale sedimentary features indicating hydrodynamic and sedimentary processes.

A direct connexion between the Saint-Etienne river mouth and submarine canyons is evidenced by the complete incision of the shelf and the presence of canyon heads connected to the modern deltaic bar. This direct connection, supplied by river torrential floods (cyclonic floods every two or three years), suggests the continuity of high-density fluvial flows to submarine gravity flows, forming hyperpycnal flows in the canyon.

The initiation of secondary submarine gravity flows by storm waves (large austral waves and cyclonic waves) is also proposed for submarine canyons with large canyon heads developed in the surf zone from a sandy coastal bar. Bedforms in active canyon axis are considered as an indicator of the frequent activity of high-density turbidity currents.

Moreover, a morphological record of last glacial and deglacial sea level variations is preserved, and particularly the Last Glacial Maximum sea level with the presence of small vertical cliffs, observed in this bathymetric data, which likely corresponds to a paleo-shoreline or paleo-reefs.

1. Introduction

Sediment transfer from land to sea is one of the key processes in the formation of landforms and submarine morphologies. Much of the sediment transport generally occurs during extreme climatic or geological events (floods, earthquakes, storms, volcanic eruptions…) that induce transport of large quantities of sedimentary material to basins during brief repetitive episodes (Korup, 2012). These events can cause significant onshore and offshore morphological changes, particularly in the coastal area, which is highly vulnerable.

Understanding the major morphological changes at land–sea interface and at the seafloor requires a better understanding of sedimentary processes and quantification of sediment flux. From the coast to the deep ocean, one of the main processes of sediment transfer is turbidity current flowing into submarine canyons. Turbidity flows are mostly responsible for submarine erosion of the upper slope and canyon incision. Submarine canyons are mainly located in the continuity of the major drainage networks (Reading and Richards, 1994). Continuity of fluvial sediment fluxes in the canyons is often indirect because of the presence of a shelf and of coastal hydrodynamic settings (waves, tides, currents) that redistribute sediments along the coast.

The origin and the triggering of turbidity currents are still discussed aspects (Piper and Normark, 2009). Scientific issues include the continuity at sea of hyper-concentrated stream flows generating hyperpycnal flows into canyons, mass wasting and re-suspension of sediment deposits under the influence of oceanographic factors (waves, currents).

The study of turbidite processes and their triggering can be addressed in several ways: with the study of modern turbidite systems on the seafloor (Piper and Normark, 2009), with numerical or physical modelling of flow processes (Eke et al., 2011), with monitoring of active currents with current metres and moorings (Johnson et al., 2001; Puig et al., 2003; Liu et al., 2006; Palanques et al., 2006; Puig et al., 2008; Paull et al., 2010), or the simple observations of communication cable breaks (Heezen and Ewing, 1952; Hsu et al., 2008; Cattaneo et al.,

* Corresponding author. Tel.: +33 298498723.
E-mail address: nathalie.babonneau@univ-brest.fr (N. Babonneau).

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2012). Monitoring and in-situ measurements of turbidity currents are particularly difficult because the gravity events occur occasionally with long recurrence time and their occurrence cannot be anticipated. In addition, the turbidity flows responsible of largest morphological changes are difficult to measure because they damage instruments (Khripounoff et al., 2003; Paull et al., 2003). Only weaker and small-scale turbidity currents can be recorded from in-situ experiments (Xu et al., 2004; Mulder et al., 2012; Xu et al., 2013).

In recent years, high-resolution bathymetric data acquired with latest-generation multibeam and sonar technologies also provides advances in outlining submarine morphological features, and in understanding the sedimentary processes in canyons (Greene et al., 2002; Lastras et al., 2007, 2009; Mountjoy et al., 2009; Paull et al., 2010, 2013), and especially at the canyon heads (Smith et al., 2007; Yoshikawa and Nemoto, 2010; Casalbore et al., 2011; Lastras et al., 2011).

In this work, the present feeding of the Cilaos turbidite system, one of the largest modern volcaniclastic systems in the world, is deduced from morphological and sedimentological interpretations of a new detailed picture of canyon heads off La Réunion Island. We propose an interpretation of these high-resolution shallow bathymetric data, focused on the head of a submarine canyon (at depths less than 220 m) in order to identify sedimentary structures to metric and decametric scales. The Saint-Etienne canyon is located off the Saint-Etienne River at La Reunion. Previous studies showed that the Saint-Etienne canyon feeds the Cilaos turbidite system that extends over the abyssal plain (Saint-Ange et al, 2011; Sisavath et al, 2011). The authors showed that a morphological continuity exists between the Saint Etienne River and the canyon, suggesting a possible triggering of hyperpycnal currents (Saint-Ange et al., 2011). The interpretation of shallow bathymetric data aims to show the detailed structure of the head of the canyon. The link between morphological and structural features that we describe and interpret in this paper, the coastal morphology and sediments (river mouth, beach, coastal erosion) and local hydrodynamic and climatic factors (river floods, waves, cyclone) provides new elements on the issue of land–sea transfer and initiation of turbidity currents at canyon heads.

2. Regional settings

La Réunion Island is a volcanic island located in the western Indian Ocean, about 750 km east of Madagascar. It is the emerged part of an active shield volcano, built on the oceanic crust, and is generally attributed to the surface expression of a hotspot (Duncan et al., 1989).

