Giant submarine landslides on the Colombian margin and tsunami risk in the Caribbean Sea

Stephen C. Leslie *, Paul Mann

Department of Earth and Atmospheric Sciences, University of Houston, Houston, TX 77204, USA

A B S T R A C T

A series of three giant, previously unrecognized submarine landslides are defined on a 16,000 line km grid of multi-channel 2D seismic reflection profiles along the active margin of northern Colombia in the western Caribbean Sea. These deposits record the collapse and mobilization of immense segments (thousands of cubic kilometers) of the submarine slope and are comparable in scale to the largest known landslides on Earth. We show that the breakaway zone for these events corresponds to the tectonically over-steepened slopes of the Magdalena Fan, an extensive submarine fan composed of sediments sourced from the northern Andes and deposited by the Magdalena River. An over-pressured zone of weakness at the base of the gas-hydrate stability layer within the fan likely facilitates slope failure. Timing of these massive slope failures is constrained by well control and occurred from the mid-to-late Pliocene to mid-Pleistocene. To understand the tsunamigenic hazards posed by the recurrence of such an event today, we model the potential tsunami source created by a submarine landslide of comparable thickness (400 m) and lateral extent (1700 km^2) derived from the over-steepened upper slopes of the present day Magdalena Fan. Our modeling indicates the recurrence of an analogous slope failure would result in a major tsunami that would impact population centers along the Caribbean coastlines of Colombia, Central America, and the Greater Antilles with little advance warning.

1. Introduction

Submarine landslides have the potential to cause unexpected or "surprise" tsunamis in regions not typically thought of as tsunami prone (Ward, 2001; Hornbach et al., 2010; Lo Iacono et al., 2012). When they occur, these tsunamis waves arrive in coastal areas with little advance warning and can devastate coastal communities. For example, in 1998 a 7.1 M_w earthquake in Papua New Guinea triggered a submarine landslide of ∼4 km^3 which caused a catastrophic tsunami with local run-up heights of up to 15 m that killed more than 2200 coastal inhabitants (Heinrich et al., 2001; Tappin et al., 2008). While only 7% of tsunamis world-wide are thought to originate by submarine landslide or a combination of earthquake and landslide (National Geophysical Data Center, 2016), the destructive potential of these events is highest when they affect areas with large coastal populations uninformed and unprepared for tsunami hazards, such as the Caribbean Sea (Fig. 1). Hundreds of thousands of residents, tourists, and tourist-industry workers are potentially at risk from tsunamis around the densely populated urban and tourist areas of the Caribbean

(von Hillebrandt-Andrade, 2013). Unfortunately, unlike earthquake generated tsunamis in seismically active coastal regions with long and meticulously maintained historical records (e.g. Japan), the infrequent nature of landslide tsunamis and the relatively brief historical records (∼500 yr) in the Caribbean region make understanding the likelihood of these events in this area difficult (Ward, 2001; Harbitz et al., 2012). In the absence of historical records of tsunamis occurring along Colombian Caribbean margin it is necessary to investigate the history and magnitude of past tsunamis using the geologic record.

