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Abstract Volume

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Foreword

The International Tsunami Field Symposium (ITFS) is the ideal forum for scientific discussions within the tsunami geoscience community. Sixty two abstracts (37 oral presentations and 25 posters) contribute to stimulate those discussions and all are presented in this document.

We very much acknowledge the authors' commitment and involvement that, coupled with the constructive reviews from the members of 5th ITFS Scientific Committee, contributed decisively to raise the scientific quality of this Symposium.

In particular, we wish to thank Ana Matias (Universidade do Algarve, Portugal), Bruce Jaffe (USGS), Bruce Richmond (USGS), Catherine Chagué-Goff (Univ. NSW, Australia), David Tappin (British Geological Survey), Giuseppe Mastronuzzi (Univ. Bari, Italy), Guy Gelfenbaum (USGS), Heinrich Bahlburg (Univ. Munster, Germany), Helmut Brückner (Univ. Köln, Germany), James Goff (Univ. New South Wales, Australia), Javier Lario (UNED, Spain), José Madeira (IDL & GeoFCUL, Portugal), Kazuhisa Goto (Tohoku Univ., Japan), Maria Ana Baptista (ISEL/IDL & IPMA, Portugal), Raphael Paris (Univ. BP Clermont-Ferrand, France), Ricardo Ramalho (IDL & GeoFCUL, Portugal and Univ. Bristol, United Kingdom), Susana Costas (Univ. Algarve, Portugal), Sue Dawson (Univ. Dundee, United Kingdom) and Witold Szczuciński (Univ. Poznan, Poland).

Finally, we are very thankful to all participants and hope we all have a great time at the 5th ITFS in Portugal.

Obrigado!

The Editors

Pedro J.M. Costa, César Andrade and Maria Conceição Freitas

Index - Abstract title and 1st author name

Keynote - Tsunami geoscience: an interdisciplinary perspective

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Abstract

The study of tsunami geoscience has advanced greatly over the last ca. 30 years since the early days when the world's media were scarcely aware of what a tsunami was! Tsunami geoscientists have made great progress since the late 1980s when the simple goal at that time was to convince and persuade the scientific community that tsunamis actually deposit sediment! Yet the key scientific advances in tsunami geoscience research have taken place when geoscientists have looked outwards and collaborated with scientists from other disciplines. In the talk, this idea is illustrated through discussion of some key tsunami research issues supplemented with examples. The presentation will address some of the difficulties associated with the identification of paleo-tsunamis in coastal sediment sequences. The talk will make use of example of several pre-historic tsunamis with particular attention given to the giant Storegga submarine slide to discuss some of the difficulties associated with constructing and interpreting numerical models of past tsunamis. Particular focus will be given to interpretations of run-up, the role of backwash and sediment transport, numerical model construction as well as the critically important issue of slide generation mechanisms. In this respect, a discussion is given of a range of processes involving aspects of Earth rheology, tectonics, oceanography, climate change and archaeological research.

Keynote - A 30-year perspective on tsunami deposits

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Abstract

Tsunami deposits represent the geological record of past tsunamis. Identifying and dating tsunami deposits in the sedimentary record thus participates to a retrospective analysis of coastal hazards. Since the early studies in the 80s and 90s, an increasing number of publications and the use of new methods have considerably improved our knowledge of tsunami deposits and their characteristics. Disastrous events such as the 2004 Indian Ocean tsunami and the 2011 Tohoku-Oki tsunami have encouraged many scientists around the world to understand these complex deposits. The criteria for identifying tsunami deposits and distinguishing them from other deposits (such as turbidites or storm deposits) are now far better established than 30 years ago. Different dating methods have been successfully tested. However, tsunami scientists are still facing big challenges, not only in terms of complex modelling strategies and hazard assessment. Sedimentologists have to answer to this question: How to link the sedimentary record of a tsunami to its magnitude? Several authors have tried to address this critical issue using both forward and inverse models. The main limitations are due to the complexity of tsunami flow dynamics in the inundation zone (e.g. effect of the microtopography), and to post-depositional processes (that rapidly modify the textural and structural characteristics of tsunami deposits).

Keywords

Tsunami deposits, sedimentology, micromorphology, geochemistry, coastal hazards

Acknowledgements

I acknowledge Pedro Costa and all the organisation team for inviting me to give a keynote conference at the 5th International Tsunami Field Symposium.

Tsunamis in the Iberian Peninsula during Antiquity: the historical sources

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Abstract

According to recent seismic catalogues of Portugal and Spain (Martins and Mendes 2001; Martínez and Mezcua 2002), a remarkable number of tsunamis were recorded in historical accounts before A.D. 1000. The catalogues list littoral inundations in 246 B.C., 218 B.C., 210 B.C. (Gulf of Cádiz); 63 B.C. (Galicia and Portugal); 47 B.C., A.D. 365, A.D. 382 (Portugal), and A.D. 881 (Gulf of Cádiz), all of which might be associated with tsunamis.

Most of these data are provided by two chroniclers: the Spanish historian Florián de Ocampo (*ca*. 1495 - *ca*. 1558) is the source for the 246 B.C., 218 B.C. and 210 B.C. events, and the Portuguese historian Bernardo de Brito (1569-1617) for the 63 B.C., 47 B.C., and A.D. 365 - A.D. 382 events. In both cases there are no known previous sources supporting their information and both authors, especially Brito, use spurious sources (Udías 2015).

In this presentation, the historiographical context of these references to tsunamis in the Iberian Peninsula during antiquity are analysed in order to assess their historical reliability, especially focusing on the alleged cataclysm in the Gulf of Cádiz at the end of the third century B.C. (Rodríguez-Vidal et al. 2011).

Keywords

Tsunamis, Spain, Portugal, Florián de Ocampo, Bernardo de Brito

Acknowledgements

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Consideration of the Tsunami Source of the Lisbon Earthquake in 1755

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Abstract

We studied the potential tsunami sources of the 1755 Lisbon earthquake. The Lisbon earthquake generated a huge tsunami not only in Portugal but Morocco. This paper focuses on the inundation height on the Moroccan side of the Mediterranean and compares the number of fatalities by using numerical models.

We used the STOC-CADMAS numerical model (Arkawa and Tomita, 2016). This model uses non-linear wave equations (STOC-ML) coupled with Navier-Stokes equations (CADMAS-SURF/3D). The accuracy of the inundation heights generated was verified by comparing with a similar model of the 2011 Great East Japan Earthquake tsunami. For the 2011 event, inundation heights in Onagawa town were compared with the observational data with results indicating that the accuracy of the model depended on the tsunami source.

At first, the tsunami source proposed by Omira et al. (2012) was used and the inundation height we produced was almost identical to their model. The maximum inundation height on the Moroccan coastline was around 6 m and the inundated distance inland was 500-800 m. The estimated number of fatalities obtained by using a relevant fragility curve was less than that in historical reports, and so we used a probabilistic approach to gradually increase the size of the tsunami source until they matched.

Keywords

Lisbon earthquake, tsunami source, run-up, mortality, numerical simulation

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Glacial-age tsunami deposits prove the tropical-ward geographical range expansion of marine cold-water species

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Abstract

The expansion and contraction of geographical range distribution of species (taxon cycles) is a common and well-studied biogeographical process. For terrestrial taxa, both fossil and extant records document poleward shifts, with range expansion of tropical species and range contraction of temperate species. For extant marine species, the geographical range contraction of cold-water taxa to higher latitudes as a result of the current global warming, as

well as the range expansion of warm-water species to higher latitudes are also documented. With reference to the fossil record, outcrops on volcanic oceanic islands testify the range expansion of tropical marine species towards higher latitudes during interglacials (Ávila et al., 2015). To date, no studies have shown the expected range expansion of cold-water marine species during glacial episodes. This is probably because such deposits are seldom preserved due to erosion by rising sea levels during the subsequent interglacial. Thus, tsunami events occurring during glacial times and transporting large amounts of sediments onshore, away from the erosive action of interglacial high sea levels, are probably the only way to have access to glacial fossil assemblages. Here we document and discuss, for the first time, the palaeobiodiversity of the Tarrafal tsunami deposit (Santiago Island, Cape Verde), attributed to a flank collapse of Fogo volcano ~73 ky ago (Paris et al., 2011; Ramalho et al., 2015), which conclusively proves the tropical-ward geographical shift of marine molluscs during the glacial MIS 5a.

Keywords

Tsunami deposits, glacial episodes, MIS 5a, palaeobiogeography, Cape Verde, mollusca

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Organic geochemical investigation of far-field tsunami deposits of Hawaii

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Abstract

Although the remotest archipelago on Earth, the Hawaiian Islands are threatened by both far-field tsunamis from around the Pacific and less frequent local tsunamis. Historical tsunami events (e.g., 1946 Aleutians, 1957 Aleutians, and the 1960 Chile) have occurred on the Hawaiian Islands, however, very little is known about prehistoric events.

In coastal sequences that do not contain easily recognizable tsunami deposits (due to a lack of a sand source or beyond the inland extent of deposition of sandy tsunami deposits) geochemical tools can be used to identify tsunami deposits. To date, only inorganic geochemical proxies showing a marine source for tsunami deposits have been studied in Hawaii (Chagué-Goff et al., 2012). In February 2017, we began using biomarkers and anthropogenic markers to fingerprint deposits on the north shore of the island of Oahu. We sampled two coastal marshes, Ukoa Pond (7 samples) and Kahana State Park, Kauai, Hawaii (22 samples), for a multi-proxy

geochemical investigation of potential tsunami deposits. Using samples of pre-tsunami sediment, tsunami deposits, and post-tsunami sediment, we split samples into two parts: an upper part identified as a potential tsunami deposit and a lower part at the base of the deposit, into which contaminants and biomarkers may migrate due to infiltration. We took samples from both a pre-tsunami sediment and post-tsunami sediment.

Gas chromatography-mass spectrometry (GC-MS) is then used to search for organic compounds, natural (biomarkers) as well as anthropogenic pollutants (anthropogenic markers). Compounds that can distinguish tsunami deposits versus non-tsunami deposits include fatty acids and n-alkanes (biomarkers), as well as PAHs and pesticides (anthropogenic markers).

Keywords

Organic geochemistry, far-field tsunami, field studies, biomarker

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Magnetic dating of floods

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Abstract

A new method using the remanent magnetization of flood boulders is presented that can be used to date paleo-floods and can help distinguish between storm floods and tsunamis, as well as constrain recurrence frequencies of jökulhlaups.

The method is based on the fact that boulders that are transported and rotated by a flood slowly become re-magnetized as the time passes post-flood. The blocking temperature of this remanent magnetization can be determined in the lab and used to calculate the age of the flood. Compared to other dating methods such as cosmogenic radionuclide dating it has the advantage that no exposed surface is required, and contrary to previous magnetic dating methods the accuracy has been improved by using a continuous thermal demagnetization technique and novel rock magnetic experiments, giving a clear understanding of the rate at which a flood boulder acquires a re-magnetization after emplacement.

In order to assess the performance of the new dating method, it has been applied to (1) jökulhlaups in Iceland, (2) storm floods in Scotland, and (3) a tsunami in Cape Verde, spanning a range of time scales from tens of years to tens of thousands of years. Preliminary results of these events are presented, along with a proposed protocol to follow for the application of magnetic dating of flood boulders.

Keywords

Flood dating, palaeomagnetism, tsunami boulders

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A long record of extreme wave events in coastal Lake Hamana, Japan

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Abstract

Coastal Lake Hamana is located near the convergent tectonic boundary of the Nankai-Suruga Trough, which gives rise to repeated tsunamigenic megathrust earthquakes (Mw ≥ 8). Thanks to its accommodation space, Lake Hamana may represent a good archive for past tsunamis and tropical storms (typhoons), also referred to as "extreme wave" events. By applying a broad range of surveying methods, sedimentological analyses and dating techniques, we attempt to trace extreme wave event deposits in a multiproxy approach. Seismic imagery shows a vertical stacking of strong reflectors, interpreted to be coarser-grained sheets deposited by highly energetic waves. Systematic sampling of lake bottom sediments along a transect from ocean-proximal to -distal sites enables us to evaluate vertical and lateral changes in stratigraphy. Ocean-proximal, we observe a sequence of eight sandy units separated by silty background sediments, up to a depth of 8 m into the lake bottom. These sand layers quickly thin out and become finer-grained land-inward. Seismic-to-core correlations show a good fit between the occurrence of strong reflectors and sandy deposits, hence confirming presumptions based on acoustic imagery alone. Sand-rich intervals typically display a higher magnetic susceptibility, density and stronger X-ray attenuation. However,

based on textural and structural differences, we can make the distinction between different types of sand units: i) massive to layered sands with a sharp, erosive lower contact, ii) thin, discontinuous sand lenses with a sharp lower contact and iii) inter-fingered sand-rich and silt-rich intervals with a gradual lower contact. Variability in appearance suggests a variety in triggering events too, going from tsunamis, over storm surges (typhoons) to the impact of sea-level changes on the interaction between tidal delta and lacustrine sedimentation. Two closely-spaced tephra layers are tentatively linked with the Osawa Fuji scoria (3090 BP) and Kawago-daira pumice (3150 BP). However, more absolute ages (^{14}C and OSL) are essential in order to obtain an accurate age-depth model and to position events in time. We are proceeding with the age determination of event sand beds based on single-grain OSL dating of feldspars.

Keywords

Coastal lake, extreme wave event deposits, multiproxy, age-depth model

Extreme wave deposits at Myanmar's coast – New insights into long-term tsunami and cyclone hazard in the Bay of Bengal?

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Abstract

Myanmar's coast is prone to flooding by both tsunamis and tropical cyclones (TCs) from multiple sources. However, while historical TCs repeatedly caused severe flooding during the last decades (e.g.TC Mala 2006 and TC Nargis 2008; Fritz et al., 2009), the only tsunami with documented regional impact was the 2004 Indian Ocean Tsunami (Satake et al., 2006). Thus, the hazard posed by tsunamis triggered at the North-Sumatra-Andaman Segment (i.e. similar events as 2004) and potential tsunamis triggered by ruptures of the Rakhine Segment (e.g. a tsunami associated with a major earthquake in 1762; Cummins, 2007) is poorly constrained and mainly based on model predictions (e.g. Cummins, 2007).

