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Mass wasting processes along the Owen Ridge (Northwest Indian Ocean)

Mathieu Rodriguez [a,b,c,*], Marc Fournier [a,b], Nicolas Chamot-Rooke [c], Philippe Huchon [a,b], Sébastien Zaragosi [d], Alain Rabaute [a,b]

[a] Institut des Sciences de la Terre de Paris, CNRS UMR 7193, Université Pierre & Marie Curie, case 129, 4 place Jussieu, 75005 Paris, France
[b] iSTeP, UMR 7193, CNRS, F-75005 Paris, France
[c] Laboratoire de Géologie de l'Ecole normale supérieure de Paris; CNRS UMR 8538, 24 rue Lhomond, 75005 Paris, France
[d] EPOC Université Bordeaux1, UMR 5805, avenue des facultés, 33405 Talence, France

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ABSTRACT

The Owen Ridge is a prominent relief that runs parallel to the coast of Oman in the NW Indian Ocean and is closely linked to the Owen Fracture Zone, an 800-km-long active fault system that accommodates today the Arabia–India strike–slip motion. Several types of mass failures mobilizing the pelagic cover have been mapped in details along the ridge using multibeam bathymetry and sediment echosounder. Here we present a synthetic map of the different types of mass wasting features observed along the ridge and we further establish a morphometric analysis of submarine landslides. The spatial variation of failure morphology is strongly related to the topography of the basement. The highest volumes of multi-events generated slides are mobilized along the southern portion of the ridge. There, the estimated volume of evacuated material during a slide is up to 45 km^3. Combining these new observations with re-interpreted ODP seismic lines (Leg 117) documents sporadic mass wasting events through time along the southern segment of the ridge since its uplift in the Early Miocene, with a typical recurrence rate of the order of 10^5–10^6 years. Although seismicity may still be the final triggering process, mass wasting frequency is mainly controlled by the slow pelagic sedimentation rates and hence, time needed to build up the 40–80 m thick pelagic cover required to return to a mechanically unstable pelagic cover.

1. Introduction

The study of mass wasting processes on continental margin has become a major topic of research during the last decades, since it plays a key role in sediment transportation to the deep ocean (Masson et al., 2006 and references herein). Mass wasting encompasses all gravity-driven mass movement processes. Failures affect the seabed morphology and its subsequent evolution in a variety of ways, in relation with the mechanical properties of the mobilized sediments and the large variation in volume, frequently less than one km^3 but exceptionally over 20,000 km^3 (Agulhas slump in SE Africa; Dingle, 1977). Although well described at continental margins (Prior, 1999; Canals et al., 2004), mass wasting along the slopes of oceanic highs standing in deep water remains poorly investigated, with the exception of the Lomonosov Ridge in the Arctic Ocean (Kristoffersen et al., 2007), the Macquarie Ridge in the South Pacific (Massel et al., 2000), and Chain Ridge off the Horn of Africa (Pimm et al., 1972). Unlike continental margins, sedimentation on these remote oceanic ridges is generally characterized by low rates of pelagic sedimentation, not directly controlled by relative sea level variations or clastic continental input. Rapid sedimentation has commonly been invoked as an important pre-conditioning factor for slope instability (Hampton et al., 1996; Lee et al., 2007), even though slope failure as a result of sedimentation alone seems unlikely based on theoretical grounds (Viesca and Rice, 2012). Other non-gravitational triggering factors invoked in deep-sea environments include earthquakes (Almagor and Wisenam, 1982; Hampton et al., 1996; Mulder et al., 2009), internal waves and/or fluid (including gas) escapes (Mienert and Posewang, 1999). To avoid any confusion, the term “failure” is hereafter used for ruptures related to mass wasting processes, and the term “fault” is used for ruptures related to tectonic processes, although both terms refer to a mechanical discontinuity in rocks.

