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Preservation potential of tsunami deposits on arid siliciclastic coasts

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ABSTRACT

Numerous post-tsunami surveys have been conducted in the last two decades, especially since the 2004 Indian Ocean tsunami. These studies have documented a variety of characteristic sedimentary and erosional features that can be ascribed to known events. Nevertheless, the question arises whether these structures are just ephemeral or have a potential to be preserved in the geological record. This review describes the changes that have affected muddy to sandy siliciclastic tsunami deposits in Peru. Each of these was surveyed in the first months after the tsunami: Chimbote (1996), Camaná (2001) and Pisco-Paracas (2007). Here, we describe the changes we observed during re-surveys in 2007 and 2008.

It has long been recognized that onshore tsunami deposits may suffer from surficial processes, tectonic movements and anthropogenic alteration. Earthquake-induced uplift or subsidence may subject a tsunami deposit to erosion or burial, respectively. Quick burial in rapidly subsiding coastal areas may enhance preservation. Deposits of the last or most landward-reaching wave may be preferentially preserved if they escape erosion by subsequent tsunami waves; however, inland areas are also vulnerable to subaerial reworking, including by wind and by humans.

The Peruvian examples reviewed here show that the preservation of arid-coast tsunami deposits depends on interactions that are more complex that hitherto perceived. These involve sediment type, grain size, depositional setting, co-seismic movement, bioturbation, winds, and anthropogenic modification. In one example, all traces of the tsunami have been removed or reworked by flash floods and ocean waves. In another example, clasts on a coastal plain from tsunami-backwash began to be rounded and abraded by eolian sands immediately after the event. Eolian processes also smoothed and filled tsunami scours. By contrast, muddy tsunami deposits in certain areas escaped erosion by wind, probably because of their greater cohesion. In still another example, 0.5 m of co-seismic uplift was not enough to prevent ocean waves from removing a tsunami sand sheet that had mantled a coastal marsh. The buried record of tsunami deposits on modern coasts may therefore not fully represent the vulnerability of these regions to tsunamigenic hazards.

Contents

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1. Introduction

In recent years the public awareness of the tsunami hazard has increased significantly. This is largely because of the catastrophic 2004 Indian Ocean tsunami (IOT) in 2004 and the Tohoku tsunami in 2011, the increasing number of buoys and tide gauges that record even small wave events (NOAA, 2009), and because news of tsunami events reaches us even from the most remote areas of the world.

Tsunami catalogues (e.g., Lander et al., 2003) and online sources (ITIC, 2013) show that between 1982 and 2009 about 200 tsunami of different magnitude were reported and at least 23 post-tsunami surveys were conducted after major events (e.g., Liu et al., 2005; Synolakis and Okal, 2005; Richmond et al., 2006; Bahlburg and Weiss, 2007; Fritz et al., 2008; Bahlburg and Spiske, 2012a; Goto et al., 2012; Richmond et al., 2012). These field campaigns, conducted by international tsunami survey teams (ITST), provide crucial data on the characteristics of tsunami deposits and connected hydrodynamic conditions during tsunami inundation.

Fine-grained tsunami sediments have been found both offshore (e.g., Bondevik et al., 1997; van den Bergh et al., 2003; Freundt et al., 2007; Abrantes et al., 2008; McAdoo et al., 2008) and onshore. Onshore deposits can be laid down immediately after a tsunami in diverse environments, such as coastal wetlands (e.g., Atwater and Moore, 1992; Bondevik et al., 1997; Hindson and Andrade, 1999; Clague et al., 2000; Chagué-Goff et al., 2002; Cisternas et al., 2005; Bourgeois et al., 2006; Moore et al., 2007; Komatsubara et al., 2008), and sandy beaches or dunes (e.g., Gelfenbaum and Jaffe, 2003; Richmond et al., 2006; Bahlburg and Weiss, 2007; Paris et al., 2007; Srinivasalu et al., 2007; Goff et al., 2008, 2009; Morton et al., 2008).

