GEOLOGICAL RECORDS OF TSUNAMIS AND OTHER EXTREME WAVES

EDITED BY

MAX ENGEL, JESSICA PILARCZYK
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Geological Records of Tsunamis and Other Extreme Waves

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Preface

This edited volume compiles the state of the art in research on the geological record of tsunamis and other extreme-wave events and guides the reader in designing goal- and site-specific research. It has evolved from an initial idea, first explored by the editors in early 2016, to final publication online and in print in mid-2020. The motivation for developing a handbook-type compendium on this topic was driven by the observation that such a unifying volume devoted to this particular discipline, which lies at the crossroads between sedimentology and tsunami science, was missed by the scientific community. What we had in mind was an exhaustive work that enables the broader dissemination and transfer of ideas, methods and concepts associated with identifying tsunami and other extreme-wave deposits. By doing so, we seek to promote their application to a wide range of different coastal sedimentary environments and their enhanced use for coastal hazard assessment.

The great success of our first thematic session "Geological records of extreme wave events" organized at the European Geosciences Union (EGU) General Assembly in 2016 was a clear demonstration that there was an active community of researchers who were enthusiastically pushing the tsunami geoscience field forward. A special issue of the journal *Marine Geology* related to this EGU session followed in 2018 (Vol. 396, edited by Ed Garrett, Jessica Pilarczyk, and Dominik Brill) compiling 16 papers on paleo- and modern tsunami and storm records. With a wide range of exciting new research being presented at subsequent editions of the EGU session, we felt that a detailed compendium would be of significant interest for the continuously growing community. Consequently, this work represents a true community effort: leading experts were invited to contribute chapters, while each chapter was peer-reviewed by at least one external reviewer and a minimum of one of the editors. It is great to see the substantial overlap between the authors and reviewers of this compendium, and the contributors to the thematic sessions at the annual EGU General Assemblies.

Two existing edited books, both well established in their scientific communities and regarded as benchmark literature resources, have inspired and guided the concept of the present work. *Tsunamiites* (Elsevier/Amsterdam) of 2008, edited by Tsunemasa Shiki and colleagues, provides an exhaustive overview on the aspect of tsunami sedimentology. It also gathers some of the most prominent figures in this field as authors, but in contrast to the present book, it combines textbook-type chapters with case studies and has a clear emphasis on the older, pre-Quaternary geological record. The *Handbook of Sea-Level Research* (Wiley/Chichester) of 2015, edited by Ian Shennan and colleagues, follows a proxy-by-proxy structure, with detailed methodological information to guide research on reconstructing relative sea-level histories. Such a structure focusing on operational workflows, methodological details, opportunities and limitations associated with specific proxies has been adopted and built upon in the present compendium.

A special merit is dedicated to the reviewers of the individual chapters of this book. The external evaluations by expert members of the community were essential to the final quality of this volume and are, therefore, gratefully acknowledged. We sincerely thank the following persons:

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Above all, we thank the authors of the individual chapters for contributing their tremendous expertise and precious time. To fulfill the purpose of this book, each chapter combines expert knowledge on a wide range of different aspects of paleotsunami research with systematic guidelines and recommendations for their implementation in research. The very positive responses that we received to invitations sent to potential authors around the globe may be an additional indication of the timeliness of this book and is hopefully a signal that it will provide a useful addition to the body of literature on tsunami geoscience.

Furthermore, we are thankful to everyone at Elsevier, who accompanied the entire process from the initial idea to printing and distribution of the book in a professional and efficient way.

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Max Engel, Jessica Pilarczyk, Simon Matthias May, Dominik Brill, Ed Garrett
Cologne (Germany), Burnaby (Canada), York (United Kingdom), February 2020

SECTION

1

Introduction

CHAPTER

1

Geological records of tsunamis and other extreme waves: concepts, applications and a short history of research

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Abstract

Increasing population and economic pressures along the world's coastlines have made, and are continuing to make coastal communities more vulnerable to hazards. The hazard management of tsunamis and other extreme waves (storm waves, seiches, infragravity waves) is based on the assessment of the frequency-magnitude relationship of these events, which uses instrumental, historical and, critically for the evaluation of long-term recurrence patterns, geological evidence. The identification of tsunami deposits in coastal sedimentary environments is challenging and has systematically evolved as a subdiscipline of sedimentology only over the last. 30 years (i.e., paleotsunami research). Nevertheless, a wide range of field sampling methods, proxy analyses, and dating approaches have been successfully applied to identify tsunami deposition in different sedimentary environments and infer tsunami impacts in the past. This compendium summarizes the state of the art in paleotsunami research in an effort to provide detailed methodological insights and aims at guiding workflows and site-specific research designs.