Sediments of past flooding events might provide useful evidence to evaluate the model-predicted tsunami hazard, but so far very limited research has been conducted. Here we present first results of a field survey along Myanmar's western (Rakhine) and eastern (Thanintharyi) coast that aimed at (i) investigating sediments of modern tsunamis and TCs as local references for discriminating both types of event deposits; and (ii) searching for potential archives that store the deposits of ancient tsunamis and TCs to allow for long-term hazard reconstruction.

Onshore deposits of 2006 TC Mala and 2008 TC Nargis were documented both at the west and the east coast, where they form sand sheets with landward extents of up to ~100 m or washover fans in back-beach areas. Significant flooding by the 2004 tsunami was only reported at the eastern coast, where it also might be reflected by washover deposits identified in the back-beach zone. However, at most sites these flooding deposits display a very poor preservation potential. After only a few years most evidence is already overprinted by soil formation that probably obliterates all differences to sandy subsoils within decades. Only where sand sheets extend into back-barrier depressions characterized by the deposition of terrestrial fine sediments during the rainy season, preservation may potentially allow for detection after longer time periods. One promising archive might be a beach-ridge plain at the west coast, where distinct marine sand layers were observed in the clayey in-situ sedimentation of swales located beyond the reach of modern TC deposition.

Keywords

Tsunami deposit, cyclone deposit, field survey, modern analogue, sedimentology

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Relevance of heavy minerals in sandy tsunami deposits

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Abstract

This work summarizes results obtained from heavy mineral (HM) studies to interpret tsunami deposits in different locations around the world, with different chronologies, and generation mechanisms: Salgados (Portugal), Lhok Nga (Indonesia), Basta Voe and Whale Firth (Scotland), and Arauco/Mataquito (Chile).

In Salgados, the AD1755 tsunami deposit revealed higher concentration of HM (0.25-0.52%) when compared with beach (<0.20%), dunes (≈0.25%) and nearshore (<0.0092%), although coastal sediments were their primary source.

In Lhok Nga (December 2004) HM in total sediment exhibited extremely low values (0.352 to 0.003%). The higher concentration in the densest transparent minerals (zircon and garnet) was observed in backwash-related and in the most inland samples, suggesting that their source was situated farther inland.

In Basta Voe (1500 cal. yr BP) the exclusive source (Lewisian gneiss) restricts the HM variability to the dominance of garnets and amphiboles (>88% of the HM assemblage in palaeotsunami sediment). In this context, higher frequency of garnets in the tsunami materials compared to likely sources (glacial drift or beach sand) could be an indicator of grain sorting during the inundation.

At Whale Firth (8200 cal. yr BP), garnets show the greatest concentration in the tsunami deposits closest to the coast, whereas amphiboles are better represented further inland. This is a consequence of different modes of

transport and densities. While garnets are more difficult to entrain due to their higher density, amphiboles tend to be transported as suspended load.

In Arauco and Mataquito (February, 2010) preliminary results revealed that the tsunami deposits exhibit very high concentration of HM (20–40%); this is in contrast with the most likely source (beach) that displays lower concentrations (<5%). In this case, the higher concentration in HM is characterized by the dominance of magnetite, representing about ¼ of the total sediment weight.

Overall, geological and geomorphological contextualization is required but results demonstrate the usefulness of HM analysis to determine sediment transport phases and mechanisms in the study of tsunami events.

Keywords

Sediment, sorting, transport modes, tsunami waves

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Tsunami geochemistry – a review and progress 30 years on

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Abstract

It has been 30 years since the first published study reporting on the use of geochemistry to identify and characterise tsunami deposits in Japan. While the uptake of geochemistry in tsunami research had been initially slow and was mostly associated with the study of palaeo-events, it was the 2004 Indian Ocean Tsunami that led to a surge in publications, like for all other tsunami-related fields. This was also the start of a new field of research, namely the assessment of environmental impact due to tsunami inundation, followed by the first studies dealing with post-depositional changes.

Geochemical data have increasingly been used to provide evidence of marine inundation, as part of multi-proxy investigations of historical and palaeo-tsunamis all around the world, sometimes even providing the conclusive proof when other proxies are missing or equivocal. The 2010 Maule and 2011 Tohoku-oki tsunamis are however associated with the first reports of geochemical markers as indicators of tsunami inundation beyond the extent of the visible (sand) deposit. This has been revealed as particularly significant following the 2011 Tohoku-oki tsunami, when it was recognised that the magnitude of previous events had been underestimated, because it was based on the extent of the sand deposit only.

Here we present the current state of geochemistry in tsunami research and its multiple facets, including inorganic and organic compounds, stable isotopes, biomarkers, DNA. We also discuss limitations and existing knowledge gaps. The main take-home message is that geochemical proxies should be used as part of a multi-proxy approach in order to identify tsunami deposits, and that while some proxies are universal, many are site-specific. A database of geochemical proxies and their interpretation is also briefly presented, with details to be found in a recently published review (Chagué-Goff et al. 2017).

Keywords

Tsunami geochemistry, source material indicators, marine indicators

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Conceptualising the British landslide-tsunami geohazard: sedimentary evidence of Holocene tsunami events in the Shetland archipelago

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Abstract

Although most tsunamis around the world are triggered by seismic activity in proximity to tectonic plate boundaries, submarine landslides can also generate major tsunami events. The largest tsunami known to have impacted the British coast was initiated by the Storegga submarine landslide which occurred on the continental slope of the Norwegian Sea approximately 8200 yrs BP. This landslide comprised a maximum volume of 3200km3 generating a tsunami which extensively affected coastlines across the North Atlantic. Palaeotsunami deposits attributed to this source have been identified at locations in Scotland, England, Norway, the Faroe Islands and Greenland. However, a site of particular interest is the Shetland Isles, where along with deposits associated with the Storegga tsunami, stratigraphic evidence for two more recent palaeotsunamis have also been described. The source of these events has still to be identified, although studies of the seabed have shown that other potentially tsunamigenic Holocene submarine slides have occurred in the North Atlantic region. We describe new sedimentary evidence from the Shetland Isles for Holocene tsunamis subsequent to the Storegga event. The implications for palaeotsunami magnitude, return periods and the consequences for understanding the risk to the UK from future landslide generated tsunamis are discussed.

Transatlantic tsunami records in Brazil

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Abstract

Record of transatlantic tsunamis are uncommon which is in contrast with the Pacific region. However, the AD 1755 Lisbon tsunami affected areas across the North Atlantic and the Caribbean (Roy et al, 2009). Recent historical research based on the colonial archives (Arquivo Histórico Ultramarino) (Veloso, 2015) have reported the impact of the AD 1755 Lisbon Tsunami in Brazil, providing details of inundation extension and (indirect) wave run-up in 3 specific coastal villages of Paraíba, Pernambuco and Bahia States.

This work aims to find geological record of the AD 1755 Lisbon Tsunami in Brazil. We conducted numerical modelling tests (Dourado et al, 2016) to complement the historical information and to help with the selection of sites for fieldwork.

To calculate the tsunami amplitude at the Brazilian coast we have used the NSWING (Non-linear Shallow Water model With Nested Grids) model (Miranda et al, 2014) that calculated heights up to 2.14 m above mean sea-level onshore and 2.56 m at Brazilian oceanic islands. Results of modelling were in very good agreement with the run-up information retrieved in the historical review.

Following analysis of historical documents and results of numerical simulations, approximately 20 sites were surveyed along 300 km of the shores of NE Brazil (namely Rio Grande do Norte, Paraíba e Pernambuco). Trenches and cores (up to 1.80 cm long) were excavated in backdunes, foredunes, lagoonal and river margins up to the mangrove limit. A peculiar unit was identified in the top meter of the coastal stratigraphy of some of the surveyed locations. It was composed of poorly sorted coarse sand with very diverse composition (quartz grains, shell debris, coral fragments, heavy minerals and other coarse lithic particles) exhibiting several criteria commonly associated with extreme marine inundations. OSL dates are being processed to provide a chronological framework for the analyzed sequence.

Results from this work stress the importance to fully understand the implications of far-field impacts of transatlantic tsunami events. Despite low frequency for these events, the potential economic costs for the Brazilian coasts need to be addressed.

Keywords

Transatlantic tsunami, Brazil, historical records, numerical modelling, tsunami deposits

Acknowledgements

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How can tide amplitude affect the tsunami vulnerability of coastal buildings? The case Study of Northern Atlantic Asilah, Morocco

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Abstract

The Moroccan Atlantic coast, open to the tsunamigenic zone of the Gulf of Cadiz, is one of the areas worstly impacted by the AD 1755 tsunami. Previous works simulating tsunami propagation and inundation along the Moroccan coast have been carried out. However, only few studies have addressed the effects of tidal variations on extreme tsunami.

In this study, we use numerical simulations to study how the tidal stage at the moment of the tsunami arrival can affects tsunami characteristics (wave heights and run-in) and, therefore, its control on building vulnerability within the inundation area. Asilah, in the northern Atlantic coast of Morocco, constitutes a study case that may again be impacted by a 1755- tsunami-like event.

Tsunami simulations are conducted for four 1755-like earthquake scenarios, considering the two different phases of the tide (i.e. high and low levels). The coastline was drawn from satellite imagery and the variation of the bathymetry was compiled based on the tide gauge data. COMCOT (Cornell Multi-grid Coupled Tsunami Model)(Liu et al., 1998), a validated open source program, was used to model the source-to-coast tsunami processes.

Results show that the tidal stage has a major effect on the Maximum Inundation Area (MIA) experienced during a tsunami event. For instance, the MIA at Asilah coast differs by at least 470m² depending on the tidal phase. When the tsunami interacts with low-tide level it produces a MIA of ~1.99 km² along the Asilah coast. This value increases

to about 2.46 km² when the simulation is performed for high-tide stage. Thus we recommend to model the tsunami hazard and vulnerability taking into account the tidal stage that can have an important effect on the predictions, namely in coasts where tidal variations are significant.

Keywords

Tidal effect, tsunami impact, modelling, vulnerability

Acknowledgements

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Evidence for an extreme marine inundation event on the Tahaddart estuary and Sidi Kacem coastal plain (Tangier, Moroccan Atlantic coast)

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Abstract

Despite a position along the passive margin of Africa, the Moroccan Atlantic coast is under the influence of the tsunami threat from earthquakes triggered along the Nubia-Eurasia plate boundary (Omira 2012). Recently, we investigated the southwestern coast of Tangier (Tahaddart estuary and Sidi Kacem coastal plain) and found out morphologies and sedimentary deposits evidencing a strong energy-flooding event. A combination of sedimentological (grain size, sorting, microtextural, AMS) and microplaentological analysis combine to provide a primary reconstruction of uprush and backwash phases of tsunami deposition and flow dynamics (Wassmer, 2009). We present results from the Sidi Kacem coastal plain, where there is evidence for wave run-up heights in excess of 9m, depositing boulders, shells, sand and lithic clasts inland. The heights reached by these waves, and the size of transported boulders along the shoreline, suggest that tsunamis rather than storm waves were the most probable transport agent.

In Tahaddart estuary, this event left noticeable traces on a hilly dissected topography. In the proximal domain, no deposits were emplaced. The high turbulence of the flow allows a complete erosion of the soil. Landward, the decreasing of the energy induced a strong depositional process. The thick brownish sandy layer deposited contains large angular rip-up clasts of dark soil. Marine origin of the deposits is attested by bioclasts and the presence of foraminifera. In the distal domain, the loss of energy, due i) to a reverse slope, and to ii) a flow

diffluence resulting from the presence of a pass between two dunes, resulted in an accumulation of unsorted marine bioclasts, pebbles, beach rock clasts, remains of microlithic industry, and pieces of pottery. Application of the AMS technique confirmed that the lower part of the deposits was emplaced by a landward flow spreading N91°-171° (uprush phase to the SE) while the upper part was oriented seaward N280°-325° with a topographical control (backwash phase to the NW).

Distinction between tsunami and storm deposits was demonstrated by amalgamation of rip-up clasts, which is considered a distinctive tsunamigenic characteristic (Goff, 2012; Dawson, 1991). Grain surface microtextural analysis proved a complementary procedure applied in the identification of extreme marine inundation deposits (Costa, 2009). Tsunamigenic grains recurrently showed fresh surfaces and percussion marks when compared with possible source material. Heavy minerals content decreased upwards within the unit, and their assemblage present similarities with beach and coastal dune sand compositions.

Keywords

Tsunami sedimentary signature, Grain size, Anisotropy of magnetic susceptibility, Morocco

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Megaclasts along the north coast of Eastern Samar (Philippines) – Implications for Holocene extreme-wave events

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Abstract

The Eastern Visayas region in the Philippines experiences some of the most violent tropical cyclones on Earth, exemplified by Typhoon Haiyan (7–9 November 2013) or Typhoon Hagupit (6 December 2014). Moreover, strong earthquakes along the Philippine Trench have triggered tsunamis in the historical past. Thus, in Eastern Samar, coastal flooding through extreme waves associated with these events represents a significant hazard for communities. However, not much is known about frequency-magnitude relationships and maximum magnitudes on centennial and millennial scales, which can be derived from geological traces and which have to be considered in a coastal hazard management process.

We investigate a large boulder field at the north coast of Eastern Samar distributed on an elevated, intertidal mid-Holocene reef platform in order to understand mechanisms of boulder transport and to derive implications for the maximum spatial extent, depth and velocity of coastal flooding during the mid- to late Holocene. In the field, we recorded location, shape, morphological features as well as length and orientation of the main axes of more than 250 boulders, the a-axes of which are between 1.5 and 10.7 m. Post-depositional, secondary calcite flowstones and pre-depositional coral were dated by ^{230}Th/U; four pre-depositional, sessile organisms attached to the boulders were dated by ^{14}C. We 3D-mapped the most important areas of the boulder field using an unmanned aerial vehicle (UAV) and created structure-from-motion (SfM) models of the most prominent boulders, which will be used for

inverse modelling of transport flows. Samples of the most common coralline lithofacies were taken for density estimations. We use interviews with elders of the local community as well as multi-temporal analyses of local Pléiades and Worldview-3 scenes to reconstruct flooding patterns and boulder movement during recent events.