Overviews of sedimentary features (e.g., Dawson and Shi, 2000; Goff et al., 2001; Nanayama and Shigeno, 2006; Morton et al., 2007; Bourgeois, 2009; Peters and Jaffe, 2010; Phantuwongraj and Choowong, 2011) indicate that fine-grained onshore tsunami deposits can exhibit a number of characteristics, such as erosive lower contacts, rip-up clasts, normal grading, lamination (e.g. from heavy mineral layers), mud caps, and landward thinning and fining. Furthermore, the sediments can comprise sub-units that may represent both the run-up and backflow of several waves of the tsunami wave train. Generally, tsunami deposits should differ from normal background sedimentation in their coarser grain size and their composition. The latter is due to the fact that tsunamis can entrain material from both shallow marine and onshore sources, resulting in a mixture of siliciclastic and calcareous (i.e., shells or microorganism tests) components. However, in many cases tsunami sediments are massive, depicting none or only few sedimentary structures. Additionally, several features, such as grading, coarse grain sizes, erosive lower contacts, etc., can also be found in onshore storm sediments. Thus, the identification of onshore tsunami deposits is challenging and may not be accomplished by using a single criterion, but by taking into account the whole range of sedimentological attributes at a specific site.

The ubiquity of deposits following recent tsunami implies that the geological record in both marine and coastal sedimentary environments should be rich in tsunami sediments (Weiss and Bahlburg, 2006). With the current methods and state of knowledge of sedimentological tsunami characteristics, as well as considering the number of published studies on paleotsunami deposits, this does not seem to be the case. Reasons for this may be that (i) not every tsunami is capable of eroding and redepositing sediment; (ii) it is not yet possible to identify all of the tsunami sediments in the geological record; (iii) the preservation potential of tsunami deposits is generally very low; or iv) some combination of the above. Hence, the evaluation of the preservation potential of event deposits is of utmost importance for the estimation of recurrence intervals of tsunamigenic earthquakes (e.g., Cisternas et al., 2005) that are used to assess the tsunami risk of a certain coastline. A low preservation of tsunami deposits in the geological record may lead to an underestimation of tsunami hazard.

In this study we re-visited sites of three recent tsunami events along the coast of Peru. These include the 1996 Chimbote, 2001 Camaná and 2007 Pisco-Paracas tsunami. We compare the findings of our resurveys in 2007 and 2008 with the observations of the respective post-tsunami ITST surveys. The focus of this study is on a review of physical, biological and anthropogenic processes to determine the preservation potential of onshore event beds. In particular, we evaluate the preservation potential for (1) different coastal environments, including tectonically uplifted or subsided areas, and (2) different sediment textures and petrographic compositions. Climatic and anthropogenic influences are additionally considered. Chemical signatures of tsunami deposits (e.g., Chagué-Goff, 2010) and their alterations by post-depositional processes, even though they might be still recognizable after the physical properties of the sediments are already destroyed (Wheatcroft and Drake, 2003), are not considered in this study.

Each depositional environment is tied to site-specific climatic or tectonic processes. Consequently, not all results of this study can be generalized. The arid Peruvian coastal region, which is mainly characterized by sandy beaches and coastal plains, introduces its own bias on the preservation potential, mostly due to climatic influences, such as strong coastal winds or infrequent El Niño events. In many cases beach sands and intercalated event sediments have the same composition and are not easily distinguished. However, the deposits of sandy coasts in arid climates are a common feature in the geological record and their modern counterparts need to be understood first. This study provides insight into the erosion or preservation of tsunami deposits within a few years after the events in arid climate regions, and may help identify coastal sedimentary environments conducive to their preservation.

2. Geological setting, field sites and climate

The western margin of the South American continent is one of the most active seismic areas worldwide (Kulikov et al., 2005). The subduction of the Nazca Plate (Fig. 1a) below the active continental margin triggers strong submarine earthquakes capable of generating tsunami. The most severe historical events that affected Peru and Chile are the two Arica tsunamis on 24th of November 1604 and 13th of August 1868, and the Chile tsunami of May 22nd 1960 (Berninghausen, 1962; Lockridge, 1985). Along the coast of Peru, the greatest local tsunami of