The ~2000-m deep Owen Ridge in the NW Indian Ocean is one of these deep-water sites of widespread mass wasting where links with active tectonics can be tested. The India–Arabia plate boundary — known as the Owen Fracture Zone — runs along the ridge for more than 800 km, where it accommodates 3 mm a^{-1} of dextral relative motion generating moderate seismicity (Fig. 1; Fournier et al., 2008a, 2011). Both the Owen Ridge and Owen Fracture Zone were extensively surveyed during the OWEN and FANINDIEN 2009 cruises (Fig. 1) aboard the BHO Beautemps-Beaupré of the French Navy. Between 15°N (Beautemps-Beaupré Basin; Fournier et al., 2008b) and 22°30'N (Dalrymple Trough; Edwards et al., 2000; Gaedicke et al., 2002; Edwards et al., 2008), the Owen Ridge is composed of three distinct bathymetric highs covered by a ~500 m thick pelagic drape (Shipboard

* Corresponding author at: Institut des Sciences de la Terre de Paris, CNRS UMR 7193, Université Pierre & Marie Curie, case 129, 4 place Jussieu, 75005 Paris, France. Tel.: +33 1 44 27 59 43.
E-mail address: rodriguez@geologie.ens.fr (M. Rodriguez).

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Scientific Party, 1989) affected by numerous submarine landslides displaying a large variety of morphological features. Here we use these newly acquired multibeam bathymetry and SBP120 (Sub-Bottom Profiler) data, together with data collected during the DSDP (Shipboard Scientific Party, 1974) and the ODP Leg 117 (Shipboard Scientific Party, 1989), to give a detailed description of mass wasting along the Owen Ridge.

The first topic of this paper is the study of spatial variations of the mass wasting process along the three segments of the Owen Ridge. The relative arrangement of slope failures and their deposits is first described to determine the variety of mass movement types. The evolution of the material during failure and transport is then investigated for each ridge segment. Using the method established by McAdoo et al. (2000) for bathymetric data, the volume of material mobilized at the initial stage of slope failure is estimated for each event, allowing a quantitative comparison of the erosive pattern along each of the ridge segments as well as on both sides of it. A statistical analysis of the morphological parameters of landslide scars is also performed to establish simple hypotheses regarding the origin and behaviour of failure along the Owen Ridge.

The second topic of this paper is to assess factors that control mass wasting processes through time, including triggering factors of submarine landslides. Such approach is limited to the southern Owen Ridge for which ODP data are available and allow us to date the mass transport deposits (MTDs hereafter) back to Early Miocene (Fig. 2). Whether the multi-failures landslides currently displayed on the seafloor are the product of one single catastrophic event destabilizing the entire southern ridge segment or the product of distinct and sporadic events destabilizing only limited areas is resolved by studying the relative arrangement of MTDs displayed on ODP seismic lines. The time recurrence of mass wasting events is compared with a model of earthquake recurrence along the southernmost segment of the Owen Fracture Zone to identify whether seismicity is a potential triggering factor of slope failure and MTDs a paleo-seismicity record. Slope failure frequency, together with the spatial distribution of volumes of sediment involved for each failure, allow us to discuss the preservation of submarine relief through time.

2. Geological background

2.1. Geodynamic setting

The present-day India–Arabia plate boundary in the NW Indian Ocean is located along the Owen Fracture Zone, which is an 800-km-long strike–slip fault system (Fig. 1; Rodriguez et al., 2011). This fault system connects the Sheba and Carlsberg ridges to the eastern end of the Makran subduction zone. Northward migration of the Arabian plate with respect to Eurasia being slightly faster than the Indian plate at this longitude, the relative plate motion is accommodated by a 3 ± 1 mm a^{-1} dextral component (Fournier et al., 2008a; DeMets et al., 2010). The present-day fault system has led to a finite displacement of about 10 to 12 km measured by morphologic offsets in the seafloor, which would indicate, at a constant rate of 3 mm a^{-1}, a Pliocene age for the youngest fault system expressed today at the seafloor (Fournier et al., 2011). Dextral motion, however, may have started as early as the Miocene (magnetic anomaly An 6, 19.7 Ma), as soon as spreading in the Gulf of Aden became effective (Chamot-Rooke et al., 2009; Fournier et al., 2010). The seismicity along the fault is rather low and scattered (Fig. 1), so that only few focal mechanisms are available (Quittmeyer and Kafka, 1984; Gordon and DeMets, 1989; Fournier et al., 2001). They consistently indicate pure strike–slip motion. The maximum magnitude recorded to date is a M_w 5.3 earthquake (Harvard CMT, 7 April 1985). However infrequent but large earthquake may be expected as at other fracture zones (Antolik et al., 2006; Robinson, 2011).