In this study, a series of giant (>1000 km^3), previously unrecognized, Plio-Pleistocene age submarine landslide deposits are identified on seismic reflection records from the submarine Magdalena fan along the Caribbean margin of northern Colombia (Fig. 1). Our observations include the frequency, location, lateral extent, and thickness of the largest slope failures in the area. We use these observations as parameters for modeling the effects of a future tsunami produced by a similar event (Lo Iacono et al., 2012; Harbitz et al., 2014). Sediments resulting from submarine slope failures range in scale from tens of cubic meters to thousands of cubic kilometers and are classified as mass transport deposits (MTDs) (Weimer, 1989; Mulder and Cochonat, 1996). MTD deposition occurs by a variety of matrix-supported, mass movement
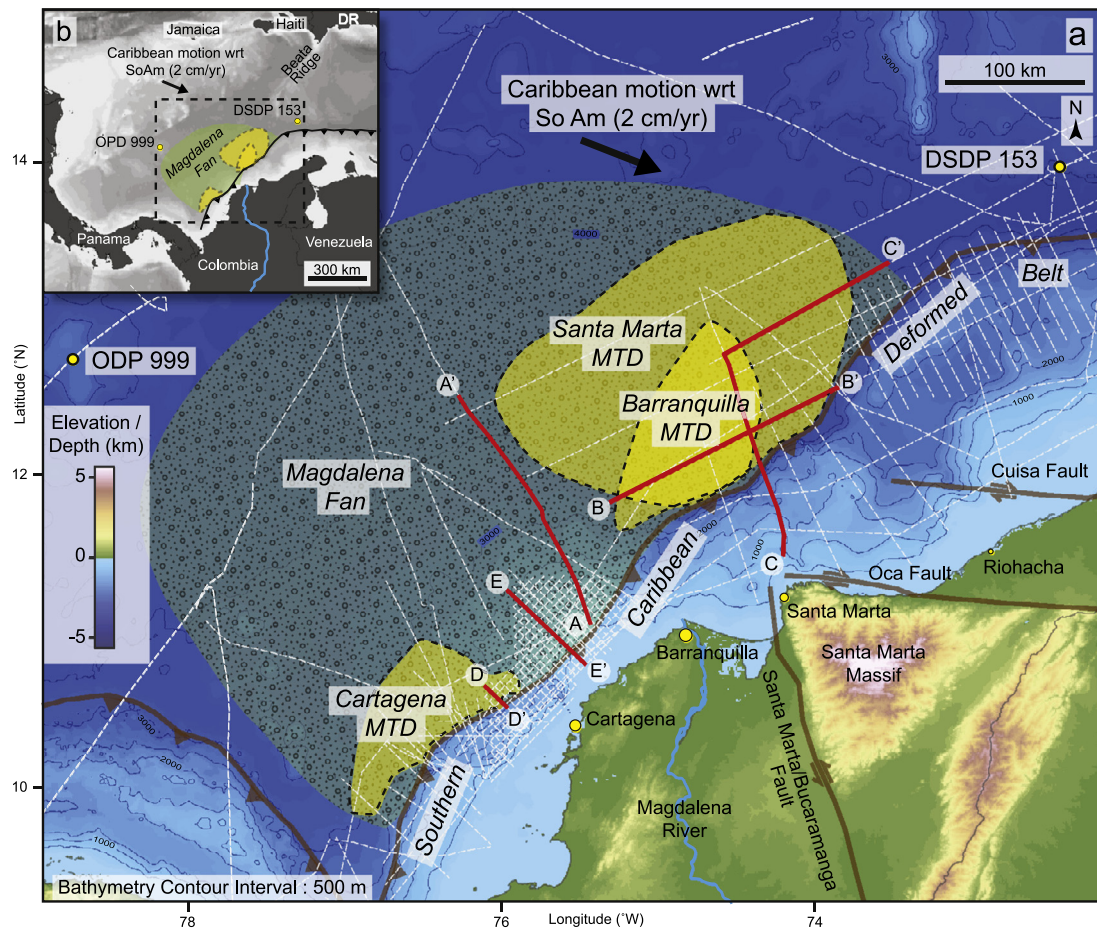
Fig. 1. a. Map of the active subduction margin along the northern coast of Colombia including its accretionary prism, the South Caribbean Deformed Belt (SCDB), and the submarine Magdalena Fan system (shaded outline). Three submarine landslides, or mass transport deposits (MTDs) are recognized from SW to NE along the proximal to distal lower slopes of the Magdalena Fan: the Cartagena MTD, Barranquilla MTD, and Santa Marta MTD. Dashed white lines indicate grid of 2D seismic reflection profiles used to map the slides including one seismic line that ties to DSDP site 153, providing age control. Additional lithologic correlation is provided by ODP site 999, located on a basement high to the west of the distal Magdalena Fan. Major, active strike-slip faults in the region shown are potential triggers for submarine slope failure evens. Large Colombian cities susceptible to tsunami hazard are shown as yellow circles. b. Location of larger map (dashed box), Magdalena Fan (green outline), and MTDs identified in this study (yellow outlines) in the tectonic context of northwestern Colombia and its offshore margin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

processes including creep, slide, slump, and debris flow (Weimer, 1989). A single deposit can cover thousands of square kilometers and can travel up to hundreds of kilometers from the source region prior to deposition (Talling et al., 2007). The volume of MTDs on a scale resolvable by seismic reflection data and reviewed in the literature follows a lognormal distribution, with a median MTD size of ∼40 km^3 (Moscardelli and Wood, 2015). Located on the distal flanks of the Magdalena Fan, the three giant MTDs recognized by our study are orders of magnitude larger than those described previously in the area (Vinnels et al., 2010; Cadena and Slatt, 2013; Alfaro and Holz, 2014; Ortiz-Karpf et al., 2015). Each of the three MTDs falls within the top 5–10% of the global distribution of all deposits as compiled by Moscardelli and Wood (2015). The largest deposit, the Santa Marta MTD, covers an estimated area of 34,700 km^2 and has a volume of 5255 km^3 – recording the mobilization, in a single event, of enough material to cover an area equivalent to the U.S. state of California with 12.4 m of sediment.

A comparable MTD and paleo-tsunami analog to the three Colombian MTDs identified in this study is the 1300 km^3 Holocene Storegga slide and its well-documented paleo-tsunami with up to 25 m of observed sediment run-up off the Atlantic coast of Norway (Bugge, 1983; Smith et al., 2004; Moscardelli and Wood, 2015). The timing of the Colombian MTDs associated with the Magdalena Fan is likely to have been strongly influenced by climate induced

changes in sea level during the late Pliocene to Pleistocene, as previously documented for similar extensive MTDs recognized from the Pleistocene section of the Amazon Fan (Maslin et al., 1998). The initial slope failures were likely facilitated by pre-existing planes of weakness along the base of gas-hydrate stability zones, which are seismically imaged as prominent Bottom Simulating Reflectors (BSRs) that are observed throughout the Magdalena Fan.

2. Geologic setting

The Caribbean Margin of Colombia extends ∼850 km from the Isthmus of Panama to the Guajira Peninsula and is actively deforming by oblique subduction of the Caribbean Plate and Colombian basin beneath the overriding continental South America plate at a rate of ∼2 cm/yr (Krause, 1971; Ladd et al., 1984; Bernal-Olaya et al., 2015). The active subduction process has formed a 65 to 165 km-wide accretionary prism, the Southern Caribbean Deformed Belt (SCDB), along the margin (Krause, 1971; Ladd et al., 1984; Bernal-Olaya et al., 2015) (Fig. 1). The Magdalena Fan is a 325 km by 390 km submarine fan that spills across the SCDB onto the subducting Caribbean Plate. The Magdalena Fan is composed primarily of late Miocene to recent sediments transported from an extensive, 260,000 km^2 watershed draining the Andean Mountains of northwestern South Amer-