Keywords: Coastal hazard assessment; Coastal risk management; Overwash deposits; Paleotsunami research; Paleotempestology; Storm deposits; Tsunami deposits.

Introduction

Globally, the coastal realm experiences intense pressures through the growth of population, tourism, and industrial activities, placing an increasing number of humans at

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risk from hazards associated with the sea and large continental water bodies (Brückner, 2000; Adger et al., 2005; Neumann et al., 2015). These hazards comprise slow-onset hazards, in particular globally rising sea levels and marine pollution, and the rapid-onset hazards of tsunamis, storm surges and storm waves, exceptional infragravity waves or meteotsunamis. The rapid-onset hazards have been significantly exacerbated by global sea-level rise of 15–20 cm over the last 100 years, and they will be further influenced by the 30–100 cm projected for the 21st century (Church et al., 2013; Rahmstorf, 2017; Li et al., 2018).

Recent tsunamis such as the 2004 Indian Ocean Tsunami and the 2011 Tōhoku Tsunami in Japan and storm surges such as those induced by Cyclone Nargis in Myanmar in 2008 and Typhoon Haiyan in the Philippines in 2013 had dramatic impacts on coastal populations and infrastructure. The exceedingly high number of fatalities and economic losses during these events can largely be explained by an underestimation of the projected site-specific impacts and ineffective or inappropriate coastal-risk management practices. Managing the risk of extreme waves, and in particular tsunamis, which are the focus of this edited compendium, requires a holistic hazard assessment that uses a wide range of information on the local and regional occurrence pattern, i.e., best characterized by its frequency-magnitude relationship. The most accurate type of such information is provided by instrumental data such as tide gauge records (fragmentarily available from c. 1850; much shorter records in most areas), data from satellite altimetry (detection of open-ocean tsunami characteristics, since the 1990s), and post-tsunami surveys (systematic and precise measurements of coastal flooding parameters; fragmentarily available since the 1883 Krakatoa Tsunami; see Chapter 10). Going back in time, the accuracy of measurements decreases during the 19th century, which is linked to the transition to qualitative and semiquantitative data. This information is usually referred to as historical data and includes newspaper reports, diaries, private letters, ship logs, colonial, church, or government archives, accounting records, or earthquake catalogue (see Chapter 2). Although less accurate, historical data adds important information to the instrumental record, as it extends the time period by a few centuries (e.g., SE Asia, Americas, Africa) to several millennia (e.g., in the Mediterranean; Soloviev et al., 2000). However, similar to tropical cyclones (Corral et al., 2010), frequency-magnitude patterns of tsunamis are described best by inverse power-law functions (Fig. 1.1), although usually without upper truncation (Burroughs and Tebbens, 2005), implying recurrence intervals in the range of 500 (e.g., Jankaew et al., 2008; Brill et al., 2012) or even 800–1000 years (e.g., Minoura et al., 2001; Sawai et al., 2012) for the largest tsunamis along major subduction zones. In many regions, these time scales are not covered by either the instrumental or the historical record. In terms of megatsunamis generated by flank collapses on volcanic islands, recurrence intervals may even exceed several tens of thousands of years (Paris et al., 2018); see Chapter 25.

Sedimentary records of tsunamis surpass this limitation and may enable the reconstruction of frequency-magnitude patterns over multi-centennial and