The subaerial part of La Réunion Island is composed of two main basaltic shield volcanoes: the now extinct Piton des Neiges volcano in the north-western part of the island, and the presently active Piton de La Fournaise volcano in the south-eastern part. The oldest products dated at Piton des Neiges volcano are ~2.5 Ma old basaltic submarine lava flows (Smietana, 2011). Piton des Neiges activity ended around 22 ka (Delibrias et al., 1986), after the emission of differentiated alkalic magmas (Upton and Wadsworth, 1972). Piton de La Fournaise is a highly active basaltic shield volcano with an average one eruption per year during the last century. A review of the main geophysical and geological characteristics of Piton de la Fournaise volcano can be found in Lénat et al. (2012).

The poorly consolidated nature of young volcanic rocks and breccias, together with a wet tropical climate characterised by frequent tropical storms and cyclones, favour high erosional rates (Louvat and Allegre, 1997) and efficient transport processes through the hydrographic network. Seasonal cyclonic conditions induce torrential rainfalls and floods, causing highly concentrated sediment load in river mouths (Bret et al., 2003; Garcin et al., 2005).

The morphology of the heart of the Piton des Neiges volcano is marked by the existence of large circular depressions, called “cirques”. The origin of the “cirques” in La Reunion is generally ascribed to the result of tectonic heritage and intense erosion, expressed by numerous landslides (Oehler et al., 2008; Salvany et al., 2012). The Saint-Etienne River is one of the main rivers on La Réunion Island. The river mouth is located in the south-western coast of the island. Its drainage area covers about 360 km^2 and includes the “cirque” of Cilaos and the “Bras de la Plaine” (Fig. 1).

At the river mouth, the whole bed of the Saint-Etienne River is 1.2 km wide. It presents a braided morphology, with numerous minor channels that are about 10 m wide. The average solid load is low with about 470 000 m$^3\cdot$yr^{-1} (excluding torrential floods), but it can reach 500 000 m^3 during major flood events and 1–2 million m^3 for centennial flood (Saint-Ange et al., 2011).

At the Saint-Etienne River mouth (Fig. 2), the coastline is formed by fluvial accumulations with poorly sorted deposits dominated by sand, pebbles and boulders that are up to 1 m in diameter (Saint-Ange et al., 2011). Northwest of the Saint-Etienne River mouth, the Etang-Salé beach extends with a pebble bar near the mouth (Fig. 2), evolving to a sandy beach in the western part. The Etang-Salé beach is composed of fine volcanic sand. On land, the Etang-Salé area is characterised by large eolian dunes covering the coastal area, up to an altitude of ~200 m.

South of the Saint-Etienne River mouth, the Pierrefonds coast (Fig. 2) is characterised by outcrops of boulders and pebble fluvial accumulations, partially covered by vegetation.

The effect of tides is low at La Réunion, with an average range of 0.6 m (1.1 m maximum). Three sources of waves contribute to the coastal erosion of the island: the trade-wind waves, the austral-storm waves, and the cyclonic waves (or tropical storm waves) (Fig. 1). The trade-wind waves are small to moderate amplitude (2 to 3.5 m high) and come from the east and southeast. Austral-storm waves have large wavelengths and high amplitudes (3 to 8 m high). They are strong and form far southwest of the island (south of South Africa). They mainly affect the western and north-western coasts. The cyclonic waves are very high (higher than 4 m) and their direction depends on the path of the cyclone or the tropical storm, but most primarily affects the north and east coasts of the island.

The Cilaos deep-sea fan (Fig. 1) is fed by a canyon network as described by Saint-Ange et al. (2011) and Sisavath et al. (2011, 2012). Two main canyons incise the submarine slope and correspond to the major feeding of the Cilaos deep-sea fan (Fig. 1): the Saint-Etienne Canyon and the Pierrefonds Canyon (Sisavath et al., 2011). The substrate, wherein canyons incise, is mainly composed of weak volcaniclastic sediments in the coastal area (river mouth and deltaic accumulations) and debris avalanche deposits forming the submarine slope of the island (see Oehler et al., 2008; Le Friant et al., 2011 for detailed discussion).

3. Data and methods

Deep-water bathymetric and backscatter data available on the submarine slope and the abyssal plain around La Réunion Island was acquired during ERODER1 and 2 and FOREVER surveys (2006 and 2008). Maps presented in Fig. 1 combine backscatter images (Fig. 1A) and swath bathymetry data (Fig. 1B) acquired with Simrad EM12D and EM120. In Fig. 1A, high reflectivity corresponds to dark grey and low reflectivity is light grey. Detailed analyses and interpretations of this dataset were already published (Le Friant et al., 2011; Saint-Ange et al., 2011; Sisavath et al., 2011, 2012; Saint-Ange et al., 2013).

A high-resolution bathymetric dataset of the Saint-Etienne River mouth was collected in December 2009 during the BATHYBAB survey, using a shallow-water multibeam echosounder (RESON SeaBat 8101). This high-resolution 240 kHz multibeam system was temporarily set up on a fishing boat, which allowed acquisition of bathymetric data in water depths ranging from 4 m up to 220 m with a vertical resolution of up to 10 cm. Vessel navigation was achieved by PPK (Post-Processed Kinematic) DGPS (Differential Global Positioning System) using reference stations located on the coast (maximum baselines of 15 km), providing positioning accuracy of a few centimetres. Sound velocity profiles