Keywords

Boulder field, Palaeotempestology, Palaeotsunami, Field mapping, Multitemporal satellite image analysis

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^{14}C dating and boulders deposits along the rocky coast of the Mediterranean sea: A Review

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Abstract

Boulders accumulations on the supratidal zone of rocky shore platforms are the morphological fingerprints of tsunami/extreme storm waves' impact on the coast. Boulders come from the subtidal/intertidal environments as indicated by their spatial distribution, setting, characteristics and the presence on their surface of marine carbonatic bio-encrustations (e.g. vermetids, serpulids, calcareous algae, corals etc.)

The definition of processes responsible for boulders carving and transport as well as the chronological determination of the catastrophic events can be performed by the integration of numerous data, as boulders

morphological features (volume, mass and setting) and coast microtopography into mathematical models that allow calculating the height of the wave that detached and transported boulders (Pignatelli et al., 2009 and references therein).

AMS dating of the bio-incrustations occurring on boulder's surface can date the catastrophic event since incrusting organisms die after the transport out of marine environment. The conventional age, however, should be calibrated to obtain the calendar age (usually a temporal range) to associate these results to chronological and historical archives of tsunami occurrence.

In this study, samples collected along the rocky coast of the Mediterranean Sea by several authors are re-calibrated using updated curves (Reimer et al., 2013) and appropriated ΔR values (Reimer and McCormac, 2002). The re-calibrated calendar ages were compared to tsunami catalogues (e.g. Papadopoulos et al., 2014; Fago et al., 2014 and references therein) to identify tsunami events that impacted the Mediterranean coasts in historical time.

Figure 1. A: boulders accumulation at Torre Colimena - Taranto (Apulia, Italy); B: vermetids/serpulids calcareous tube incrustiations above boulders.

Keywords

^{14}C Dating, Boulders, Mediterranean Sea.

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The Project of the WebGIS on the morphological evidence due to the impact of sea storm on the Mediterranean rocky coast studied during last 20 yrs

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Abstract

In the context of the Mediterranean basin a geodatabase about sea storm events identified along the Mediterranean coasts, as reported in recent scientific papers, has been realized in the framework of the project START - SisTemi di rApid mapping e contRollo del Territorio costiero e marino, a CLUSTER of the Apulian Region.

In the last 20 years, morphological evidences ascribed to the impact of sea storm/extreme waves impact on the Mediterranean rocky coasts have been identified and analyzed throughout field surveys performed in Algeria, France, Italy, Malta, Greece, Egypt and Lebanon.

Evidences are represented by boulders deriving from subtidal/intertidal environments, accumulated onshore, both isolated or in field/berms, and by damages on anthropic facilities. Each evidence has been mapped in order to

recognize the geographical areal distribution of the main sea storm impacts and to obtain a quick referenced digital list. Such a computerized tool, expanding the information derived by the WebGis for Italian Tsunami (Fago et al., 2014), increases its importance in its use by stakeholders and the scientific community; it represents not only a valid scientific aid for the preliminary understanding of the local geomorphological coastal dynamics but also a valid support for the coastal planning.

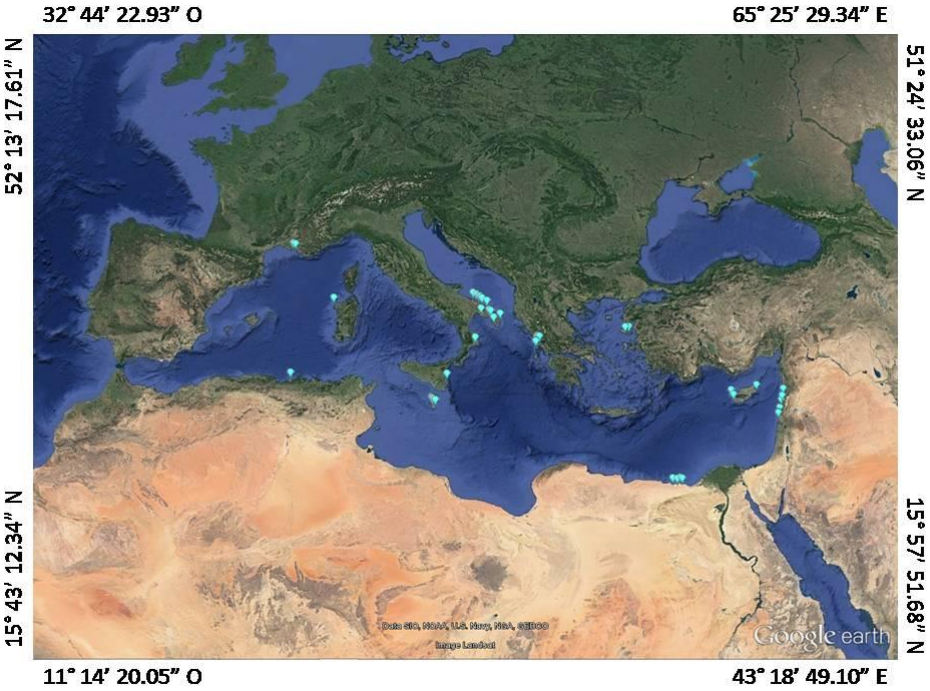

Figure 1. Localization of the analyzed boulders fields on Google Earth.

Keywords

Storm, Coastal Dynamics, WebGis.

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A tsunamite in the Canary Islands caused by a distant earthquake

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Abstract

Several tsunamites have been recognized in Canary Islands, being related to megalandslides. However, the island coasts have been affected by tsunamis generated by earthquakes, such us the 1755 Lisbon earthquake (Baptista & Miranda, 2009). So far no tsunami deposits have been associated with this type of processes.

We present here the reinterpretation of a coastal sedimentary deposit previously interpreted as a Holocene littoral ridge (García-Talavera, 2002) from La Graciosa, the most northerly islet of the archipelago. This deposit erodes the underlying units and is situated to +2 m asl, being the longest distance from the coast 22 m. It is a cemented coarse-grained (pebble to boulder size) conglomerate embedded in a white bioclastic calcarenite matrix. The boulders are up to 1 m^3 and from angular to well-rounded in shape. The biggest ones have a major axis dipping roughly perpendicularly into the cost line. Their lithology includes marine and aeolian calcarenites, black and reddish basaltic lavas, *Vermetus (vermetid)* reef fragments, beach rocks and paleosoils. The matrix incorporates marine molluscs, calcareous algae and terrestrial fossils (*Rebuffoichnus sp.* and ovicapride bones), as well as ceramic and metal fragments.

The mixture of fossils and rocks of very diverse ages (including historical) and marine and terrestrial origin, suggests that this deposit was formed during a tsunami in historical times. The origin of this tsunami could be a historical earthquake with epicentre in the SW of the Iberian Peninsula.

Keywords

Tsunamigenic-earthquake deposit, far-reaching-effects, historical time, Canary Islands

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Did a tsunami accompany the 1737 Chilean earthquake? Contrasting evidence from historical records and coastal sediments

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Abstract

The Chilean megathrust's Valdivia segment nucleates great earthquakes (M8+), with resulting tsunamis posing local and trans-oceanic hazards. Historical records document four tsunamigenic great earthquakes in the last 450 years (Cisternas et al., 2005). While devastating tsunamis accompanied the earthquakes of 1575, 1837 and 1960, there is no such record of inundation in 1737. Sparse populations may influence the completeness of the historical record; however, the absence of evidence for a tsunami in 1737 contributed to Moernaut et al.'s (2014) conclusion of a magnitude below 8 and maximum slip of just a few metres. The majority of accumulated strain remained unreleased, with the 1737 earthquake constituting a small mid-cycle rupture within the supercycle that culminated with the M9.5 1960 earthquake (Cisternas et al., 2005).

To refine understanding of the rupture zones of historically documented earthquakes in the northern Valdivia segment, we investigated coastal sediments at Chaihuín. The stratigraphy of tidal marshes preserves evidence for palaeoseismicity. We use sedimentology and microfossils to infer a local tsunami origin for three sand layers. Crucially for discounting other extreme wave events including storms and far-field tsunamis, evidence for abrupt land-level change accompanies each sand layer. We quantify vertical deformation using a diatom transfer function (Hocking et al., in press) and show variability in the magnitude of deformation between events. Our radiocarbon chronology suggests a tsunami layer consistent with the 1737 earthquake. We discuss the consequential implications for locating and characterising this poorly-known rupture.

Keywords

Palaeoseismology, diatoms, transfer function

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Historical extreme wave and landslide deposits on the Shirasuka coastal lowlands, Shizuoka Prefecture, Japan

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Abstract

Megathrust earthquakes and consequential tsunamis pose exceptional hazards to densely populated and highly industrialised coastlines facing the Nankai-Suruga Trough, south central Japan. Geological investigations of coastal sedimentary sequences play a key role in understanding megathrust behaviour and developing seismic and tsunami hazard assessments. In this study, we revisit a previously published palaeoseismic site at Shirasuka, located on the Enshu-nada coastline of Shizuoka Prefecture, seeking both to provide further information on past earthquakes and tsunamis and to explore the prospects and limitations of geological data with respect to assessing seismic and tsunami hazards.

At Shirasuka, six closely-spaced vibrocores reveal four sand layers interbedded with organic muds. Photographs, X-ray CT scans and granulometry reveal a variety of sedimentary structures within these layers, including abrupt contacts, massive sands, rip-up clasts, internal mud drapes and cross bedding. Microfossil assemblages (diatoms, pollen, non-pollen palynomorphs) and optically stimulated luminescence overdispersion values of single grain feldspars highlight varying sediment sources and transport mechanisms. We suggest that the uppermost sand layer records a landslide from the landward margin of the site, while the remaining three sand layers reflect at least four extreme wave events. We refine the published chronology using AMS radiocarbon, radionuclide and infrared stimulated luminescence approaches. Our Bayesian age models suggest that the oldest two sand layers relate to historically-documented tsunamis in AD 1361 and 1498. The second youngest sand layer provides ages consistent with tsunamis in both AD 1605 and 1707 and potentially also storm surges in 1680 and/or 1699. The modelled age of the landslide sand layer is consistent with the AD 1944 earthquake. The presence of a fresh scarp in aerial photographs from 1947 is consistent with possible coseismic triggering of this landslide.

Difficulties in correlating sand layers between cores, the identification of overprinting of evidence and the lack of prehistoric deposits exemplify ongoing issues in the search for palaeotsunami deposits along the Nankai-Suruga Trough.

Keywords

Palaeoseismology, Nankai-Suruga Trough, multi-proxy

Acknowledgements

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Significance of paleotsunami deposits for tsunami hazard assessment in the Kuril-Kamchatka region

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Abstract

The PTHA (Probabilistic Tsunami Hazard Assessment) methodology, that is widely used for evaluation and mapping of the tsunami hazard, is largely based on the assessment of maximum credible earthquakes and their recurrence rate in the main tsunamigenic zones threatening a particular part of the coast. The length of the historical tsunami catalog for the Kurile-Kamchatka seismic zone is only 275 years (Gusiakov, 2016) that hardly exceeds the length of the main seismic cycle in this zone that is equal to 190±40 years (Vikulin, 1990). Under these conditions, the study of the paleotsunami traces found in coastal deposits in the tsunami-prone areas has become an indispensable and irreplaceable tool for the long-term tsunami hazard assessment and mapping. In this paper we present and evaluate the results of 20-years field studies of the paleotsunami traces along the coast of Kamchatka and Kuril Islands that has allowed us to largely (more than 10 times) extend the historical tsunami catalog for this area. One of the most important results of these field studies is tracing and mapping of the inundation limits of the two largest known tsunamis in the area, resulted from M9-class mega-earthquakes occurred in 1737 and 1952 (Pinegina and Bourgeois, 2001). For the nearby parts of the Kamchatka coast, these paleotsunami traces mark realistic ultimate limits of the in-land inundation expected for 200-300 years recurrence intervals. In addition to tsunami deposits, another useful tool for identification of the largest pre-historical subduction earthquakes is the identification and dating of coastal subsidence typically identified as breaks in the normal sedimentary processes in the coastal marshes. The paper presents several examples of these subsidence episodes that occurred during the last 3500 years along the Kuril-Kamchatka coast.

Keywords

Tsunami deposits, hazard assessment, subduction earthquakes, run-up, inundation limit

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Difficulties in the recognition and interpretation of paleo- and historical extreme-event deposits in the Andalusia Atlantic coast (Cadiz, SW Spain)

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Abstract

Tsunami deposits show depositional features that may differentiate them from other high-energy wave-deposited sediments. However, their recognition and interpretation is not always straightforward due to both facies similarity and post-depositional processes. The sedimentary infill of the Guadalquivir Basin (Atlantic coast of Andalusia) preserves several high-energy event-layers dated from the Pliocene onwards. Pliocene event-layers consist of poorly-cemented bioclastic accumulations of warm marine-water fossils in association with large boulders sourced from nearby outcrops of late Oligocene - early Miocene sandstones. Pleistocene event-layers show lower fossil contents and consist of boulders formed by well-cemented marine shells. More recent event-deposits dated to 869 BC AD 1755 are also present. The best preserved correspond to marine shells and median and small clast on beaches, while deposits associated with fluvial soils are thinner and poorly preserved.

Main difficulties in the recognition and interpretation of tsunami deposits among event-layers are: a) Facies similarity with those formed by major storm ; b) Unreliable dating caused by mixture of fossils of different ages; c) Questionable age values, due to uncertainties in reservoir-effect corrections; d) Mixture of sediment from different sources and environments; e) Incorporation of elements from older events; f) Loss of syndepositional features due to later reworking ; g) Effects of neo-tectonic activity, climate, sea-level changes, and diagenetic processes related with meteoric water, including karstification; h) Misinterpretations due to assignment of each facies to a specific and unique depositional mechanism, when the same facies type may actually result from late sedimentary processes.