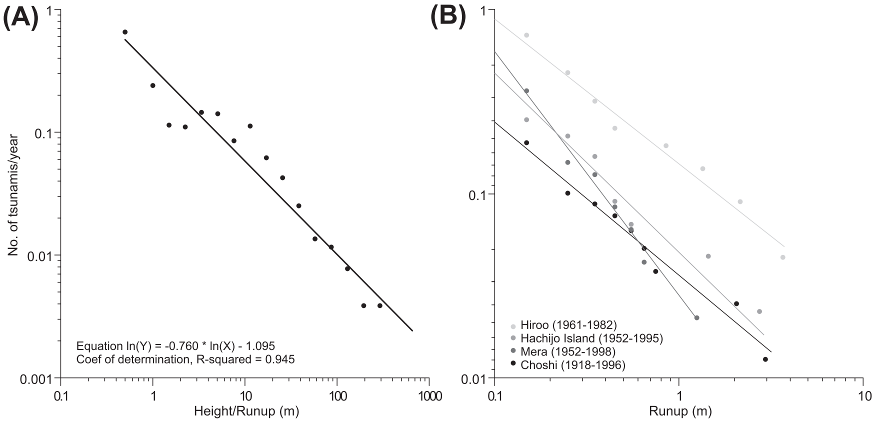
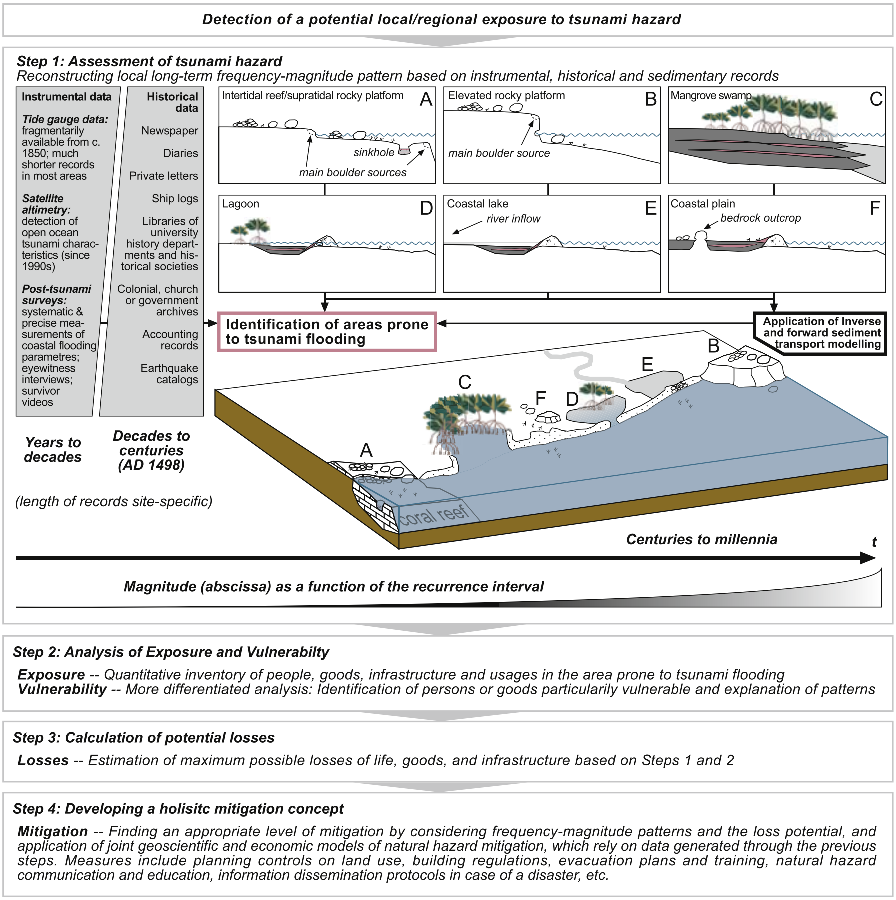


FIGURE 1.1

Frequency-size distribution of tsunamis can often be described by an inverse power-law function. (A) Maximum observational and instrumental accounts of wave height or runup height documented for each tsunami at a global scale between 1498 CE and 2015 CE. For height/runup, quasi-logarithmic binning was applied (Engel et al., 2016). Each event is only represented once by its highest value. (B) Frequency-size distributions for tsunami runup at four different locations in Japan, considering instrumental data only.

(A) Data are based on NGDC/WDS (n.d.) (B) Burrough and Tebbens (2005)

