



Microtextural characteristics of quartz grains transported and deposited by tsunamis and storms

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ABSTRACT

The complex transport and depositional processes associated with tsunamis and storms and the peculiarities of local inundation present questions associated with the recognition and differentiation of the sedimentary signature of these events. This work presents a study of quartz grains transported and deposited by tsunami and storm waves with the objective of identifying specific microtextural signatures caused by high-energy marine inundations and to correlate them with their principal sedimentary sources. In this empirical study, 1150 quartz grains (78 samples) and their microtextural signatures were observed, analyzed and classified using scanning electron microscope photomicrographs. The results suggest that although no specific microtextural signature is associated with high energy inundations, there are strong increases in the percentage of fresh surfaces and percussion marks when compared with the potential source material. Moreover, tsunami and storm grains present the greatest microtextural variance among all the grains analyzed. Nevertheless, specific local conditions and sediment concentrations constrain the microtextural implications on tsunami or storm grains. One laboratory experiment was designed to test microtextural implications in grains subjected to variable velocities, sediment concentration and time. The surface microscopic signature in quartz grains of high-energy events further contributes to the development of more efficient sedimentological criteria to identify deposits associated with tsunami and storm events.

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1. Introduction

Over the last three decades, the study of paleotsunamis and paleostorms has increased greatly. In contrast to modern tsunamis, for which eyewitness accounts and field measurements of both erosional and depositional effects are utilized in modeling studies, paleotsunami recognition depends on the identification of ancient tsunami deposits (e.g. Bourgeois et al., 1988; Long et al., 1989; Smit et al., 1992; Bondevik et al., 1997; Dawson and Stewart, 2007; Mahaney et al., 2010; Chagué-Goff et al., 2011). Tsunami deposition is commonly characterized by the re-deposition of coarse shallow marine or coastal sediments in terrestrial and/or transitional (estuarine) environments, and recognition of these deposits is the primary field method for reconstructing tsunami minimum inundation distance, run-up and inland penetration, although patterns of erosion and deposition by both landward- and seaward-directed flows are complex (Moore and Moore, 1984; Synolakis et al., 1995; Bondevik et al., 1997; Dawson and Shi, 2000; Paris et al., 2007), thus introducing uncertainties in

those reconstructions. Understandably, the nature of tsunami deposits varies greatly with coastal and nearshore morphology, the height of tsunami waves at the coast and run-up, and with the nature and amount of existing sediment in any coastal setting when affected by such an event. Consequently, the possible variations in sedimentary processes and products during these complex events remain poorly understood. Sediment characterizing tsunami run-in can be recognized as shallow-sourced marine, beach or coastal dune, and as such, is usually found in a stratigraphically narrow band with a large lateral extension landward, as clear evidence of re-deposition by an extreme and extensive wave-borne inundation. More recently, the subsequent backwash, or return flow, has been regarded as a process of significant geomorphic and sedimentologic consequence (e.g. Dawson, 1994, 1999; Hindson and Andrade, 1999; Dawson and Shi, 2000; Le Roux and Vargas, 2005; Paris et al., 2010), though the lateral extension of the correspondent signature is usually more restricted due to channeling effects. Constraints to the preservation of tsunamigenic deposits in coastal stratigraphy have also been discussed by Szczucinski (2011). Recently, a number of papers revisited the issue of distinguishing tsunami and storm deposits. Nanayama et al. (2000) described deposits associated with the 1993 Japan Sea tsunami and the 1959 Miyakojima typhoon in the same location of the Hokkaido coast, Japan. The main differences detected were

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that the tsunami deposit consists of four beds, showing evidence of bidirectional currents associated with landward and seaward flow of the two main waves that caused the deposition of marine sand, gravel, seashells and clasts of eroded soil. In contrast, the storm deposit recorded a unidirectional current, foreset bedding, and better sorting when compared to the tsunami deposit.

Goff et al. (2004) compared 15th century tsunami deposits with sediments emplaced by an Easter 2002 storm along the coast of the southeast part of the North Island, New Zealand. Both deposits are peculiar in local extent, thickness, and grain size. According to Goff et al. (2004), the tsunami deposit thins abruptly at the margins and fines inland, as opposed to exhibiting the highly variable grain size characteristic of the storm deposit with a marked coarsening at its landward extent. Furthermore, the authors suggest that the storm deposit is slightly better sorted and coarser than the tsunami deposit, thus indicating that the poorer sorting reflects the wider range of grain sizes entrained by the tsunami both on offshore and on land.

Kortekaas and Dawson (2007) analyzed a group of samples from Martinhal (SW Algarve, Portugal), recognizing tsunami deposits associated with the AD 1755 event, as well as several, more recent storm deposits. The authors concluded that foraminiferal assemblages and grain size characteristics are almost identical in both types of events, although tsunami deposits present higher concentration of foraminifera and incorporated boulders with borings of molluscs, which are absent in storm layers. Nevertheless, it has been demonstrated that the preservation of small bioclasts in tsunami deposits is highly variable, and their evidence could disappear within a few years after the tsunami (Yawsangratt et al., 2011). The main difference detected was the inland extent of the tsunami deposit when compared with the sedimentary signature of storm events. A similar observation was made by Tuttle et al. (2004) when performing a comparative analysis among the deposits emplaced by the AD 1929 Grand Banks tsunami with those associated with the AD 1991 Halloween storm along the eastern coast of Massachusetts, the United States.