Keywords

Differentiation of marine event deposits, facies similarity, post-depositional processes, Bay of Cadiz.

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Tsunamigenic evidences along the Algerian coast

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Abstract

Main Algerian cities are concentrated on the coastline where paradoxically the hazard from active tectonics is associated to submarine and near coast fault systems. Although seismic activity is rather moderate, sometimes strong earthquakes occur (El -Asnam 1980, Ms 7.3 and Boumerdès 2003, Mw 6.9).

During and shortly after major earthquakes, landslides generating tsunami waves and coastal floods are even felt until Spain, France and Italy coasts. Boumerdes earthquake generated coastal uplift (Meghraoui et al. 2004) and triggered moderate tsunamis waves recorded by tide gauges of the neighboring countries (Alasset et al. 2006). It also induced landslides and turbidity currents that caused sub-marine cable breaks. Historical seismicity catalogs reveal minor to moderate tsunamis, coastal flooding and sea waves during 1365 (Algiers), 1790 (Oran) and 1856 (Djidjelli) earthquakes. Concerning this latter, a tsunami modelling reveals that the sea wave did not overlay 1m height (Yelles-Chaouche et al., 2009).

Recently geological investigations evidence seismites and boulder accumulations along the Algiers coast. This led to suppose the occurrence of large sea waves in the past (Maouche et al., 2009). Also, recent study shows that earthquake-triggered turbidites are more frequent close to Algiers than offshore El Asnam. Events identified and dated in these turbidites are correlated to the main historical earthquakes in the Algiers area (2003, 1716 and 1365 CE) but have not been yet linked to onshore tsunami deposits. Near the shoreline, many areas are currently under investigation to improve our knowledge about tsunamis in northern Algeria to better assess seismic risk.

Keywords

Tsunami waves, boulders, fault, seismic risk, Algeria

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The interaction of tides and tsunami

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Abstract

Numerical modelling of palaeotsunamis requires a cross-disciplinary approach incorporating new software development, sea-level change dynamics, tectonics, fluid dynamics, sedimentology and even archaeology. There is a huge potential for this field to make a significant contribution to tsunami hazard assessment

by recreating and understanding past events. The interaction of tides with past events is key to interpreting the sedimentary record they leave behind. Tidal dynamics affect past sea-level reconstructions, as well as the maximum wave estimates from the sedimentary record. Here, the first reconstruction of the Storegga tsunami that incorporates the effects of the tidal dynamics at the time is presented. The Storegga tsunami was caused by a large (~3200 km^3) submarine slide that generated waves of up to 40m on the Norwegian coast, 20m in the Shetlands, before reducing to several meters along the UK coastline. It left behind a number of deposits as widespread as Greenland and Denmark. The wave is recreated using up-to-date palaeobathymetric reconstructions and the tsunami event is simulated in conjunction with tidal forcing. The slide is initiated at several points in the tidal cycle to assess the effect it has on timing and wave run-up at key deposit sites along the UK coast, as well as the Faroes and Norway. There are non-linear effects that act between the tsunami wave and the tidal wave that mean the effects of tides cannot be simply added on afterwards. The work shows the need for a range of disciplines to work together to fully understand past tsunami events, which in turn are crucial to understanding future risk, even in regions that experience only infrequent events.

Keywords

Modelling, tides, deposits

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The 1755 tsunami in Terceira Island (Azores): nannoliths as a marine tracer in the recognition of tsunami deposits

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Abstract

The geographic and geologic settings of Azores Archipelago make it susceptible to tsunamis. Written accounts indicate at least 13 flooding events attributable to tsunamis generated by local or distal sources (Andrade et al. 2006; Cabral, 2009).

A discontinuous flood deposit is found up to 50m in elevation in the east and south low-lying coastal areas of Terceira Island. The sedimentological (marine sand and shells and terrestrial elements) and textural features (erosive basal contacts, rip-up and directivity flow-induced structures) indicate tsunamigenic origin. The occurrence of pottery and a mammal tooth indicate a post-settlement age. Radiocarbon age of coal fragments from the deposit is compatible with the 1755 event.

The presence of nannoliths was checked to confirm the marine provenance of the sediments. Nannoliths are mainly composed of coccoliths, calcified scales produce by calcareous nannoplankton (coccolithophores). Coccolithophores represents the major component of the extant nannoplanktonic communities throughout the world's oceans and can also be found in coastal facies providing a marine tracer in coastal sediments (Ferreira & Cachão, 2005). Nannoliths abundance and distribution were used to characterize a recent tsunami deposits (e.g.

Paris et al., 2010). Despite the age of the flood deposit and its exposure to unfavorable weather conditions (promoting swift wash-out and/or dissolution of nannoliths), coccoliths were found. We highlight the occurrence of one coccosphere; the preservation of such a fragile structure indicates a non-turbulent transport of marine water and sediment.

Nannoliths content have proven to be a good proxy for tsunami deposits, especially in recent volcanic islands where calcareous sediments are rare.

Keywords

1755 tsunami, Azores, Terceira Island, nannoliths, tsunami deposits

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Annual low-cost UAV monitoring of dislocated boulders in Greece

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Abstract

Coastal areas are under permanent change and their present-day morphology and stratigraphy also result from past processes, involving transport, accumulation and erosion of sediment by both normal and extreme waves (storms or tsunamis). In order to estimate the relative effects of different processes, coastal monitoring approaches are of interest.

For the estimation of annual changes, we have applied terrestrial laser scanning (TLS) in an annual monitoring approach (2009-2011) to coastal sites in Greece exhibiting dislocated boulders, which are an indication for high-energy events (Hoffmeister et al., 2014, 2013). In 2014, we changed to an approach based on dense imaging and structure-from-motion, applying low-cost unmanned aerial vehicles (UAVs) to conduct annual surveys of a coastal test-site. All surveys were conducted using a manually-structured image acquisition methodology with large overlap between images. Ground control points (GCP) were measured by tachymetric surveying.

The 2014 measurements were controlled by an additional TLS survey, which revealed the high accuracy and more suitable coverage obtained from UAV-based data. Overall, high-resolution digital elevation models with ground resolution of 10 mm and an equal accuracy were achieved with this low-cost equipment. The data reveal only minor changes in the study area and no movement of the boulders at the test-site. These results are in agreement with results inferred from wave transport equations and estimated wave decay curves.

Keywords

Tsunami, storm, boulders, wave transport equations, wave decay curves

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Paleotsunami history at northern Sanriku coast of Japan –Possible evidence of the northern extent of the AD 869 Jogan tsunami

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Abstract

Historical and observational records show that large tsunamis have frequently affected to the Sanriku coast on the Pacific coast of Tohoku, Japan, facing toward the Japan Trench (Utsu, 2004). However, paleo-tsunami deposits along the coast have not been studied well. The Sanriku coast is one of the most important places for paleotsunami research in Japan to understand the recurrence interval and size of historical and pre-historic tsunamis so that more geological data should be collected (e.g. Goto et al., 2014). This study performed a field survey at Noda Village of northern Sanriku and identified four gravelly sand layers as tsunami deposits based on the results of continuity of the distribution and the sedimentary features. We further conducted numerical modeling for storm surges and waves and confirmed that the distribution of gravelly sand layers cannot be explained even by unusually large storm surges and waves. We thus suggest that the numerical method is a useful way to identify tsunami deposits at certain geomorphological settings. One of the identified tsunami deposits had probably been formed by the AD 869 Jogan tsunami according to the radiocarbon dating results. The tsunami is known as a

possible predecessor of the 2011 Tohoku-oki tsunami. Since our study site currently defines the northern extent of the AD 869 Jogan tsunami, our results are crucial to improve the tsunami source model.

Keywords

Paleotsunami, Sanriku coast, tsunami deposit, storm surge and wave, numerical modelling

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Probabilistic regional correlation of tsunami deposits along the Pacific coast of Tohoku, Japan

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Abstract

Correlation of tsunami deposits in the regional scale can contribute to estimate the affected area of tsunami. The ages of tsunami deposits are crucial to confirm whether or not widely spread tsunami deposits can be correlated. However, the regional correlation of tsunami deposits has mostly been conducted by qualitative comparison of their age ranges while each probability distribution of the depositional age has not been taken into account. This might causes stochastically unlikely correlation and has possibility to overestimate (or underestimate) the size of paleotsunamis.

In this study, we conducted probabilistic correlation of tsunami deposit at Iwate prefecture, Northeast part of Japan. Samples were taken from 7 sites which covered the coastal area of Iwate Prefecture (Ishizawa et al., 2015; Takada et al., 2016). Depositional ages of tsunami deposits were estimated from sequentially measured ^{14}C dating results. We compared each probability distribution of tsunami deposit by statistical tests, and identified regionally contrastable tsunami deposits which did not show a significant difference between these probability distributions. Even if there were significant difference between these probability distributions, we confirmed the degree of superiority in the correlation or discrimination. Then, all possibility of regional correlation results were summarized and we probabilistically reconstructed the size and its recurrence interval of the paleotsunami in Iwate prefecture.

Using this method, paleotsunami history would be estimated statistically warranted way, so it can contribute to better hazard assessment.

Keywords

Tsunami deposit, ^{14}C dating, regional correlation, Japan Trench

Acknowledgements

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Evidence of Tsunamis and Storms in a Coastal Mangrove Pond, NW Puerto Rico

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Abstract

The written record of tsunamis in the Caribbean extends back over 500 years, yet, is incomplete. In particular, it is not known whether great earthquakes or submarine landslides near the Puerto Rico Trench have generated large tsunamis that impact the northern coast of Puerto Rico (Morton et al., 2006). We cored a coastal mangrove pond in NW Puerto Rico to search for tsunami deposits. The pond extends from 150 to 350 meters from the shoreline, and is 0.5 meters above sea level. Pond sediments are predominately mud or mangrove peat, with prominent sand layers. At the sediment surface is a tabular sandy overwash deposit up to 40-cm thick that extends inland approximately 30 m from the pond's seaward edge and abruptly ends. This sand layer contains no evidence of vertical grading and was likely formed by one or more recent hurricanes, which with the removal of coastal dunes about 50 years ago are able to flood the pond. In contrast, underlying the overwash deposit and mangrove peat at a depth of approximately 60 cm is a thin (1 – 7 cm thick) sand layer extending to the landward limit of the pond. This layer has features of a tsunami deposit including suspension grading, an erosive basal contact, and an organic cap. Radiocarbon dates from organic material above and below the thin sand layer constrain deposition to 1446 and 1919 AD. We present the features of the coastal mangrove pond deposits and evaluate whether these deposits could be correlated with an extreme wave overwash that left a deposit on Anegada, BVI, sometime between 1200 and 1480 AD (Atwater et al., 2017), which would support a great Puerto Rico Trench earthquake and tsunami about 600 years ago.

Keywords

Tsunami deposits, field studies, Caribbean, overwash

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Numerical Analysis of Tsunami Wave Force Acting on a Seawall –Considering the Effect of the Obstruction

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Abstract

In 2011, the Tohoku-Oki earthquake generated a tsunami that inflicted a severe damage on the Fukushima Daiichi Nuclear Power Station. A review of the seawall aimed at protecting the nuclear power station from similar accidents was conducted. Accurate prediction of the wave force acting on the seawall is necessary for evaluating the seawall's safety. Many design formulae concerning the wave force acting on a seawall have been proposed; however, data on the mechanism of the effect of the obstruction in front of a seawall is insufficient. In particular, it is especially important to understand how the shape of the obstruction influences the wave force acting on a seawall.

In this study, a three-dimensional numerical analysis model (Yoneyama et al., 1998) was used for the simulation of the wave force acting on a seawall, while considering the effect of the obstruction. The main feature is that the volume of fluid (VOF) method (Hirt et al., 1981) is applied for flow involving a free surface. Comparisons with past experimental data show that the model works well and is capable of producing reliable predictions for the wave force. In addition, it shows that compared with the absence of the obstruction, whether or not the wave force acting on a seawall is multiplied, depends on the shape of the obstruction.

In the future, we plan to clarify the mechanism of the wave force acting on a seawall by performing numerical analysis, while accounting for the various shapes of the obstruction.

Keywords

Tsunami, numerical analysis, seawall, wave force, obstruction

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Geological evidence for extreme wave events on a coastal lowland facing the Tōkai segment of the Nankai-Suruga Trough

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Abstract

Located close to Japan's densest concentrations of people and industry, the easternmost region of the Nankai-Suruga subduction zone has long been the focus of attempts to forecast and even precisely predict future earthquakes. While historical records attest to the occurrence of great earthquakes and subsequent tsunamis that may have originated from the Tōkai segment, past rupture zone extents and recurrence intervals remain poorly understood. Coastal stratigraphy has the potential to record the occurrence of both tsunami inundation and coseismic vertical land-level change over timescales far exceeding the historical record, with important implications for refining understanding of future hazards (Garrett et al., 2016).

Here we present initial results from an extensive coring survey of the lower reaches of the floodplain of the Sagara River, close to the town of Sagara, Shizuoka Prefecture. The site lies at an altitude of ~1 – 5 m and is within the anticipated inundation zone of future worst-case tsunami scenarios. Typhoon-driven storm surges and river floods are also likely to have inundated the site, complicating the interpretation of potential tsunami deposits. Using CT

scans, multi-sensor core logs, diatom assemblages and radiocarbon dates, we evaluate sedimentary processes and make the distinction between extreme wave events and fluvial deposits. Where possible, we assess methods to differentiate between storm surges and tsunami deposits. Finally, we evaluate the potential for the site to provide a long and continuous record of extreme wave events and highlight the probable influence of changing thresholds of evidence creation and preservation over time.