millennial time scales. These time scales cover the largest events, for instance those generated by megathrust earthquakes (e.g., Dawson et al., 2004; Engel et al., 2016; Garrett et al., 2016). At the same time, sedimentary and geomorphological records may not only indicate the timing of past events, but they may also provide relative, approximate insights into extreme-wave characteristics such as approach direction, flow depth, inundation area, or magnitude of the triggering earthquake (Weiss and Bourgeois, 2012; Switzer et al., 2014; Sugawara, in press). Ultimately, these deposits help to delineate areas prone to tsunami flooding as well as forecast the possible future impacts that can be expected, both of which are essential when assessing exposure and vulnerability and developing site-specific mitigation strategies (Fig. 1.2) (Dall'Osso and Dominey-Howes, 2010; Engel et al., 2016). Nevertheless, there are only a few cases in the literature that present holistic tsunami-hazard management strategies at a high spatial resolution and take all these steps and information into account. The probabilistic tsunami flooding maps of Seaside, Oregon (González et al., 2009), are a best-practice example in this regard. The devastating 2011 Tōhoku Tsunami causing the Fukushima nuclear incident, however, represents an example of the failure of hazard management. The tsunami was anticipated by geologists based on deposits of its predecessor, the 869 CE Jōgan Tsunami (Minoura et al., 2001; Chagué-Goff et al., 2012), but came unexpected for Japan's tsunami-hazard policies, as the geological data was not taken into account (Goto et al., 2014).



Step 2: Analysis of Exposure and Vulnerabilty

Exposure -- Quantitative inventory of people, goods, infrastructure and usages in the area prone to tsunami flooding
Vulnerability -- More differentiated analysis: Identification of persons or goods particularily vulnerable and explanation of patterns

Step 3: Calculation of potential losses

Losses -- Estimation of maximum possible losses of life, goods, and infrastructure based on Steps 1 and 2

Step 4: Developing a holisitc mitigation concept

Mitigation -- Finding an appropriate level of mitigation by considering frequency-magnitude patterns and the loss potential, and application of joint geoscientific and economic models of natural hazard mitigation, which rely on data generated through the previous steps. Measures include planning controls on land use, building regulations, evacuation plans and training, natural hazard communication and education, information dissemination protocols in case of a disaster, etc.

FIGURE 1.2

The role of tsunami deposits in a tsunami-hazard management workflow. The schematic depiction and classification of sedimentary archives corresponds to tropical coasts of the Caribbean, but can be adapted to other coastal environments as well. The original concept was inspired by Dall'Osso and Dominey-Howes (2010).

Modified after Engel et al. (2016).

Disciplinary background

A tsunami is defined as a "set of ocean waves caused by any large, abrupt disturbance of the sea surface" induced by subaquatic vertical deformation of the lithosphere during earthquakes, submarine or subaerial landslides, explosive volcanic activity, or meteorite impacts (Bernard et al., 2006, p. 1989 ff.); see Chapter 4. A paleotsunami is a "tsunami occurring prior to the historical record or for which there are no written observations" (IOC, 2019, p. 7). Paleotsunami research is rooted in the scientific discipline of sedimentology, as it uses the sedimentary evidence deposited by past tsunamis (e.g., Goff et al., 2012; IOC, 2019), but it also involves micropaleontological applications, as the microfossil record of tsunami deposits provides essential information about the hydrodynamic and depositional process, and sediment source areas (e.g., Pilarczyk et al., 2014). As such, it is closely connected with the discipline of paleotempestology, defined as the "field of science that studies past tropical cyclone activity mainly through the use of geological proxy techniques" (Liu, 2004, p. 13). However, the reconstruction of extratropical storminess (e.g., May et al., 2013; Degeai et al., 2015; van Hengstum et al., 2015) as well as the use of biological archives such as the isotopic records of annually banded corals (Nyberg et al., 2007; Hetzinger et al., 2008) or tree rings (Miller et al., 2006) may also be categorized as paleotempestology.

A number of conceptual approaches and methods in paleotsunami research are also adopted from neighboring disciplines such as geomorphology, geophysics, or geochemistry. Numerical and experimental modeling plays an increasingly important role in the quantitative reconstruction of physical parameters of past events, which are represented by sedimentary deposits in the field (e.g., Sugawara et al., 2014). In certain settings, sedimentary evidence of tsunamis can be identified in archaeological contexts; thus, archaeological, anthropological, and ethno-historical evidence may also add to the reconstruction of past tsunamis and the assessment of the associated long-term hazard (Goff et al., 2012).