Switzer and Jones (2008) have analyzed and compared tsunami and storm deposits in a closed freshwater back-barrier lagoon located in southeast Australia. They differentiated among tsunamis and storm emplacements based on: a) source (e.g., tsunamis have a wider range of sediment sources); b) the presence of the organic-rich clasts, which often indicate that the depositional event was not only capable of breaching the barrier, but also able to enter the lagoon with enough force to erode the organic-rich sediments of the lagoon; c) the degree of sorting (e.g., tsunamis are poorly sorted and with bimodal particle size distribution); d) sedimentary features that may distinguish storm deposits from tsunami deposits, including graded beds and evidence of bidirectional flow.

Several sedimentological techniques have been recently explored to improve the understanding and differentiation among tsunami and storm deposits, noting that the underlying principles and techniques have been previously used in distinguishing depositional sedimentary environments such as microtextural-signature analysis performed in this investigation. The use of scanning electron microscope (SEM) in sedimentary studies, for example, was initiated by Biederman (1962) and developed by Krinsley and Doornkamp (1973) to the study of the microtextures on quartz grain surfaces. Furthermore, SEM microphotographs and micromorphological diagnostic features of quartz grains have been compiled in the form of atlases (e.g., Krinsley and Doornkamp, 1973; Gillott, 1974; Le Ribault, 1977; Mahaney, 2002). Bruzzi and Prone (2000) were the first to use SEM micrographs in the study of abrupt marine events by performing a comparative analysis among the microtextural signatures of quartz grains deposited by the AD 1755 tsunami along the coast of Boca do Rio, Portugal, and those deposited by a November 1997 storm, recorded in the Rhône Delta, France. According to these authors, several microtextural similarities existed among the two sets of samples, making differentiation complex and difficult. However, they point to a few microfeatures

specifically characteristic of the tsunami event, such as upturned plates, fractures and marks of considerable size.

Furthermore, Dahanayake and Kulaseena (2008) proposed a number of diagnostic criteria to distinguish tsunami from storm-surge sediments in southern Sri Lanka. They noted that in tsunami sediments, reworked marine microfauna is abundant, quartz sand is not well rounded, and heavy minerals are rare, when compared with storm-surge sediments. Tsunami sediments were less well sorted than both storm-surge and nearshore sediments. More recently, Lakshmi et al. (2010) presented an integrated methodology using proxies such as single grain morphoscopy and textural analysis, which provided a means to identify and differentiate extreme wave events. The authors used SEM images of magnetite and ilmenite, attempting to characterize the microtextural effects caused by extreme events. In both cases (Dahanayake and Kulaseena, 2008; Lakshmi et al., 2010), ilmenite was used because it was considered an important component of the heavy mineral fraction.

The few studies specifically designed to compare characteristics of historical tsunami and storm deposits (Nanayama et al., 2000; Goff et al., 2004; Tuttle et al., 2004; Kortekaas and Dawson, 2007; Morton et al., 2007; Dahanayake and Kulaseena, 2008; Switzer and Jones, 2008) were conducted at the same or nearby sites. This eliminated or reduced inter-site sediment and landscape variability, but prevented the comparison of impacts of events of similar intensities, elsewhere, thus reducing the chance of identifying space-independent signatures specific to tsunami or storm inundation.

In this study, we uniquely try to overcome this limitation by combining, in the same database, sediments of which represent present-day sedimentary environments with materials deposited by both tsunamis and storms in coastal contexts that differ in geographic location and geological, geomorphological and oceanographic settings. The focus of this empirical work is to study quartz grains transported and deposited by tsunami and storm waves with the aim of identifying specific microtextural signatures caused by high-energy marine inundations and to correlate them with their likely sedimentary sources.

2. Study areas

Six coastal locations subjected to important high energy marine inundations were carefully selected for this work, as they have excellent sedimentary records of events responsible for the deposition of distinctive sand layers detected at considerable distances (up to ca. 3000 m) inland. Moreover, they provide a superb array of chronological, stratigraphical and sedimentological characteristics that allow a more rigorous analysis of the different settings and factors involved with high-energy inundation events. This includes many of the sedimentary criteria used to recognize tsunami and storm deposits, and important to this investigation, optimal test sites for identifying and characterizing the microtextural signatures of quartz grains caused by specific high-energy marine inundations and correlating them with their respective emplacement event.

2.1. Scotland

2.1.1. Shetland Islands

About 8100 calendar years ago (ca. 7300 ¹⁴C yr BP), a large-magnitude tsunami inundated the shores around the Norwegian Sea and North Sea. The tsunami was generated from the Second Storegga slide (displaced volume of about 5400 km³) located to the west of Norway. Widespread tsunami deposits from this event have been discovered to be widespread throughout the Shetland Islands (Bondevik et al., 2005; Dawson et al., 2006). A field survey was conducted, and ten trenches were dug to collect paleotsunami deposits from two locations in the Shetland Islands (Fig. 1A; Voe Scatsta and Loch of Scadafleck). Eight paleotsunami samples, collected in two different trenches, are used for this work. In this study area, sand beaches are rare despite the tsunami deposits being principally composed of sand.

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