Keywords

Tsunami deposits, Sagara floodplain, CT-scanning

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Pre-classic Mayan Extreme Wave Event in eastern Yucatán, Mexico

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Abstract

The Yucatán Peninsula, Mexico has usually been considered to be a tectonically stable region, without seismic activity, in contrast, it is an area regularly affected by hurricanes. A detailed survey of ca. 100 km of the coast between Playa del Carmen and the Tulum coast, and the east coast of Cozumel Island identified the presence of three ridges containing boulders measuring >1 m and reaching five metres in height associated to Extreme Wave Event (EWE) activity.

The application of different approaches to calculate the minimum height of the tsunami wave or storm wave capable of moving these boulders demonstrates that the minimum wave height for the displacement ranges from 2.5 to 2.9 m for a tsunami and from 10.5 to 11.5 m for a severe storm (using formulas for a JBB scenario by Engel and May, 2012). The submerged scenario of Nott (2003) produces ranges from 2.0 to 2.4 m (Ht) and from 8.0 to 9.8 m (Hs). Models of tsunami propagation in the Caribbean (Engel et al., 2016) show that a tsunami generated by a Mw 7.99 earthquake from the Muertos Thrust Belt (MTB) cannot reach the Yucatan coast. However, a tsunami generated by a Mw 8.8 earthquake generated in South Caribbean Deformed Belt (SCBD) can reach the north-eastern Yucatan coast with a wave height lower than 1.0 m. However, the occurrence of hurricanes in this area is more common, and two of the most destructive produced 6-8 m high waves at the coast and an inundation up to 5 km inland (Hurricane Gilbert, 1988), and 8-10 m high waves at the coast (Hurricane Wilma, 2005). Even though

evidence of ancient earthquakes has been identified in the area, the tsunami origin of the boulder ridges is not reliable and the data collected suggests that the ridges can be associated to a mega-hurricane.

Keywords

EWE, boulder ridge, transport models, hurricane

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Holocene Extreme Wave Event in Cope Basin, Spain, Western Mediterranean

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Abstract

The Iberian Mediterranean coast has very few geological records of EWE (Extreme Wave Events) such as tsunamis or storm surges. Some historical tsunamis have been reported in the region, however, their impact at the coast has been negligible. In Cope Basin (Murcia) there is a boulder ridge containing boulders of >1 m extending up to 8 masl, which was generated by a EWE, either a tsunami or storm surge. The area's regional geodynamics are governed by the indentation process of the Aguilas Arc that gave place to a major left lateral transcurrent zone, known as the Eastern Betics Shear Zone (EBSZ). Stronger seismic activity in the area is clearly concentrated along faults within the EBSZ which are oriented perpendicular or oblique to the main stress field. These ENE-WSW to E-W faults have produced instrumental earthquakes of 5.2 Mw and historical ones with an estimated magnitude of 6.2 to 6.9 Mw, although very low instrumental seismic activity has been recorded within the proper Aguilas Arc (Bardají et al., 2015).

Different approaches to calculate the minimum height of the tsunami wave or storm wave capable of moving these boulders have been applied using formulas for a JBB scenario by Engel and May (2012) and for a submerged scenario (Nott, 2003). These models show that storms in this part of the Mediterranean cannot generate these boulder ridges, whereas the decision matrix for tsunamis on the Spanish Mediterranean coast indicates that a 6.0-6.5 Mw earthquake less than 40 km offshore and at a depth of less than 100 km would have the potential to generate a locally destructive tsunami (IOC, 2011). Tsunami generation models also show that in the Iberian

Peninsula, Murcia is the province affected by the greatest tsunamis, mainly generated in Northern Algeria (Alvarez-Gómez et al., 2011).

Keywords

EWE, boulder ridge, transport models, tsunami, Murcia

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Tsunami inundation of Santiago Island (Cape Verde): distribution and characterization of the correlative deposits

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Abstract

Chaotic conglomerates and sandstones attributed to tsunamigenic inundation were first reported for the islands of Maio (Madeira et al., 2011) and Santiago (Paris et al., 2011) in Cape Verde. These deposits are ascribed to the flank collapse of Fogo Island, whose age was determined by ^{3}He cosmogenic exposure on megaclasts from Santiago (73.3±6.8ka; Ramalho et al., 2015) and U/Th on corals from Maio (78.8±0.9ka). Here we describe tsunamigenic sediments correlated with that collapse, located on the north, east and south shores of Santiago, but apparently absent in the west coast, which faces the tsunami source. The deposits feature an erosive base (both on soft and hard rock basement), occasional rip-up clasts, cover alluvia, colluvia, and aeolian deposits, and mantle steep slopes (up to 20°) developing from present sea-level up to 100 m in elevation and at distances up to 750 m inland. The conglomerates are composed of angular and rounded boulders embedded in a biogenic marine sand matrix. The texture varies from matrix- to clast-supported depending on the amount of sand available. A layer of laminated sandstones, sometimes with floating boulders, locally covers the conglomerates. Fossils include abundant molluscs, corals, echinoderms, bryozoans, calcareous algae and foraminifera, indicating a marine source for part of the sediment, whereas their stratigraphy and geomorphological position indicate onshore deposition. Some outcrops present moderate to strong calcretization whilst in others this alteration is faint or absent, suggesting the presence of two asynchronous inundation events. This hypothesis is also supported by the presence of three separate tsunami deposits on Maio.

Keywords

Tsunami sediments, Fogo Collapse, Cape Verde, Santiago,

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Tsunami deposits from the Island of Maio (Cape Verde): paleocurrent markers and basal erosion features

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Abstract

Tsunamigenic chaotic conglomerates and sandstones occur along the whole littoral of Maio in Cape Verde. These deposits were tentatively attributed to a tsunami generated by the flank collapse of the Island of Fogo (Madeira et al., 2011). The deposits feature several tsunamigenic characteristics: erosive bases (both on soft and hard rock basement), rip-up clasts, cover slopes, overlie terrestrial deposits, and occur from sea level up to 40 m in elevation and up to 5 km inland. The conglomerates are composed of angular and rounded boulders set in a biogenic marine sand matrix and the texture varies from matrix- to clast-supported. A layer of laminated sandstones, sometimes supporting floating boulders, locally covers the conglomerates. Fossiliferous content includes abundant molluscs, corals, echinoderms, bryozoans, calcareous algae and foraminifera, indicating a marine source for part of the sediment, while their stratigraphy and geomorphological position indicates onshore deposition. In one location, three different tsunami deposits are exposed on a continuous outcrop indicating the same number of tsunamigenic inundations.

The deposits present several paleocurrent indicators, ranging from imbrication, oriented flat clasts, grooves on the basal surface, lineations in laminated sandstone beds, clasts transported up-stream from their source, and bedrock plucking structures; the paleocurrent directions indicate that the tsunami waves arrived from the western quadrants and were refracted around the island. Erosional features at the basal surface of the deposits include trenches excavated into weathered basalt flows and plucking and levering of blocks from massive compact mudstone layers.

The sediments were dated by U/Th on corals (78.8±0.9ka), an age compatible with the 73.3±6.8ka obtained for the emplacement of megaclasts in the neighbouring island of Santiago (Ramalho et al., 2015) and interpreted as the result of the tsunami generated by Fogo's flank collapse.

Keywords

Cape Verde, Maio, tsunami sediments, directional structures, basal erosion features

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Ramalho, R.S. et al., (2015) Hazard potential of volcanic flank collapses raised by new megatsunami evidence. Science Advances, 1, e1500456.

OSL surface exposure dating of wave-emplaced coastal boulders – first results from the Rabat coast, Morocco

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Abstract

Fields of wave-emplaced blocks and boulders represent unambiguous evidence of storm and tsunami flooding over Holocene time scales. However, their use for coastal hazard assessment is impeded by the absence of appropriate dating approaches needed to generate robust chronologies. AMS-^{14}C, U/Th or ESR dating of coral-reef rocks and marine organisms attached to the clasts depends on a – mostly hypothetical – coincidence between the organisms' death and boulder displacement, and inferred event chronologies may be biased by the marine ^{14}C-reservoir effect and reworked organisms. This contribution discusses the potential of the recently developed optically stimulated luminescence (OSL) surface exposure dating technique [1] to directly date the relocation process of wave-emplaced boulders. We sampled coastal boulders from the Rabat coast, Morocco, which were either (re-)located by tsunami-induced flooding (e.g. during the 1755 Lisbon tsunami and similar events) or by exceptional winter storms [2]. All these boulders (i) show clear indication of overturning during wave transport in the form of downward-facing bio-eroded surfaces; (ii) are composed of sandstones that contain quartz with adequate luminescence signals; and (iii) are of Holocene age and, therefore, in the dating range of OSL surface exposure dating. Measuring the depth-dependent resetting of luminescence signals in those rock surfaces that were exposed due to relocation, and comparing it to the signal-depth profiles of known-age samples (e.g. modern storm boulders), OSL surface exposure dating may be capable to model direct depositional ages for boulder transport. Thereby, it promises to overcome the limitations of existing dating techniques and will, in the best case, provide quantitative information about the frequency-magnitude relationship of extreme wave events at the Rabat coast. Exposure dating may even allow to decipher more complex transport histories of boulders that were relocated and overturned repeatedly, thus experiencing multiple phases of exposure and burial.

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Evaluation of waves flooding: a new methodological approach

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Abstract

The impact of extreme waves on the coastal area implies the possibility of the occurrence of extensive flood phenomena; past impacts are highlighted by the presence of numerous geomorphological evidences that can indicate both the maximum flooding and the features of the supposed impacting waves (Mastronuzzi & Sansò, 2004; Mastronuzzi et al., 2007). The first is function of the wave features but also of the topographical and morphological features of the coastal area (Pignatelli et al., 2009; Nandasena et al., 2011; Engel & May, 2012). Starting from these assumptions it should be possible to elaborate a hydrodinamique model that could permit to reconstruct different inland penetration in function of different waves impact (Mastronuzzi et al., 2013). The detailed study of the sea conditions offshore and morpholitological and topographical characteristics of the coastal area, along with the use of specific hydrodynamic equations, allow us to get an evaluation of the maximum inland penetration during the waves' impact. The bathymetry, captured by LIDAR images and detailed surveys, from the proximity of the breaker line up to the coast/shore line, allows to calculate the average slope. Through this parameter it is possible to get the evolution of the wave height from offshore up to the shore line, using specific hydrodinamic equations (i.e.: Hsu et alii, 2006; Guza et alii, 1981). The knowledge of the different classes of land use from the shore line towards land let us to estimate the "roughness" parameter through the Manning'number (Manning, 1981; Pignatelli et al., 2010). Starting from the geometrical and dynamic parameters of waves recorded by wave measuring sensors, in function of the morphobatymetrical data it is possible to calculate the modifications that the wave height undergoes at breaker line up to the shore line. This last value, together with the coastal slope and the "roughness" that characterizes the different land uses, allows us to estimate the extension of the water flooding inwards. The maximum inland penetration results from the envelope of all decreasing wave heights from

the shore line towards inland as a result of the interaction between the water flooding and the different surface roughnesses.

Keywords

Waves, flooding, roughness, inland penetration.

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Inundation phases of the AD 1755 tsunami recorded on the Salgados Lagoon (S Portugal)

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Abstract

A tsunami sandy deposit, related with the AD 1755 event, has been identified in Salgados Lagoon based on sedimentological, exoscopic, palaeontological and dating proxies (Costa et al., 2012). Due to the unawareness of the number of inundation phases preserved in this deposit, an innovative approach combining XRF core-scanning and image analysis was applied in six box-cores representative of the lagoonal infilling.

The obtained high-resolution geochemical and grain-size data magnify intra-deposit details (at sub-centimeter scale) that otherwise would not be perceived and, consequently, valuable information could be overlooked. Despite the contrasting composition of the tsunami sandy deposit comparatively with the lagoonal muds, the Si/Al and Ca/Ti allowed the precise delimitation of its upper and lower limits, even when the contact was not macroscopically visible. In the absence of textural evidences, the identification of salinity indicators (Cl, S and Br) peaking

concentrations in a continuous muddy sequence implies that the tsunami inundation, in this location, extended farther inland than originally thought.

This methodology provided new insights in the capability to resolve coarse clastic tsunami sediments for different modes of transport and inundation pulses. Median grain-size and Si/(K+Ti) discriminate at least four different inundation phases within the sandy tsunami deposit in the seaward region subjected to the inundation, whereas in the landward region only one phase was identified. The lowermost massive or coarsening upwards sequence(s) tend to be finer than the overlying sequences, showing lower values of Si/(K+Ti) and probably corresponding to bedload transport in a high sediment concentration flow. By contrast, the following packages are normally graded and settled from graded suspension, indicating lower flow velocities and less sediment incorporation in the water column.

Keywords

XRF core-scanning, grain-size image analysis, inundation phases, sediment transport, Portugal

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Storm or tsunami? Or Storm and tsunami? Boulder transport histories on the shoreline of Malta

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Abstract

The Maltese archipelago is subject to marine processes and influences from across the entire Mediterranean. Mottershead et al. (2014, 2015) demonstrated the presence of deposition and erosion signatures along the east-facing coastline characteristic of extreme wave impacts including tsunami. These signatures demonstrate overwashing of the rocky shoreline landscape to elevations of 20 m above sea level or more in places and include distributions of boulders indicative of tsunami impact. This paper presents and considers the nature of evidence at the interface of storm and tsunami activity.

Within this context, we here report on evidence at two sites (Zonqor and Qorrot) where distinctive lithologies permit reconstruction of boulder transport histories by coastal waves. These reveal how boulders travelled to their current positions by various processes, including pivoting over a scarp, sliding, rotating and coming to rest as velocity diminished or where arrested by obstacles. Reconstructed velocities permit interpretation of the flows required to transport and deposit them. Field mapping of boulders from source to settling destinations at varying elevations up to 11 m above sea level and distances up to 90 m inland from the shoreline and suggests varying agencies of movement and deposition.

By applying various published transport models, processes attributable to both tsunami and storm waves are capable of moving boulders upslope such that their observed pattern on the present shoreline should properly be

interpreted as the superimposition of varied scales of event magnitude and frequency. As boulder transport histories within the overlap zone of storm and tsunami waves are likely to be defined by both tsunami and storm waves, there is a risk that the "storm *or* tsunami" dichotomy prevalent in the literature might serve to limit scientific explanation in some cases.