2.2. Morphology of the Owen Ridge and sedimentary setting

The Owen Fracture Zone follows a major morphological feature, the Owen Ridge, which is a SSW-NNE trending ridge-and-through system that may be divided — starting from the Beautemps-Beaupré Basin in the south — into five geographic provinces (Fig. 1): the southern ridge, which consists of a 300 km-long, 50 km-wide, up to 2000 m-high relief (Fig. 3); the central ridge, which is a 220 km-long, 50 km-wide, and up to 1700 m-high relief (Fig. 4); the 20°N pull apart basin; the Qalhat Seamount (or northern ridge) which is a 210 km-long, more than 55 km-wide, and up to 2700 m-high relief (Fig. 5); and the Dalrymple Trough. The Owen Ridge topographic highs act as a barrier for the Indus turbiditic sedimentation and isolate the Owen Basin, located west of the Owen Ridge, from any sediment supply from the east (Whitmarsh, 1979; Mountain et al., 1990). Since its uplift in the Early Miocene (Shipboard Scientific Party, 1989), the ridge has mainly supported the deposition of a ~500 m thick chalk and ooze pelagic blanket, and minor terrestrial input from monsoonal eddies (Clemens and Prell, 2006) and oceanic jet (Ras al Hadd jet; Böhm et al., 1999; Fig. 6). The establishment of an upwelling zone in the Late Miocene induced an increase in sedimentation rates (from 8–15 m Ma^{-1} to 54 m Ma^{-1}) (Mountain and Prell, 1989). Since the Pliocene, the sedimentation is mainly oozy in composition, with sedimentation rates typical of pelagic deposition (30 to 40 m Ma^{-1}) (Mountain and Prell, 1989; Shipboard Scientific Party, 1989), and is controlled by seasonal monsoon (Clemens and Prell, 2006).

2.3. Geological and tectonic history of the Owen Ridge

The present-day morphology of the Owen Ridge results from successive tectonic and volcanic events. The southern and central segments of the Owen Ridge were uplifted ~19 Ma ago, as attested by the rapid transition from turbiditic to pelagic deposits in DSDP and ODP cores (Whitmarsh et al., 1974; Shipboard Scientific Party, 1989; Weissel et al., 1992). The southern ridge appears as a large-scale tilted and relatively flat slab, interpreted as flexural response to compression (Weissel et al., 1992). Several seismic lines run as pre-site surveys for ODP reached the basement of the southern ridge, and show an uneven paleo-topography (Fig. 2). The substratum is basaltic in composition and of Paleocene age (Shipboard Scientific Party, 1974, 1989). Both the southern and the central ridges may have stand as positive basement features being progressively buried under turbiditic deposits during the Paleogene to Early Miocene interval, as suggested by the Oligocene turbiditic deposits drilled between two basement highs on the southern ridge (Fig. 2) (Shipboard Scientific Party, 1989; Clift et al., 2001; Gaedicke et al., 2002). The southern and central segments rose significantly above the level of the Indus fan to their present-day configuration following the 19 Ma uplift episode (Fig. 6).

At the northern end of the OFZ, the history of the Qalhat Seamount is not clearly established. The nature of the underlying basement remains unknown since it has never been directly sampled. The nearby presence of the Little Murray Ridge volcanic seamounts buried under the Oman basin (Gaedicke et al., 2002; Mouchot, 2009), coupled with the existence of a strong magnetic anomaly in the vicinity of the seamount and a typical flat top morphology, strongly suggest that the Qalhat Seamount is a volcanic guyot (Edwards et al., 2000; Fournier et al., 2011). Onlap of Paleocene sediments onto the Qalhat Seamount (Edwards et al., 2000; Gaedicke et al., 2002; Edwards et al., 2008) demonstrates that the seamount is Cretaceous in age or older.

3. Materials and methods

3.1. Bathymetry and sub-bottom profiles

Swath bathymetry and backscatter data were collected using a hull-mounted Kongsberg-Simrad EM120 multibeam echosounder