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# Giant fossil mass wasting off the coast of West India: The Nataraja submarine slide

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## ABSTRACT

We use two-dimensional pre-stack depth migrated seismic reflection profiles and seafloor bathymetry to describe the continental margin structure and a massive mass-transport deposit off the west coast of India. This giant slide runs from the Gujurat–Saurashtra margin to the Laxmi Basin. It is over 330 km long, a maximum of 190 km wide and its run-out basal gradient is 1.2°. We name this giant mass wasting deposit the Nataraja Submarine Slide. This slide covers $49 \pm 16 \times 10^3$ km$^2$ and represents a volume of $19 \times 10^3 \pm 4 \times 10^3$ km$^3$, making it the second by volume of any passive margin landslide/mass-transport deposit. Seismic facies analysis allows the internal structure of the mass-transport deposit to be described as far as the toe. This slide has been able to circumvent massive seamounts, thus highlighting the capacity of the flow and its potential energy during emplacement in a funnel between the slope of the Western Indian passive margin and the Laxmi Ridge. Stratigraphically, the emplacement of the Nataraja Slide predates the main pulse of sedimentation during the late Miocene–Recent associated with the Indus Fan but follows rapid sedimentation across S and SE Asia during the Early–Middle Miocene. The margin architecture at the head of this slide is associated with a gravity-controlled fold and thrust belt that may have caused slope steepening and triggering of the slide.

## 1. Introduction

Landslides occur on- and offshore, and range in volume from dm$^3$ to $\times 10^3$ km$^3$. Triggering mechanisms are often unknown and almost certainly differ between settings (Hampton et al., 1996). Mass wasting/mass-transport deposits represent some of the most challenging and important sedimentary and mechanical features for geoscientists and structural engineers to understand (e.g., Masson et al., 2006). Offshore, along both passive or active margins (Moscardelli and Wood, 2015), mass wasting plays an important role in shaping most continental slopes that lead to deep abyssal plains and helps to form the architecture of deep-water sedimentary systems when associated with turbidity currents (Embley, 1976; Woodcock, 1979; Bellaiche et al., 1986). Mass movements can, in certain circumstances, affect man-made installations, such as deep sea cables or subsea offshore structures (Gennesseaux et al., 1980; Piper et al., 1988). Movement of the overlying water column during emplacement may generate tsunamis, as documented for the well-known Holocene Storegga Slide in the North Atlantic offshore Norway (Jansen et al., 1987; Bugge et al., 1988; Yamada et al., 2012). Despite the numerous seafloor features described and the proposed mechanisms for triggering slides (e.g., overpressure, fluid/sediment remobilization, earthquake) the limited number of giant slides in the rock record that have been studied in detail do not allow a definitive analogy to be made between these modern and ancient examples.

The morphology of the present day margin of western India (Naini and Kolla, 1982; Chakraborty et al., 2006) is characterized by a series of arcuate concave-up and concave-down features at the shelf to slope transition (Fig. 1). At this scale we can define the margin as being associated with a series of prograding sedimentary wedges and/or retrograding erosive slopes (Steffens et al., 2003). The main sedimentary body within this part of the western Indian Ocean is the Indus Fan (Fig. 1B) that contains up to 11 km of sediments (Exxon, 1985; Clift et al., 2001). The surficial shapes found along the margin can be summarized by three dip bathymetric profiles (Fig. 1C). The northern profile corresponds to the Indus Fan and shows a convex upward profile reflecting the excess of Plio–Pleistocene sediments accumulated by this thick sedimentary body (Fig. 1B). Although the influence of deltaic sed-

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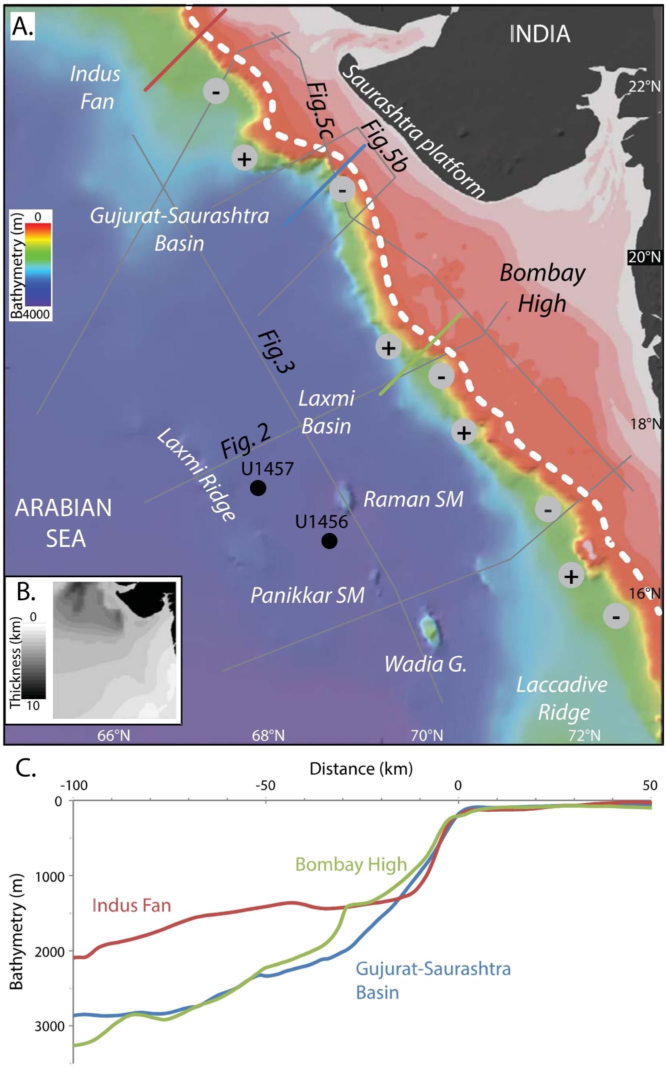