Keywords

Malta, Mediterranean, boulder deposits, storm waves, tsunami

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Revisiting dimensionless coefficients of boulder transport equations: a small-scale experimental investigation on coefficient of lift

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Abstract

Geological traces after high-energy events (tsunamis and big storms) such as big boulders and sand sheets become key to modelling the magnitude, in terms of local height/velocity, of the high-energy events. The numerical models introduced in Nott (2003) (later revised in Nandasena et al., 2011) have been prominent in modelling historic high-energy events from their boulder deposits and the results have been used for mitigation planning. However, these models have been developed based on a number of assumptions (Nandasena et al., 2011) and include dimensionless coefficients which have control over the magnitude of each force component (drag, lift, and friction) of the models. Therefore, the accuracy of the values used for these coefficients affect the results at different scales for different cases. The values for some of these coefficients have been derived based on simple experimental studies which do not exhibit the characteristics of the phenomenon concerned (e.g. the coefficient of lift; referred from Einstein and El Samni, 1949).

In this study, the coefficient of lift was investigated in a small-scale experimental study. Models of boulders with different shapes (spherical, cubic, and cuboid), and roughness (smooth and rough) were tested. Different flow regimes (from sub-critical to super-critical) to simulate different stages of a high-energy event that could entrain the boulders were considered. Further, the orientation of the boulders to the flow was tested. Due to the limitation of experimental facilities, the case of submerged boulders at the pre-transport location was considered. The new values derived from the experimental study were compared with the typical value used (0.178; Einstein and El Samni, 1949) for the coefficient of lift. The comparison indicates that the coefficient of lift is dependent on the characteristics of the boulders, orientation and flow regimes at different scales. It also indicates that the dimensionless coefficients (lift and drag) should be revisited in large-scale experiments for better results from these models.

Keywords

Numerical models, boulders, tsunami, dimensionless coefficients

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Tsunami deposits in coastal areas surrounding perialpine lakes in Switzerland

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Abstract

On the basis of historical reports, multibeam bathymetric datasets, seismic reflection surveys and numerical wave modelling, previous studies have shown that devastating tsunamis occurred in perialpine lakes in Switzerland. These events have diverse trigger mechanisms such as earthquakes, rockfalls or spontaneous subaquatic mass movements displacing large amounts of water. For instance, a tsunami with a height of 4 m occurred in Lake Lucerne after an earthquake (M_w 5.9) in 1601 AD. (Cysat, 1969; Schnellmann et al., 2002; Fäh et al. 2011; Hilbe and Anselmetti, 2015). At Lake Geneva, a major subaerial rockfall triggered a partial subaquatic collapse of the Rhone delta in 536 AD causing a tsunami with a height of several meters (Montandon, 1925; Kremer et al., 2012).

This study uses cross-sections based upon sediment cores to identify historic tsunami deposits in coastal settings of Swiss lakes. It will provide the foundation to confirm and quantify historic tsunami events and to extend the event catalogue to the prehistoric period. We will investigate in which way lacustrine tsunami deposits differ from their marine counterparts, how they can be discerned from terrestrial flood deposits and infer run-up height, inland penetration distance and flow regime. Results will establish a tsunami chronology that will be correlated with major mass-transport deposits observed in various lake basins (Schnellmann et al., 2002; Kremer et al., 2015). This study is part of an interdisciplinary project addressing the causes, controls, frequency of this to date underrated lacustrine tsunami hazard and also includes numerical modelling of tsunami propagation and inundation. Furthermore the information gained from historic tsunami deposits will serve to ground truth results yielded by numerical models.

Keywords

Onshore tsunami deposits, lacustrine setting, perialpine lakes, tsunamiites, field studies

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Physical modelling of tsunami-induced boulder transport

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Abstract

In the aftermath of the destructive 2004 and 2011 tsunamis, researchers around the world intensified their studies of tsunami hydrodynamics. An improved understanding of the whole process, from the triggering mechanism over wave propagation to coastal transformation and flooding, leads to improved early-warning systems as well as emergency or evacuation protocols in affected areas. Our study focusses on nearshore tsunami hydrodynamics by applying downscaled (1:50), field data-based, physical experiments and an improved numerical modelling approach.

By conducting experiments in a 33.5 m-long and 1 m-wide flume using four different coastal setups from stepped to linear inclination – including one roughly reproducing the onshore topography of a boulder field on the island of Bonaire (Lesser Antilles, see Engel and May, 2012) – we investigate the influence of the nearshore bathymetry on boulder transport path, mode and distance. We apply 3D-printed irregular shaped replicas of Bonaire's boulder record as well as idealized boulder models (cubes and cuboids) in order to compare their behaviour during the bore impact. Computerized pumps and valves secure reproducible experiments of tsunami bores. Boulder replica are equppied with Inertial Measurement Units (IMU) (Deng et al., 2014) recording crucial parameters such as boulder acceleration and inclination directly from the boulder model's center of mass. Furthermore, we investigate boulder behaviour utilizing Matlab® toolboxes for video and image processing as well as ultrasonic sensors, micropropellers, acoustic velocimeters and one laser-doppler velocimeter.

The collected flow characteristics (velocity, bore height, run-up height) and boulder behaviour datasets (acceleration, velocity, inclination, path, transportation mode) provide the basis for the numerical model. Recreating the flume numerically and applying the bore characteristics as boundary conditions enables the first validation and calibration.

Keywords

Tsunami, boulder, run-up, physical experiments, field studies

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Fields of stranded megaclasts as potential evidence for tsunami inundation in Sal Island (Cape Verde)

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Abstract

The recent confirmation that a ~73 ka catastrophic flank collapse of Fogo volcano triggered a megatsunami with devastating effects on nearby Santiago Island (Ramalho et al. 2015), necessarily raises the question whether or not this megatsunami incurred in widespread devastation across the Cape Verde Archipelago and even further beyond. Here we document possible evidence for important tsunamigenic inundation on Sal Island, tentatively attributed to the impact of Fogo's megatsunami. The evidence reported here comprises fields of megaclasts stranded over the topographic surface of the W (north of Palmeira), and N sectors of Sal Island, and as far as 1.2 km inland from the present-day coastline. These megaclasts (with a mass of up to 20 Mg) dominantly correspond to submarine lava flows, either composed of fragile pillow lavas and hyaloclastites – which crumbled to form isolated piles of pillow rubble – or to more massive submarine sheet flows – which are more coherent and consequently still stand largely unbroken. Importantly, all these megaclasts correspond to lithologies that, on northern Sal, are only (but seldom) exposed along the adjacent coastline, at or below sea level, suggesting an origin at lower elevations and attesting to an extreme inland transport and deposition. Previous interpretations have assigned these features as vestigial remains of a submarine volcanic unit subsequently eroded, however no clear unequivocal in situ outcrops were found so far to support this hypothesis. The distribution of the megaclasts

dominantly inland from the western shore of northern Sal possibly denotes the impact of a tsunami incoming from the western quadrant, consistent with the Fogo event. These preliminary results therefore suggest that Fogo's megatsunami possibly resulted in significant devastation even as far away as Sal, which is located ~240 km from the tsunamigenic source. Surface exposure dating (cosmogenic ^{3}He) will be used to determine the boulders' depositional age and therefore test this hypothesis.

Keywords

Collapse-triggered tsunami, Cape Verde, Sal, Fogo, megaclasts

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Evidence for megatsunami inundation on SE Santiago Island (Cape Verde) – the field of megaclasts of Ponta do Lobo

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Abstract

Fields of stranded megaclasts and chaotic conglomerates have recently been found on northern Santiago Island (Cape Verde) and shown to attest the impact of a megatsunami triggered by the ~73 ka catastrophic flank collapse of Fogo volcano (Ramalho at al. 2015). Here we report deposits with similar characteristics, on the southeastern side of Santiago, which further document the effects of extreme tsunami inundation, presumably by the same event. These deposits are located around Ponta do Lobo, a low-relief headland ranging 15–40 m in elevation and extending eastwards about 1.8 km from the higher Vale da Custa plateau. The deposits consist of an extensive field of boulders – composed of submarine lava flows and marine limestones – chaotically stranded on top of subaerial lava flows. The largest boulders correspond to pillow lavas and submarine sheet flows, and attain masses up to 2000 Mg. They occur in clusters, and are often broken into smaller clasts, suggesting shattering upon deposition. The internal structure of the boulders (foresets of pillow lavas and hyaloclastites) are randomly oriented, dipping to different quadrants and with different inclinations, even for boulders located just a few meters apart. All boulders correspond to lithologies that crop out lower down, near sea level or at an adjacent seacliff, denoting transport towards the northern quadrant; this direction is generally parallel to Santiago's southeastern coastline, but roughly perpendicular to the southern coast of the protruding headland. These characteristics suggest extreme inland and upslope inundation, compatible with the impact of a tsunami that refracted around the southern coast of Santiago, traveling northwards along the southeastern coast of the island. These preliminary

results are therefore compatible with the impact of Fogo's megatsunami, which was generated to the west of Santiago, and presumably refracted around the southern coast of this island to cause significant damage along its far side.

Keywords

Collapse-triggered tsunami, Cape Verde, Santiago, Fogo, megaclasts

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Results from a multi-method sediment analysis of pre- and late-Roman deposits: Tsunami sediments in Baelo Claudia and surroundings (southern Spain)

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Abstract

Baelo Claudia in southern Spain offers a huge broad variety to study both archeological and geological processes as it is located in a closed bay, which provides natural limiting boundaries and sediment sources (e.g., beach, river inlets, rock falls, landslides). The pre-Roman sedimentary history has been studied in the eastern necropole, where we excavated a pit and dated coarse-grained deposits (c. 4 ka old; by OSL and radiocarbon) that maybe tsunami deposits. Furthermore, we have cored the so-called “lagoon” directly behind the eastern necropole. The ruined Roman harbour zone of Baelo Claudia was investigated in nine vertical sediment profiles in the lower city sector

(*Decumanus Maximus*, Bolonia Beach and *thermae* outside the city walls). Using a multi-method approach, including granulometry, magnetic susceptibility measurements and micropalaeontology, we found fining upward sequences, incised channels, chaotic sediment layers, intensely varying magnetic susceptibility and well preserved exotic marine microfauna assemblages (*Ammonia* sp., *Cibicides* sp., *Elphidium* sp., *Globigerina* sp. and different species of Miliolida). Selected samples were subjected to ^{14}C-dating. Based on field observations and resulting data it can be concluded that a destructive high-energy event hit the littoral area in late-Roman times (around AD 400-450). A tsunami run-up of minimum 8 m and a landward inundation of about 200 m are estimated. As a result, no conclusive geological data are available for tsunamis accompanying the earthquakes of the first 1st and 3rd century (if they triggered tsunamis?). At least no clear remnants have been discovered to date. In contrast to this, the coastal area north of Baelo Claudia to Conil shows two tsunamites, the most prominent impact of the 1755 Lisbon tsunami (Gracia et al., 2006) and an older event, dated preliminarily around 4 ka BP. The 4 ka event has already been described from the Zahara and Barbate beaches (Reicherter et al., 2010; Koster and Reicherter, 2014).

Keywords

Far-field tsunami, field studies, coastal impact, Gulf of Cadiz

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Finding deposits of historic and prehistoric tsunamis in the Hawaiian Islands

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Abstract

Over their past 200 years of written records, the Hawaiian Islands have experienced many tsunamis generated by earthquakes in subduction zones of the Pacific "Ring of Fire" (e.g., Alaska-Aleutian, Kuril-Kamchatka, Chile, and Japan). Mapping and dating anomalous beds of sand and silt along the coasts of these subduction zones has been critical in assessing the hazard from distant as well as local tsunamis. Here we report on similar efforts to estimate future tsunami inundation through stratigraphic study of potential tsunami deposits beneath present and former Hawaiian coastal lagoons, lakes, and river floodplains. Coastal wetland sites on the islands of Hawai'i, Maui, O'ahu, and Kaua'i were selected based on historical tsunami runup, numerical inundation modeling, proximity of sandy source sediment, degree of wetland disturbance, and breadth of prior geologic and archeologic investigations. Marine-sourced sand beds within peaty and/or muddy wetland deposits on the north and northeastern shores of Kaua'i ,O'ahu, and Hawai'i may be tsunami deposits. At some sites, known deposits of the 1946 and 1957 Aleutian tsunamis are possible analogs for deeper, potential tsunami deposits. At three sites, ^{14}C-based age models date sand beds at ~120 cm depth to ~800-600 cal yr BP, suggesting they may correlate with local tsunami deposits of about the same age in the eastern Aleutians (Witter et al., 2016). If further mapping,

dating, and sedimentological and micropaleontological analyses of these deposits confirm their tsunami origin, it will imply that a high, distant-source tsunami inundated the Hawaiian Islands about this time.

Keywords

Hawaii, paleotsunami, deposits, distant-source

Acknowledgements

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Records of the 2009 South Pacific Tsunami in the Pago Pago Bay, Tutuila Island, American Samoa

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Abstract

The South Pacific Tsunami (29th Sept. 2009) severely hit the Tutuila volcanic island (American Samoa) and caused significant damage along the shoreline and more than 30 deaths.

A tsunami wave is composed of two main successive stages: the uprush and the backwash resulting in the deposition of subaerial and marine sediments on the coastal plain and seaward. In general, shallow marine deposits have a low preservation potential because of alteration by atmospheric and hydrodynamics agents, bioturbation and anthropic activities. Tutuila is characterized by an indented shoreline including a highly sheltered and deep bay (Pago Pago Bay), where the preservation potential of shallow marine deposits related to the tsunami may be exceptional.