A short history of paleotsunami research

Until the late 1980s, accounts of sedimentary deposits laid down by tsunamis were mostly restricted to isolated post-disaster reports focusing on a range of observations of secondary effects emanating from major earthquakes or volcanic eruptions (e.g., Verbeek, 1886; Platania, 1908; Marinatos, 1939; Shepard et al., 1950; Wright and Mella, 1963; Reimnitz and Marshall, 1965). The detailed study of Shepard et al. (1950) on the effects of the tsunami following the 1946 Aleutian Islands Earthquake on the coastlines of Hawaii is probably the first to systematically report on sedimentary and erosive patterns associated with an event. Further reports followed after the 1960 Chile Tsunami (e.g., Wright and Mella, 1963; Reimnitz and Marshall, 1965), for which Bourgeois (2009, p. 59) identifies the contribution of Kon'no et al. (1961) as the first "detailed sedimentological description of a tsunami deposit." Mainly based on the aforementioned reports, Coleman (1968) provided a first review on "tsunamis as geological agents", where the involvement of tsunamis in shaping a range of coastal landforms was proposed. However, it took quite some time until tsunamis were generally recognized as episodic processes influencing coastal geomorphology, adding to coastal sedimentary environments and being of significance for coastal hazard management. The turn of the tide during the mid- to late 1980s is demonstrated by the following regional example: a distinct, ubiquitous subsurface layer of sand and gravel along the eastern coast of Scotland (>7000 years BP) was originally interpreted as a deposit of the Flandrian Transgression (Morrison et al., 1981; Smith et al., 1983) or a storm surge of extraordinary magnitude (Smith et al., 1985). Today, this unit is associated with the early Holocene Storegga slides off the Norwegian shelf, which triggered a major tsunami impacting the circum-North Sea coasts. Sediments transported onshore during this event have been found along the northeast coast of the United Kingdom (Dawson et al., 1988; Long et al., 1989; Smith et al., 2004), Norway (e.g., Bondevik et al., 1997), the Faroe Islands (Grauert et al., 2001), Shetland Islands (e.g., Bondevik et al., 2005), east Greenland (Wagner et al., 2007), and possibly as far south as the German Bight (Fruergaard et al., 2015; Willems et al., 2019).

The paradigm shift from qualitative post-event descriptions to the examination of the sedimentological evidence deposited by tsunamis was initiated mainly by the contributions of Atwater (1987), Dawson et al. (1988), and Long et al. (1989). For the first time, their case studies established a link between coastal stratigraphies and seismic or landslide-induced tsunamis of the recent geological past, i.e., in this case, the Holocene. From this point on, systematic concepts and principles of tsunami-laid sediments or tsunami deposits started to thrive. In several cases, they triggered a reassessment of coastal sedimentary sequences and landforms and Holocene shoreline evolution (e.g., Bryant, 2001), leading to spirited debates (Dawson, 2003; Felton and Crook, 2003; Courtney et al., 2012). Furthermore, tsunamis have been recognized as causal factors of destruction layers at coastal archaeological sites and gave rise to new approaches in archaeological interpretation (e.g., Smith et al., 2004; Pantosti et al., 2008; Hoffmann et al., 2018; Rosi et al., 2019).

Even though paleotempestology as a discipline is also quite young, the impact of strong storms had been recognized by coastal geomorphologists at a significantly earlier stage compared to tsunamis, most likely due to the fact that they occur much more frequently. Prominent early works include studies of coral-rubble ridges and ramparts formed by individual tropical cyclones in the south Pacific and Great Barrier Reef (e.g., Moorhouse, 1934; McKee, 1959; Baines and Lean, 1976), which founded our understanding of coastal ridge sequences and their implications for past storminess (e.g., Scoffin, 1993; Nott and Hayne, 2001; May et al., 2013). Furthermore, Hayes (1967) provided a seminal work on the geological effects of tropical cyclones on coastal sedimentary environments of the siliciclastic, low-gradient coast of south Texas. Sandy ridge sequences began to be used in a similar way to infer variability in storminess, in particular since the 2000s (Dougherty et al., 2004; Nott et al., 2009; May et al., 2013), even though their significance has been under debate (Tamura, 2012; Nott, 2014). Furthermore, paleotempestology has focused on coastal wetlands and lagoons, where marine overwash during severe storm conditions creates significant sand layers, the thickness and spacing of which may relate to variabilities of storminess over millennial timescales (Liu, 2004). These studies have developed since the 1990s with a particular spatial focus on the Gulf of Mexico, the Caribbean (e.g., Liu and Fearn, 1993; Donnelly and Woodruff, 2007; Wallace et al., 2014), and the US East coast (e.g., Donnelly et al., 2001).

