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Analysis of environmental controls on tsunami deposit texture

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ABSTRACT

Tsunamis transport large amounts of sediment and can leave recognisable signatures in the landscape. The form and composition of onshore tsunami deposits are a function of wave dynamics, sediment availability and characteristics of the local environment, the latter of which also partially controls preservation of the deposit. This research reviews these relationships in a global context and assesses the connection between tsunami deposit particle size and four controlling parameters: climate (temperature and rainfall), density of tsunami sediments, degree of coastal protection and distance between tsunami source and sediment deposition. An international dataset of tsunami deposit locations and texture was compiled from published literature and existing databases. Values for environmental variables were calculated for each location from global datasets of temperature, rainfall, coastline shape and tsunami source locations. Spearman's rank-order correlation, Principal Component Analysis (PCA) and hierarchical Cluster Analysis (CA) were used to analyse relationships between these variables. PCA results show an inverse relationship between particle size and sediment density, climate variables and distance from source. CA results support this, suggesting a cluster structure controlled primarily by particle size and secondly by climate and sediment density. These relationships can be explained by the influence of the environment on antecedent morphology and the composition of sediments available for tsunami transport.

1. Introduction

1.1. Tsunami deposits

A tsunami has the power to erode, transport and deposit large amounts of sediment, leaving signatures in the sedimentary record that may be used to infer the hydrodynamic mechanisms of inundation. Tsunami deposits take a variety of forms, resulting from differences in the waveform, local bathymetry, topography, and coastal configuration, as well as sediment type and its availability to be transported (e.g. Sugawara et al., 2008). Sediment characteristics and coastal form are in turn controlled by interacting external parameters, which include tectonics, continental lithology, coastal and fluvial energy and climate (e.g. Hayes, 1967; Masselink and Hughes, 2003). Deposits from an individual tsunami will differ considerably at different locations and significant internal variability may occur within a single deposit. This has significant implications for the interpretation of tsunamis from their deposits.

Tsunami deposits are often initially identified by their stratigraphic context, occurring frequently as anomalous sediment (often sand) layers laid down in a lower-energy coastal environment (e.g. Chagué-Goff et al., 2002; Clague and Bobrowsky, 1994; De Martini et al., 2010; Kelsey et al., 2005; Nanayama et al., 2007; Nichol et al., 2007; Sawai et al., 2008; Sugawara et al., 2012). Tsunami deposits may occur onshore or offshore, but research has tended to focus on the most accessible onshore deposits. These deposits commonly take the form of a large sediment sheet, usually sourced from the adjacent nearshore or beach environment during inundation (e.g. Sugawara et al., 2008), although deposits may be discontinuous or absent where the signature is predominantly erosional (e.g. MacInnes et al., 2009). It is common for deposits to contain mud, gravel layers and clasts up to large boulder size, depending on the source material available (e.g. Chagué-Goff et al., 2012a; Goto et al., 2011; Maouche et al., 2009; Mastronuzzi et al., 2007; Medina et al., 2011; Nandasena et al., 2011; Paris et al., 2010; Scicchitano et al., 2007). The thickness of a deposit can vary from millimetres to tens of metres (e.g. Sugawara et al., 2005), depending on the energy of the wave, amount of sediment available and preservation potential of the deposit (e.g. Sugawara et al., 2008).

Characteristics of tsunami deposits have been reviewed extensively in recent decades (Chagué-Goff et al., 2011; Dawson, 1994; Dawson and Shi, 2000; Engel and Brückner, 2011; Etienne et al., 2011; Fujiwara, 2008; Goff et al., 2001; 2012; Shanmugam, 2012; Shiki et al., 2008; Tappin, 2007) and research has expanded considerably following the 2004 Indian Ocean tsunami (IOT) and 2011 Tohoku-oki tsunami (ToT). Common defining sedimentary features include: predominantly marine sediment origin, graded sediment layers that generally fine

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and thin upwards and inland, erosional lower contacts, loading structures and rip-up clasts, and evidence of repeated reversal of current direction (e.g. Chagué-Goff et al., 2011; Fujiwara, 2008; Goff et al., 2012; Kortekaas and Dawson, 2007; Morton et al., 2007; Nichol et al., 2007; Peters and Jaffe, 2010a; Peters et al., 2007; Sugawara et al., 2008; Switzer and Jones, 2008). It is important to note that not every indicator is present in a given deposit and tsunami deposit identification relies on the use of multiple proxies, which have been added to in recent years as new techniques have been developed and applied from other disciplines (Chagué-Goff et al., 2011; Goff et al., 2012).

The geographical distribution of tsunami research is not evenly spread, which has implications for any patterns inferred from this research. Studies of both recent and palaeo-tsunami deposits have been particularly focused on landmasses adjacent to the Pacific Ocean, where tsunamis frequently result from subduction zone earthquakes (e.g. Cisternas et al., 2005; McFadgen and Goff, 2007; Minoura et al., 1996; Nanayama et al., 2007; Nichol et al., 2010; Switzer and Jones, 2008). This gap is partially addressed by the increasing availability of tsunami databases, which are continually updated as new research becomes available and new tsunamis occur. These include global catalogues of tsunami events and deposits (Dunbar and McCullough, 2012; NGDC/WDS, 2014; Peters and Jaffe, 2010b) alongside ongoing projects with a palaeotsunami and/or a regional focus (e.g. New Zealand: Goff, 2008; Australia: Goff and Chagué-Goff, 2014; France: Lambert and Terrier, 2011; Western North America: Peters et al., 2003; Italy: Tinti et al., 2004).