Here we present preliminary results from an extensive seismic and bathymetric exploration and sedimentary cores in Pago Pago Bay (SAMOA-SPT cruise, R/V *Alis*, August-September 2015). The sedimentary infilling of the bay reaches about 15 meters in thickness and is characterized by subhorizontal and subparallel reflectors with strong acoustic impedance changes related to vertical lithological contrasts. The sedimentation within the bay is dominated by carbonate-rich silt deposits alternating with coarse intervals, mainly composed of allochtonous gravel-sized coral fragments. The silt intervals are very well sorted and do not show any vertical grain size trend, but they can contain coral fragments at base. Meanwhile, the magnetic fabric of the uppermost silt interval attests

to deposition under alternated currents. The chemical composition (XRF) of silty intervals shows positive anomalies for Pb, Zn, Ti, Zr and Fe, confirming terrestrial inputs.

The coarse intervals are interpreted to record a tsunami inflow bringing coral fragments from the external barrier into the bay, while the silt intervals are interpreted as mud deposition during ebbing backwash. Further dating will be made to confirm if the observed sequence composed of basal coral fragments and upper silt layer resulted from the 2009 South Pacific Tsunami.

Keywords

South Pacific Tsunami, backwash, uprush, shallow marine tsunami deposits, sediment record

Acknowledgements

We acknowledge Captain Jean-François Barazer and the crew of R/V *Alis* and Dr. Bruce Jaffe (USGS, Santa Cruz, USA) for assistance during the cruise and scientific support. The *SAMOA-SPT* project is funded by the French INSU-CNRS and Région Poitou-Charente.

Multiple dating approach (14C, 230Th/U and 36Cl) of tsunami-transported reef-top boulders on Bonaire (Leeward Antilles) – Current achievements and challenges

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Abstract

On Bonaire (leeward Antilles, Caribbean), supratidal coarse-clast deposits form prominent landforms, and transport by one or several Holocene tsunamis is assumed at least for the largest clasts. Even though abundant electron spin resonance and radiocarbon ages are available for coral rubble ridges and ramparts, it is still disputed whether these data reflect the timing of major events, and how these datasets are biased by the reworking of coral fragments. To overcome the current challenges for dating the dislocation of singular boulders, three distinct dating methods are implemented and compared: (i) ^{14}C dating of boring bivalves attached to the boulders; (ii) $^{230}Th/U$ dating of post-depositional, secondary calcite flowstone and subaerial microbialites at the underside of the boulders; and (iii) surface exposure dating of overturned boulders via ^{36}Cl concentration measurements in corals. The three ^{14}C age estimates are older than 40 ka. This is attributed to post-depositional diagenetic processes, shedding doubt on the usefulness of this method in the local context. The convergent $^{230}Th/U$ ages, all pointing to the late Holocene period (1.0–1.6 ka), are minimum ages' for the transport event(s). The microbialite sample yields an age of 1.23 ± 0.23 ka and both flowstone samples are in stratigraphic order: the older and younger flowstone

layers yield ages of 1.59 ± 0.03 and 1.23 ± 0.03 ka, respectively. Four coral samples collected from the topside of overturned boulders yielded similar ^{36}Cl concentration measurements. However, the computed ages are affected by large uncertainties, mostly due to the high natural chlorine concentration. After correction for the inherited component and chemical denudation since platform emergence, the calculated ^{36}Cl ages cluster between 2.5 ± 1.3 and 3.0 ± 1.4 ka for three of four boulders whilst the fourth one yields an age of 6.1 ± 1.8 ka, probably related to a higher inheritance. These ^{230}Th/U and ^{36}Cl age estimates are coherent with a suggested tsunami age of< 3.3 ka obtained from the investigation of allochthonous shell horizons in sediment cores of northwestern Bonaire. Whilst ^{230}Th/U dating of post-depositional calcite flowstone appears to be the most robust and/or accurate approach, these results illustrate the potential and current limitations of the applied methods for dating the dislocation of supralittoral boulders in carbonate-reef settings.

Keywords

Tsunami, storm, boulders, wave transport equations, wave decay curves

Acknowledgements

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High energy events in the Holocene stratigraphy: the Astarte EU Project Siracusa test site case study, SE Sicily, Italy

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Abstract

In the last decade several paleotsunami deposits have been recognized along the coast of eastern Sicily. Since the Siracusa town was selected within the Astarte EU Project as the Italian test site and taking into account the data already available in the literature, we selected and investigated the recent stratigraphy of two new sites: Torre Barbagianni site located in the central part of the Vendicari natural reserve area and Vigne site, actually the "backyard" of the old Siracusa salt-pan.

Data collected and elaborated at Torre Barbagianni site underlined an abrupt change in depositional environment, at about 1 m depth, from lagoonal/alluvial to marine (testified by a clear basal erosional contact of the sandy marine deposits overlying the lagoonal/alluvial finer sediments). The related marine interval is probably due to the development of a foreshore beach paleoenvironment at the study site, intrinsically related to the establishment of a direct connection to the sea (at ca. 800 m far from the coring site).

At the Vigne site a more complex and interesting stratigraphy is displayed and again sudden changes in the paleoenvironment (here from fluvial to a protected shallow marine and vice versa) were recognized.

The two sites, investigated so far by coring coupled with stratigraphical, sedimentological and micropaleontological analyses, exhibit some interesting data in terms of abrupt changes in the paleoenvironment. Since no typical tsunami-related deposit was found, we are tempted to interpret them as potentially related to earthquakes or tsunami wave(s) that produced a significant modification of the coastline, disrupting the morphologic sandy coastal barrier able to protect the sites, thus favoring a direct connection to the sea. Radiocarbon dating and detailed geomorphological mapping will help us in better constraining the recognized high energy events and comparing chronological constraints with the age of some tsunami deposits found in the nearby areas.

Keywords

Paleoenvironment reconstruction, geomorphology, high-energy events, Eastern Sicily.

Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013), grant agreement n 603839 (Project ASTARTE - Assessment, Strategy and Risk Reduction for Tsunamis in Europe).

A natural laboratory for offshore paleotsunami studies: The Augusta Bay case study (Eastern Sicily-Italy)

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Abstract

In 2009 during a coring campaign with the Italian Navy Magnaghi, four gravity SW-104 cores, were sampled from the northern part of the Augusta Bay, along a transect 60 to 110 m of water depth. The objective of this study is to retrieve the details of the MS06 core with a special attention to the recent most part. In fact, the results obtained from the MS06 piston-core, a 6.7 m-long, collected 2.3 km offshore Augusta, at a water depth of 72 m bsl, highlighted 12 anomalous intervals, marked by peaks with high percentage of displaced epiphytic foraminifera and sandy component increment. These twelve anomalous peaks were interpreted as the primary effect of tsunami back-wash waves (Smedile et al, 2011).

On the MG cores, physical properties and grain size analyses point out the presence of a peculiar interval made of *Posidonia* remnants, coarse sand and shell debris on the two cores closer to the shore. The two far-off cores seem to be more homogenous but few thin sandy lenses enriched of *Posidonia* remnant were also recognized. Detailed micropaleontological counting, grain size and their comparison with the ITRAX X-ray fluorescence (XRF) were performed. Moreover, a multivariate analysis was used both for the micropaleontological and geochemical analysis in order to highlight a cross correlation between such results in correspondence of the identified peculiar

intervals rich of *Posidonia* remnants. In all the MG cores, at least one to three of the MS06 twelve anomalous intervals were identified.

Age correlation between the MG cores with the MS06 was obtained by merging paleomagnetic measurements with ^{210}Pb short-lived radionuclides for the uppermost 0.20 m and radiocarbon dating.

Keywords

Offshore cores, multidisciplinary analysis, Eastern Sicily.

Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013), grant agreement n 603839 (Project ASTARTE - Assessment, Strategy and Risk Reduction for Tsunamis in Europe) and from the project E.C. n.196 TRANSFER (contract no. 037058).

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Exploring the effects of submarine slide aspect ratio and rheology on tsunami characteristics

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Abstract

The amplitude of submarine slide-generated tsunami depends on many variables. Sensitivity analyses have shown that acceleration and maximum velocity of the slide are of first-order importance for tsunami magnitude [1]. These variables depend on factors such as drag, basal friction, added mass, and slide rheology. Here we use numerical simulations to investigate the role of slide length:thickness ratio and rheology on slide acceleration and tsunami generation potential.

In order to investigate the effect of aspect ratio on slide dynamics, a dense Newtonian fluid slide on a shallow slope was modelled using the flexible, multi-scale model Fluidity. The acceleration of this slide was compared to a momentum balance derived theoretical velocity profile for large slides on continental slopes [2], which included terms for basal friction, and skin friction – the drag on the upper surface of the slide. Previous studies [3], as well as results of the current study, show this profile is a good match for high aspect ratio slides. However, slides with smaller aspect ratios modelled in Fluidity were slower than the profile predicted. We show that this is because, for small aspect ratio slides the drag force on the front of the slide (form drag) must be included in the momentum balance. Additionally, in the viscous Newtonian fluid model, the submarine slide shortened as it travelled and developed a bulbous front, leading to greater form drag, and a smaller contribution from skin friction.

The aspect ratio of a submarine slide is sensitive to its deformation, and therefore, its rheology. Models of landslides have previously incorporated complex rheologies such as Bingham, Herschel-Bulkley and Coulomb/Voellmy [4]. This work aims to investigate the uncertainties related to slide rheology, including quantifying the effects different rheologies have on tsunami characteristics. The quantification of these uncertainties will inform probabilistic tsunami hazard assessment.

Keywords

Numerical modelling, submarine slide, rheology, uncertainty

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The Human occupation at paleo-estuary of the Boca do Rio(Vila do Bispo, Algarve, Portugal)

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Abstract

The banks of the old estuary of the Boca do Rio attracted the man since prehistoric times. From the middle of the 1st century AD to the 5th century AD, there was an important Roman settlement on the place. In the following centuries, the populations retreat inland returning to the shoreline in the 16th century and again in the 18th century. Archaeological excavations, carried out in recent years by the University of Algarve in collaboration with the Municipality of Vila do Bispo, has studied these different occupations, detecting various remains, both from the historical occupation as natural events like the tsunami of 1755. This communication aims to present these testimonies, as well as the results of the latest research on the site.

Resumo (*in Portuguese*)

A ocupação humana no paleoestuário da Boca do Rio (Vila do Bispo, Algarve, Portugal)

As margens do antigo estuário da Boca do Rio atraíram o Homem desde os tempos pré-históricos. A partir de meados do século I d.C. uma importante povoação romana instalou-se no local até ao século V d.C. Nos séculos posteriores as populações recuaram para o interior, voltando à linha de costa no século XVI e ainda no século XVIII. As escavações arqueológicas dos últimos anos, efetuadas pela Universidade do Algarve em colaboração com o Município de Vila do Bispo, têm estudado estas diferentes ocupações, detetando diversos testemunhos quer da ocupação histórica quer de eventos naturais, como o tsunami de 1755. A presente comunicação pretende apresentar estes indícios, bem como os resultados das mais recentes investigações no local.

Transport characteristics of coarse clasts under tsunami-bore conditions based on large-scale model experiments

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Abstract

Previous sparse laboratory studies on tsunami-induced transport of coarse clasts were conducted with several important constraints regarding model scale, flow characteristics and clast properties (e.g. Nandansena and Tanaka, 2013; Liu et al., 2014 and Freund et al., 2015). Moreover, bore generation facilities operating with a limited impoundment depth (usually up to 0.3 m) were used. This resulted in reduced bore capability to transport larger boulder models and subsequently in smaller models (commonly a-axis length from 0.08 to 0.12 m).

Therefore, large-scale systematic laboratory studies (using impoundment depth up to 0.6 m and maximum a-axis length of 0.44 m) were performed in order to provide a better insight into the mechanisms of bore-induced motion of coarse clasts (Fig. 1).

A total of 16 coarse clast models (a-axis 16 - 44 cm, b-axis 16 - 22 cm and c-axis 8 - 22 cm) were fabricated of concrete. Keeping the density constant (ca. 2.1 g/cm^3), two boulder shapes (cubes and cuboids), different volumes and submergence depths were investigated (Fig. 1).

Bore kinematics and characteristics of the clast motion (transport modes, time and distance, expressed as a function of clast geometry, initial submergence conditions and flow properties) were analyzed.

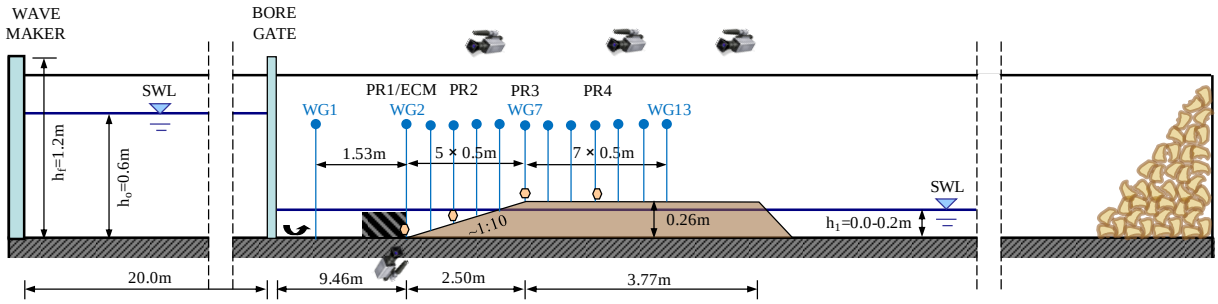

Fig. 1: Model set-up

Keywords

Tsunami bore, coarse clast transport, incipient motion, experiments

Acknowledgements

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Were both the 2004 Sumatra tsunami and the 2016 Kumamoto earthquake natural warning?