**Fig. 1.** A. Regional setting of the Western India margin and adjacent Arabian Sea Basin. The seismic data used for this study are marked by grey lines. Along margin, convex up and convex down morphology of shelf to slope are expressed by positive and negative grey symbols, respectively. B. Thickness map of sediments within the study area (Exxon, 1985), note the extent of the Indus fan depocentre north of the study area. C. Bathymetric profiles across shelf and slope from three locations along the margin, these profiles are either convex up (Indus Fan, i.e. high sediment rate and important deep-sea fan) or concave up (Bombay High or Gujurat–Saurashtra Basin). The two IODP drill sites U1456 and U1457 are located in the southwestern part of the study are (Pandey et al., 2015).

imentary systems differs between the three areas, we note that the profile along the Gujurat–Saurashtra sector shows a concave upward geometry compared to its neighbors, suggestive of mass wasting (Coleman and Prior, 1998; Adams and Schlager, 2000). Slope failure of Plio–Pleistocene deposits spatially associated with hydrates, rapid sedimentation rates or seismicity has been documented along the slope of the Western Indian margin (Rao et al., 2002).

The Laxmi and Gujurat–Saurashtra Basins have been extensively described and analyzed in relation to the rifting history of Gondwana, with particular attention having been paid to the continent-ocean transition (e.g. Bhattacharya et al., 1994a; Todal and Edholm, 1998; Chaubey et al., 2002; Krishna et al., 2006; Calvès et al., 2008, 2011; Misra et al., 2015). Nonetheless, detailed description of the drift sequences of the Gujurat–Saurashtra and Laxmi Basins has not been performed previously because of the limited available seismic reflection coverage and modest number of wells/boreholes drilled in the area. Our study builds on previous studies and uses two dimensional Pre-Stack Depth Migrated (PreSDM) seismic reflection data to describe the large-scale geometry of the margin. We identify some key facies that form a major sediment volume and represent the product of a major late Miocene event in the history of this margin. We define the spatial extent, the internal structure and tectonic origin of this previously undescribed sedimentary body. This seismically observed structure has recently been calibrated during International Ocean Discovery Program (IODP) Expedition 355 (Pandey et al., 2015). Preliminary results from Sites U1456 and U1457 (Fig. 1A), support our initial interpretations that were completed before drilling.

## 2. Materials and methods

The approximately 3500 km of seismic reflection data used in this study (Fig. 1A) are part of the much larger regional India SPAN™ survey acquired and processed by ION GX Technology in 2006–2007. The acquisition was designed for crustal-scale imaging by using a long receiver cable with a 10.1 km maximum offset and a large source size of 7480 cu in. Crustal-scale imaging is achieved by an 18 s two-way time record (equivalent to around 40 km depth). The pre-stack depth-migrated data were migrated (Kirchhoff PreSDM) using velocities derived from iterative tomographic velocity modeling. Vintage single-channel seismic reflection profile RC 1707 from the Lamont–Doherty Earth Observatory has also been used (Fig. 1; accessed by the GeoMapApp 3.3.9 – link: http://www.geomapapp.org/).

We analyzed these seismic reflection lines at two different scales, from the mega- (basin) scale to the architectural element scale. At the scale of the architectural elements, seismic facies analysis (Mitchum et al., 1977) was used to document and describe the kinematic indicators of the mass-transport complexes (MTC) as defined by Bull et al. (2009). Identification of the headwall, extensional domain, translational domain and contractional toe domains (Prior et al., 1984) is based on the external and internal geometry of the mass wasting package, as imaged by the seismic reflection data. The classification of attached/detached MTC follows the scheme of Moscardelli and Wood (2008). The regional GEBCO (British Oceanographic Data Centre, 2003) bathymetric data are used to describe the margin and locate the various structures where the slide is present.

In spring 2015, two IODP sites were drilled in the southwestern part of our study area (Fig. 1A). We refer to this preliminary age control and sedimentary facies from onboard analysis to calibrate our geophysical observations (Pandey et al., 2015).

## 3. Results

### 3.1. Margin scale structure – Nataraja slide location

The present day structure of the western Indian margin is mainly dominated by a series of infilled rift basins spanning from the landward Gujurat–Saurastrah margin to the Laxmi Basin and bounded to the west by the Laxmi Ridge, where seaward-dipping reflectors (SDR) mark the transition between aborted oceanic basin crust to the true oceanic accretion generated along the Carlsberg Ridge (e.g. Naini and Talwani, 1982; Calvès et al., 2011; Misra et al., 2015). This setting is the result of repeated ridge jump marked by SDR sequences on both sides of the Laxmi Ridge.

The main geodynamic event to have shaped the onshore part of the margin is the Deccan Large Igneous Province (e.g. Wellman and McElhinny, 1970; Mahoney, 1988). This event is marked seaward by a prominent seismic reflection package overlain by carbonate platforms (Calvès et al., 2008, 2011) and in turn buried by Cenozoic siliciclastic deposits largely sourced from the Indian continent and Himalaya via the Indus River (e.g., Clift et al., 2001) (Fig. 2A).