1.2. Statistics in tsunami science

Exploratory statistical analysis of a dataset provides insight into data trends, structure and variability. These techniques are commonplace in social science and biological research, but are less so in earth science, because this type of data is not often obtained in a systematic experimental manner that meets statistical criteria for sample size and data type (Borradaile, 2003). However, some areas of earth science have successfully applied statistical methods, and as such there is a precedent for their implementation in physical tsunami research. Multivariate techniques are regularly applied in geochemical investigations of water composition, to determine source and transport pathways (e.g. Praus, 2006; Zhang et al., 2009), and similar methods have also been applied to dust and soil (e.g. Yongming et al., 2006). Other research has used a combination of multivariate techniques in a less direct manner, to explore the influence of environment and geology on complex physical processes such as landslide susceptibility (e.g. Baeza and Corominas, 2001; Komac, 2006) and river hydrology and channel evolution (e.g. Bertrand et al., 2013; Thoms and Parsons, 2003).

The science of tsunami deposits has largely been developed through observational studies and, more recently, modelling of sediment transport processes. Statistical analysis is sometimes applied to individual aspects of a tsunami deposit, such as grain size or geochemical data processing (e.g. Chagué-Goff et al., 2012a; 2012c; Jagodziński et al., 2012; Sakuna et al., 2012; Szczuciński et al., 2005; Yoshii et al., 2013), but statistical methods are not generally appropriate for solving the research questions of tsunami-focused geological investigations. Nevertheless, statistics is an underutilised tool for the analysis of the dense information catalogued in tsunami databases.

Relationships between tsunami deposit form and the local environment have been well documented in an observational context for individual deposits, but have not yet been explored from a global predictive perspective. The purpose of this research is to investigate the relationships between tsunami deposit texture and four key parameters in the depositional environment: climate (temperature and rainfall), density of tsunami sediments, degree of coastal protection (as will be explained later) and distance between tsunami source and sediment deposition. These parameters were chosen due to their fundamental importance in controlling coastal morphodynamics and sediment supply (Masselink and Hughes, 2003).

2. Material and methods

2.1. Data sources and preparation

A database of tsunami deposit characteristics and grain size information was compiled from published literature and other available tsunami databases (Fig. 1, Table 1). Entries were restricted to deposits emplaced within the late Holocene, based on the assumption that the environment has remained relatively constant during this timeframe. Where multiple tsunami deposits were described for distinct events at the same site, these were included as separate entries. This database is not intended as an exhaustive list of all possible tsunami deposits, but rather a representative sample to allow a robust global analysis. Additionally, some published research that was initially consulted did not contain sufficient numerical data to allow inclusion in the database.

Database parameters are presented in Table 2, along with sources of information, calculations and percentage of entries with values for each variable. In the case of climatic variables, global temperature and rainfall datasets were obtained from Hijmans et al. (2005) and together act as a proxy for weathering processes and chemical weathering in particular. Values at tsunami deposit locations were extracted from a raster using *ArcGIS*, then manually cross-checked to eliminate errors in the extraction process. Where a deposit location had no corresponding value for one of these parameters, this was interpolated from the nearest area. Mean monthly temperature and rainfall values were averaged to provide a mean annual value for each parameter. We acknowledge the uncertainty introduced in the averaging process, but the values compared well with deposit locations' classifications on the Köppen-Geiger Climate Classification system (Kottek et al., 2006) and the resolution was deemed satisfactory for our purpose. Sediment density was either reported directly from the original research or calculated based on descriptions of the mineral composition of tsunami deposits. Where the tsunami source was reported, this was mapped and the shortest travel distance calculated across the Earth's surface. If no information for composition or tsunami source was available, a value of NA was reported for that parameter. The protection factor is a dimensionless empirical parameter that represents the degree of coastal exposure, with values of 0 corresponding to a promontory, 1 equal to a straight coast and values increasing with higher levels of protection. This was calculated for each deposit location based on the level of embaymentisation and the presence of protective features such as islands or reefs. The following equation was developed, where Sl refers to shoreline length and Cl to chord length between headlands, after Short (1996). K refers to a sheltering factor, measured on a scale of 1–10 based on the percentage of protection offered by reefs or offshore islands.

$$\mathrm{PF} = \mathrm{Sl}/\mathrm{Cl} * \mathrm{K}$$

The final database contains 273 entries, of which 92 have values for all parameters and 199 have values for at least 5 of the 6 variables.

2.2. Statistical analyses

Numerical analyses were undertaken using the open source statistical package, *R*. Descriptive statistics were calculated for each variable and data distributions were assessed. Correlation analysis was performed by Spearman's rank-order correlation, which is a nonparametric test that is more robust for data that are non-linearly related or contain outliers that must be included (Schuenemeyer and Drew, 2011). A matrix of Spearman's correlation coefficients was constructed to assess individual relationships between variables, with significant