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Abstract

The 2004 Sumatra tsunami seriously damaged coastal countries of Indian Ocean. The appalling frame of the tsunami shook people in front of TV all over the world in Christmas holidays. An important risk crisis news about nuclear plant in India got buried a lot of information about unidentified victims and situation damaged by tsunami. The tsunami flooded the Kalpakkam nuclear plant near Chennai, India. 65 people including 10 nuclear plant scientists were reported dead in the tsunami tragedy at Kalpakkam. Few countries about this news reported outside India (2005 San Francisco Chronicle). I worked for supporting reconstruction for Aceh in economic division, Japanese Embassy in Indonesia from 2005 to 2007. At that time Japanese government mainly concentrated both reconstruction Aceh and peace building between Indonesia government and Aceh National Liberation Front (GAM). Tsunami early warning system in Indonesia was not decided by Japanese government in 2005. Both government and media did not pay attention to the Kalpakkam nuclear plant flooded in Japan. However US government caught the information and dispatched the tsunami expert for supporting in Chile, South East Asian countries and India. IAEA held an international meeting with nuclear experts related with nuclear plant in India in 2005. However there was no change the regulation. Japanese government missed the chance to countermeasure for nuclear plant by tsunami until the 2011 Tohoku tsunami and Fukushima nuclear accident (Soeda 2014).

Such risk information about warning from nuclear plants tend to keep secret not only to local residential people but also to Medias all over the world. I interviewed residential people near Oyster Creek nuclear plants, a level-2 warning was issued, just after the 2012 hurricane Sandy. Few persons knew the warning. A Chinese officer said the information lost just after the 2008 Sichuan earthquake in 2016. Scientists should share such information, appeal the society and pay attention risk information.

The biggest foreshock PGA of the 2016 Kumamoto earthquake (Mw 6.2) was 1580 Gal. 1580 Gal is over the nuclear regulation in Japan. Japan missed the natural waning from both the 2004 Sumatra tsunami. If scientists do not notice such natural warning and take action to change regulations, will it repeat to fail again?

Keywords

Nuclear accidents, regulations, risk, information sharing

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Sedimentary record of tsunami on polar coasts: 2000 AD landslide-generated tsunami in Vaigat Strait, West Greenland

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Abstract

Arctic coasts, although known to be affected by tsunamis of various origin, e.g. landslide (Buchwał et al. 2015) or iceberg-generated events (e.g. Long et al. 2015), are little known in regard to tsunami sedimentary evidence. Here we report on the effects of a landslide-triggered tsunami that occurred on 21st November 2000 in Vaigat, northern Disko Bugt in west Greenland. We studied the erosional and sedimentary features of this tsunami along coast-perpendicular transects in a range of settings. The field descriptions were supplemented by terrestrial laser scanner and DGPS mapping, as well as grain size, mineralogical and geochemical analyses. The tsunami run-up reached 50 m a.s.l. and inundated over 300 m inland. The tsunami frequently caused erosion of existing beach ridges whilst erosional niches were formed inland. The tsunami deposits mainly comprised gravels and very coarse sand and formed sheets up to 30 cm thick. Their deposition was likely mainly related to backwash as evidenced by field observations, deposits mineralogy and grain size trends (coarsening landward). At several sites boulder deposits were left, often transported as parts of icebergs. A characteristic feature related to tsunami deposits were "mud pats" - up to 1 m in diameter and about 20 cm thick silty deposits arranged in circles and covering the tsunami deposit. They are interpreted as the result of melting of icebergs washed inland by the tsunami. The specific polar coast environment including relatively steep fjord coasts, presence of permafrost and icebergs affect the final sedimentary record of tsunamis.

Keywords

Tsunami deposits, icebergs, backwash, landslide, Arctic

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Megatsunami Generation from Landslides on oceanic volcanic Islands: insights from coarse-grained clastic deposits on the Hawaiian and Canary Islands

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Abstract

Generation of tsunami from the catastrophic collapse of intraoceanic volcanoes remains controversial. There are few locations where evidence of tsunami inundation is preserved in the sediments deposited when the tsunami floods the land. In Hawaii, numerical modelling of flank collapse demonstrates the potential tsunami hazard, but validation from sediments is compromised by the alternative interpretation that they resulted from interglacial, sea level high stands. In the Canary Islands, controversy over tsunami magnitudes is from uncertainty over collapse mechanisms, whether they are 'incremental' or 'all-in-one-go'? Validation of tsunami generation models here is available only at one location on Gran Canaria. Field data on coarse-grained sedimentary deposits from the Hawaiian and Canary islands is presented which illustrates the complexity of their depositional history. On the Hawaiian Islands, coastal deposits of coralliferous conglomerates preserved as planar, less than metre thick beds, are interpreted as primary tsunami deposits, whereas those in gullies, which are much thicker and with a significant proportion of non-marine material, are considered to be reworked by sheet wash and fluvial processes. At Agaete on Gran Canaria in the Canary Islands, very coarse-grained, dominantly bouldery, deposits with subordinate marine material, up to 3-4 metres thick at up to 180 m elevation, are preserved in gullies and road cuts. These deposits are interpreted as tsunami deposits mainly reworked by processes similar to those in Hawaii. At both locations the sediments evidence tsunami inundation. On the Big Island of Hawaii, tsunami inundations attain over 370 m above sea level at time of deposition. The confusion over the Hawaiian deposits origin, tsunami or sea level highstand is for a number of reasons; 1) uncertainty over the vertical tectonic history of the islands, 2) evidence from reworked gulley deposits that confuse interpretations of original sediment sources, and 3) that the deposition of the deposits takes place at the end of glacial periods when sea levels are rising and volcanic collapse takes place. The reworked deposits at Agaete indicate that they represent a minimum tsunami inundation elevation.

Keywords

Tsunami, field studies, reworked, Hawaii, Canary Islands

Insights of the AD 1755 Lisbon tsunami in the estuary of the Alcabrichel River (Portuguese western coast)

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Abstract

Several extreme marine inundation events affected the Portuguese coast but most descriptions focus on the tsunami of AD 1775, considered the most devastating in Portugal.

Our research was developed in a sediment core CF2 (retrieved under the FMI project) on the right bank of the Alcabrichel River, 650 m upstream the river mouth, on the West Portuguese coast (approximately 50km NW of Lisbon). The main goal of our work was to detect potential tsunami deposits indicators, especially morphoscopic, geochemical and microtextural features (Tudor, 2017).

Stratigraphic and textural interpretation allowed the identification of 5 lithostratigraphic units that correspond to the sedimentary infilling of an alluvial plain downstream the Alcabrichel River. The basal unit ***UL_1***, as well as ***UL_2*** and ***UL_4*** consist mainly of silt and clay, with some sandy material intercalations, while at the top, the ***UL_5*** unit corresponds to the present day dune system. In the ***UL_2*** unit a very thin sand laminae (3cm thick), named ***UL_2a***, was detected and its origin was originally associated with a possible tsunamigenic event. A massive thicker layer, ***UL_3***, essentially sandy (10cm) is interposed between ***UL_2*** and ***UL_4*** units and was associated with the event of AD 1755 tsunami (Ramos-Pereira et al., 2013).

Results of textural and geochemical analysis confirmed the tsunamigenic origin of the ***UL_3*** and allowed to consider the ***UL_2a*** subunit as a likely storm deposit, due to a large presence of terrigenous elements.

Morphoscopic analysis were able to discriminate different sedimentary environments and associate the tsunami sands with their potential sediment source, identifying three different tsunami phases related to the inundation and backwash waves.

This was complemented with microtextural analysis of the tsunami sands, using scanning electron microscopy, which revealed the presence of more mechanical marks which are common in extreme marine inundation deposits (Costa et al., 2012).

Additionally, it was demonstrated that local geomorphology played a crucial role in the propagation of the tsunami flow, conditioning the extent of the deposit and the inner boundary of the tsunamigenic flood. This allowed to establish the area more vulnerable to tsunami flooding, thus demonstrating the importance of this study for Spatial Planning.

Keywords

Tsunami deposit, geochemical indicators, morphoscopy, microtextural signatures

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High-resolution textural analysis of the AD 1755 tsunami deposits –comparison of grain-size methods

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Abstract

The AD 1755 tsunami spread throughout the Atlantic affecting several countries in Europe. Costa *et al.* (2012) attributed to this tsunami the deposition of a sandy layer found interbedded in low-energy late Holocene muddy materials of the Salgados lagoon (central Algarve, Portugal). Grain-size analysis is the most-applied sedimentological technique in the study of sandy deposits. Contiguous 1-cm thick sediment samples obtained from seven cores taken from this tsunami deposit were investigated using three different grain-size techniques: mechanical sieving, wet laser diffraction and digital grain-size analysis (using Lira, 2015 MATLAB script). Sediment consisted mainly of fine to medium sand with minor to significant contributions of silt and clay

Digital grain-size analysis struggled to get accurate results when the sediment contained abundant mud particles mixed with the sand. In this case, laser diffraction yielded better results and required less analytical time than mechanical sieving.

The texture of sediments suggests that a signature of three inundation phases was preserved within the apparently massive tsunami deposit, in agreement with the depositional stages described in Jaffe et al. (2012). It was also

possible to determine the likely (NNE) direction of incoming waves, based in the spatial variation of the event-layer thickness.

Keywords

Salgados lagoon, inundation phases, mechanical sieving, laser diffraction, digital grain-size analysis.

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Tracing historical tsunami signatures at the Gulf of Kyparissia (Peloponnese, Greece) using Direct Push in situ sensing techniques combined with geophysical studies

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Abstract

The western Peloponnese is known to have been hit by major tsunami impacts during historical times as reported by historic accounts and recorded in historical earthquake and tsunami catalogues. During the past years, abundant geomorphological and sedimentary evidence of repeated Holocene tsunami landfall was found between

Cape Katakolo in the north and Kyparissia in the south. Additionally, neotectonic studies revealed strong crust uplift along regional faults with amounts of uplift between 13 and 30 m since the mid-Holocene.

This study focuses on the detection of historically young tsunami impacts, sedimentary and microfaunal evidence of which were reported from the eastern shore of the Kaiafa Lagoon (Koster et al. 2015). We conducted detailed surface-based geophysical prospection by means of electrical resistivity measurements (ERT) and seismic studies. These investigations were completed by direct push *in situ* sensing at specific points along geophysical transects. A Nordmeyer drill rig RS 0/2.3 with a mounted Geoprobe pushing device was used to carry out direct push electrical conductivity (EC) measurements. We further used a hydraulic profiling tool (HPT) and carried out cone penetration tests (CPT), the latter also in the form of seismic CPT.

Direct push methods helped to decipher *in situ* high-resolution stratigraphical records that can be used to document different kinds of sedimentological and geomorphological indicators of high-energy inundation, such as abrupt increase in grain size and fining upward sequences representing different tsunami inundation pulses. We further coupled surface-based ERT and seismic data with highly resolved vertical datasets obtained by direct push sensing and sediment core characteristics in order to improve the quality of geophysical models.

We will present details of this new methodologial approach and discuss how the obtained results can help to improve tracing tsunami signatures in the sedimentary record and deciphering geomorphological characteristics of past tsunami inundation.

Keywords

Direct push sensing, geophysics, tsunami deposits, Peloponnese, Greece

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Factors controling distribution of storm deposits: Numerical modeling of the sediment transport during Typhoon Haiyan

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Abstract

Previous geological studies suggested sedimentary features which could be used to identify sandy deposits as being from storm origin (e.g. Morton et al. 2007), but factors that determine the distribution of storm deposits are still uncertain. We examined the factors controlling sedimentation due to storm waves and surge during the 2013 typhoon Haiyan in the Philippines based on numerical simulations (after Watanabe et al., in press).

Our numerical results showed that wave-induced shear stresses attenuated rapidly in the inland direction after wave breaking, so that sandy deposits were not formed far inland. Consequently, the maximum extent of storm deposits was remarkably shorter than the inundation limit. However, the maximum extent is affected by topography because the simulated inland inundation distance becomes shorter if the inland topography has gradient steep slope.

We also revealed that vegetation (roughness coefficient) and typhoon intensity greatly affect the calculation of maximum extent and thickness distribution of storm deposits. Moreover, storm deposits tend to be thicker than tsunami deposits, and multiple layers can be formed in the internal sedimentary structure of the deposits because the duration of wave impact on a coast is relatively long during a storm. Thus, shorter maximum inland extent of the deposit, multiple layers found within the deposit, and thicker deposits could be used as appropriate identification proxies for storm deposits as opposed to tsunami deposits.

Keywords

Storm deposits, numerical simulation, sediment transport, field survey

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Geological Evidence for Tsunamis and Crustal Movements associated with Intraplate Earthquakes in Beppu Bay, Japan

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Abstract

Onshore sediment cores obtained from the Oh-enji marsh on the south coast of Beppu Bay were studied to establish a detailed chronology of tsunamigenic intraplate earthquakes that occurred in the bay in prehistoric age. The up to 8.8 m thick sedimentary succession is mainly composed of non-marine organic-rich mud and marine silt. Three sand layers are observed in the organic-rich mud, and one in the marine silt. All sand layers exhibit sharp upper and lower contacts with the surrounding mud, implying that they were deposited by a sudden event. They are characterized by higher magnetic susceptibility with higher counts of Ti and Fe, as well as Si, S, K, Ca, Sr, and Ba than in the mud. This suggests that the sand grains were supplied from a source different from the freshwater marsh. Moreover, the occurrence of brackish–marine diatoms in the sand layers, but not in the mud, infers a marine and/or shore source for the sand. Chronological control based on the K-Ah tephra (ca. 7300 years BP) and radiocarbon dating, indicates that at least four probable prehistoric tsunami deposits (3300–3450, 4230–4530, 5160–5290, and 6670–6790 cal. yr BP) are preserved in the marsh succession. Their recurrence intervals are estimated to be approximately 850–1500 years.

The brackish–marine species dominate the fossil diatom assemblages in the surface muddy sand above the organic-rich mud. As the facies change from non-marine to marine sediments cannot be due to sea level change, since the eustatic sea level has been falling since 6000 years ago, the most likely explanation is a local subsidence associated with faulting. Though the accurate timing and single amount of faulting are not known, the marsh must have repeatedly subsided in the Late Holocene.

This study provides the accurate ages of prehistoric tsunami inundations as well as the possibility that the easternmost area of the south coast of the bay has episodically subsided by past faulting. Further studies collaborating with active fault researches will unravel a detailed faulting history of the active faults in Beppu Bay.

Keywords

Tsunami deposit, Submarine active fault, Diatom, Geochemistry, Radiocarbon dating

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