Both tsunamis and storms impose high-energy marine incursions along coastlines and lead to the deposition of allochthonous sediment in coastal lowlands, mostly with larger grain sizes and/or different microfaunal characteristics compared to the background sedimentation. The techniques and proxies applied to investigate geological records of tsunamis and of storms overlap, as do the types of sedimentary archives. Therefore, even though the primary focus of the book is on tsunamis, deposition by storm surges or storm-wave overwash is also discussed.

Scope of the book

Research on extreme wave events has made important progress during the last 15 years. The 2004 Indian Ocean Tsunami represents a milestone in paleotsunami research and related disciplines, since it triggered numerous follow-up studies refining tsunami facies models and increasing our knowledge about past tsunami occurrence and characteristics. At the same time, the multitude of post-2004 studies has exposed major challenges in paleotsunami research, in particular in distinguishing between storm and tsunami deposits.

The influx of new information in the aftermath of the 2004 Indian Ocean Tsunami motivated Shiki et al. (2008) to edit the book *Tsunamiites* as a first systematic compilation of geological aspects of tsunamis. At that time, however, numerous influential studies on the Indian Ocean Tsunami had not yet been published (e.g., Jankaew et al., 2008; Monecke et al., 2008; Sawai et al., 2009; Chagué-Goff et al., 2011; Szczuciński, 2012). Considerable progress was also subsequently achieved in the wake of other notable extreme wave events, such as Hurricane Katrina in 2005, Tropical Cyclone Nargis in 2008, the 2010 Maule Tsunami in Chile, the 2011 Tōhoku Tsunami, and Supertyphoon Haiyan in the Philippines in 2013. These events collectively killed almost 170,000 people, approaching the 226,000 fatalities of the Indian Ocean Tsunami (UCL-CRED, n.d.).

Apart from their catastrophic effects and fatalities, most of these events have contributed important new information regarding sediment deposition and erosion by extreme-wave events. Progress since 2008 includes important methodological developments such as the use of μCT scans for microstructure analyses (May et al., 2016; Falvard and Paris, 2017); see Chapter 17 or the pioneering application of ancient sedimentary DNA (Szczuciński et al., 2016); see Chapter 20. Furthermore, these events have provided the opportunity for further study of modern tsunami and storm deposits. The 2011 Tōhoku Tsunami and the 2013 Supertyphoon Haiyan in particular added crucial information regarding the interpretation of extreme-wave deposits, often in the form of washover deposits, and the differentiation between those relating to tsunamis and storm waves. While the 2011 Tōhoku Tsunami, for instance, unequivocally showed that inundation limits are not equivalent to the extent of sand deposition (e.g., Chagué-Goff et al., 2012; Sugawara, in press), Supertyphoon Haiyan raised awareness of the hazards posed by infragravity waves and seiches, which further complicate the interpretation of geological records and the issue of distinguishing between storm and tsunami deposits (e.g., May et al., 2015a; Soria et al., 2018). Further progress is also implied by the study of Spiske et al. (2019), emphasizing the significance of post-depositional processes, which strongly alter the original deposit. The authors convincingly demonstrate how this may lead to misinterpretation and erroneous inverse-modeling results.

Against this background, we feel that it is the right time to provide a compilation of state-of-the-art research on geological records of tsunamis and other extreme-wave events in the form of this compendium. Its goal is to summarize the advances made by research during the last few decades, and at the same time to provide a methodological overview with the character of a handbook. Differentiation between tsunami and storm deposits in the geological record continues to be challenging, and while the combination of different pieces of evidence may point to either process in some studies, in other cases differentiation is not unequivocally possible: similar depositional characteristics may be related to storm and tsunami, and the geomorphological impact may be very similar as well.

The cover of this book, and Fig. 1.3A, provide classical examples of allochthonous sand layers within finer-grained coastal lowland sediments, reflecting repeated

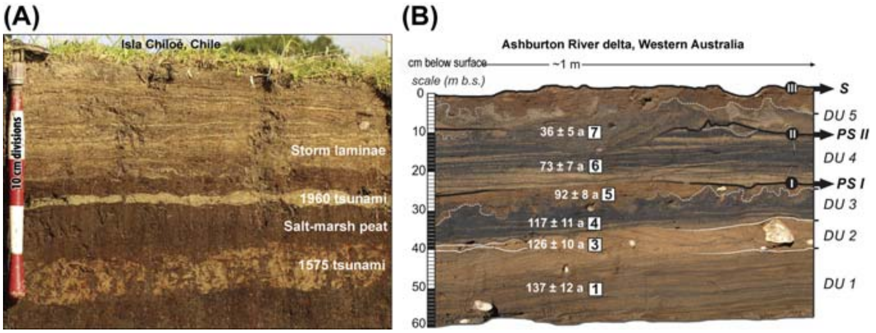


FIGURE 1.3

(A) Exposure at the eroding front of a tidal marsh on Isla de Chiloé in south-central Chile showing a sequence of well-defined allochthonous tsunami and storm deposits bracketed by in-situ, organic-rich salt-marsh deposits; the same exposure (in different light) is shown on the book cover. It shows the massive, bioturbated deposit of the tsunami resulting from the 1575 Valdivia Earthquake, separated from the 1960 Chile Tsunami deposit by in-situ marsh sediment. Overlying the 1960 deposit is a thin layer of autochthonous marsh sediment and a ~20-cm-thick section including recent storm laminae. (B) Washover sequence deposited on an estuarine tidal flat located in the back of a dune belt of the Asburton River delta in Western Australia. It contains five depositional units (DU), some of which are separated by clear temporarily stable surfaces (*PS*, paleo-surface; *S*, surface; *black lines I-III*) characterized by bioturbation. DU 1, 3, and 4 show (sub-)planar heavy-mineral laminae as a typical signature of storm overwash. DU 2 appears more massive, coarser, shows a richer and more diverse foraminiferal assemblage as well as higher carbonate contents and was linked with tsunami deposition. High-resolution optically stimulated luminescence dating permitted to link DU 1, 3, and 4 with specific historical tropical cyclones, and DU 2 with the 1883 Krakatoa Tsunami, which created significant flooding in the area according to historical accounts (*dashed gray lines*, lower limit of bioturbation; *white continuous lines*, erosional boundaries).

(B) Modified after May et al. (2015b).

inundation by extreme-wave events. Both photographs are from the eroding front of a tidal marsh on Isla de Chiloé, south-central Chile. Tidal marshes and coastal lowlands in this region preserve deposits from tsunamis generated by magnitude 8 to 9+ earthquakes along the Chilean subduction zone (Garrett et al., 2015; Cisternas et al., 2017). The dark-brown organic-rich layers reflect the background sediment accumulation in high intertidal or supratidal peat-forming environments, while the light-gray silt-rich sand layers are interpreted as abruptly emplaced deposits from a sequence of tsunamis over the last millennium. At the top of the section, thin sand laminae probably reflect marsh overtopping during storms over the last 60 years. The tsunami deposits drape the underlying marsh topography and are laterally extensive over hundreds of meters, thinning as they rise toward the landward limit. Fig. 1.3B shows a stacked sequence of historical storm-washover deposits of the last 150 years in Western Australia punctuated by a deposit of the 1883 Krakatoa Tsunami; the site is characterized by very low net background sedimentation (May et al., 2015b).

This book aims to provide the first systematic compendium of paleotsunami research, sediment types and sources, field methods, sedimentary and geomorphological characteristics, as well as dating and modeling approaches. By contrasting tsunami deposits with those of competing mechanisms in the coastal zone, such as storm waves and surges or long-term coastal processes, the book is also relevant to readers interested in (paleo)tempestology, coastal geomorphology, coastal sediment dynamics, and coastal hazards in general. The variety of relevant sedimentological, geochemical, geophysical, and biological proxies typical of tsunami-deposited sediments is clearly at the heart of the book.

We aim to provide a comprehensive volume for researchers who investigate tsunami deposits, reflecting state-of-the-art methods in data acquisition, analysis, and interpretation. Its systematic, handbook-like character and its proxy-by-proxy structure may serve as a manual and will guide site- and goal-specific research designs. A comprehensive index at the end of the book, in combination with the use of clear and concise keywords at the beginning of each chapter, provide easy access to any application and proxy. It offers advice on the most appropriate mapping, sampling, and analytical approaches to researchers, which widely vary according to local coastal settings and sedimentary environments. At the same time, the chapters are designed and structured to also work as stand-alone, review-type contributions.

Outline of the book

The book comprises a total of 36 chapters, which are grouped into five main sections. Section 1 (Introduction) introduces paleotsunami research (Chapter 1), emphasizes the significance of historical records (Chapter 2), and explains different tsunami magnitude scales that help to quantify individual events (Chapter 3).

Chapter 4 then summarizes the most important triggers and hydrodynamic characteristics of tsunamis, before the main challenges in establishing paleotsunami databases are introduced (Chapter 5).

Section 2 (Field methods) gives a comprehensive overview of state-of-the-art field methods applied within the framework of paleotsunami (and paleostorm) research. While Chapter 6 summarizes the most promising onshore environments for the search for tsunami deposits, Chapter 7 guides the prospection and sampling of offshore deposits. As the main body of the book is devoted to onshore tsunami deposits, this chapter also provides a brief overview of the main characteristics of offshore tsunami sediments and geomorphological impacts. Section 2 also contains a contribution on the application of ground-penetrating radar in mapping subsurface tsunami deposits (Chapter 8) and an overview on mapping subaerial coarse-clast deposits dislodged by extreme-wave events (Chapter 9). Suggestions of how to organize and conduct field surveys of the effects of recent tsunamis are provided by Chapter 10.

In Section 3 (Fine-grained deposits: proxy data and modeling), the most important analytical methods and proxies for investigating and identifying fine-grained extreme-wave deposits are presented and explained, covering the topics of sedimentology and geometry (Chapter 11), foraminifera (Chapter 12), ostracods (Chapter 13), diatoms (Chapter 14), molluscs (Chapter 15), anisotropy of magnetic susceptibility and magnetic susceptibility (Chapter 16), X-ray computed tomography (Chapter 17), geochemistry (Chapter 18), microtexture on quartz grains (Chapter 19), and ancient sedimentary DNA (Chapter 20). Further notable aspects of Section 3 include post-depositional changes of tsunami deposits (Chapter 21), erosional signatures with a focus on ridge-and-swale sequences (Chapter 22), and a review of experimental and numerical modeling of fine-sediment transport by tsunamis (Chapter 23).

Section 4 (Coarse-clast deposits: sedimentary patterns and modeling) is dedicated to the coarse-clast record, comprising spatial patterns of coastal boulders and blocks (Chapter 24), megatsunami conglomerates (Chapter 25), and the impact of tsunamis on rocky coastlines and the post-depositional weathering of subaerial clasts (Chapter 26). The remaining three chapters of this section are dedicated to the modeling of boulder transport, both experimentally (Chapter 27) and numerically. While Chapter 28 provides an overview of the available range of inverse and forward modeling approaches, Chapter 29 puts a special focus on the often-used initiation-of-motion criteria pioneered by Nott (1997, 2003) and further developed by others.

Finally, the most important dating approaches for both fine-grained and coarse extreme-wave deposits are presented in Section 5, including radiocarbon dating for coastal stratigraphic sequences (Chapter 30), radiocarbon and U/Th dating applied to boulder deposits (Chapter 31), optically stimulated luminescence dating (Chapter 32), archaeological dating (Chapter 33), tephrochronology (Chapter 34), cosmogenic nuclide dating of boulder deposits (Chapter 35), and pioneering approaches of paleomagnetic dating of boulders (Chapter 36).

Concluding remarks

Paleotsunami research has grown rapidly since its foundations in the late 1980s, and the appreciation of sediment records resulting from hazardous extreme-wave events for coastal risk management has increased continuously since then. Given the long recurrence intervals of the largest magnitude tsunamis, the value of these records for potentially extending instrumental and historical records is generally recognized, while they also may provide important insights into extreme-wave characteristics. However, numerous challenges in terms of their sedimentary interpretation and a clear linkage of these deposits to past tsunami or storm events of particular magnitude remain.

This edited volume aims at tackling these challenges by summarizing the state-of-the art in research on tsunami deposits and associated methodological approaches and workflows, including numerous references to those deposits associated with other extreme-wave events, mostly severe storms. In the wake of some of the most exceptional events such as the 2011 Tōhoku Tsunami or Supertyphoon Haiyan in the Philippines in 2013, which occurred during the last decade, substantial research progress has been achieved, which we think deserves to be highlighted in the form of a new systematic compendium. We hope that the background information on tsunamis and other extreme waves, the presentation of sampling and dating approaches, the detailed proxy-by-proxy structure, and the demonstration of available modeling techniques are perceived to be useful when designing and conducting future research in a broad, i.e., global, range of coastal environments.

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