Coastal Research Library 8

Charles W. Finkl
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Environmental Management and Governance

Advances in Coastal and Marine Resources

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Preface

This volume in the Coastal Research Library (CRL) considers various aspects of coastal environmental management and governance. As the world population grows, more and more people move to the coastal zone. There are many reasons for this drang to the shore, not the least of which are increased opportunities for employment and relaxation in a salubrious environment. But, as population densities increase beyond the carrying capacity of fragile coastal zones and sustainability seems ever more elusive, more than remedial measures seem required. Because governance in the coastal zone has generally failed the world over, it is perhaps time to reconsider what we are doing and how we are doing it. Depopulation of many coastal zones would be a laudable goal, but just how this might be accomplished in a socially acceptable manner is presently unknown. Perhaps some socioeconomic incentives can be devised to lure people back towards hinterlands, but until such goals or efforts are implemented there seems little choice other than trying to make things work with the present state of affairs.

This volume thus considers a range of selected advances that highlight present thought on a complex subject that invariably, one way or the other, involves consideration of coastal natural resources. Whether it is coastal hazards, sustainability of fishers and aquaculture, resolution of environmental conflicts, waste disposal, or appreciation of biophysical frameworks such as coastal karst or impactors such as fluctuating sea levels, more advanced *out of the box* thinking is required to solve today's problems. Approaches to potential solutions are sometimes based on models or perhaps more commonly on an individual's ratiocinative powers where one can deduce logical outcomes. It is unfortunate that in many cases governmental approaches to solutions are lethargic and ineffective, making it all the more imperative to suggest advanced approaches to old problems that linger on. This book thus attempts to highlight some examples of advancements in thought processes, observation, comprehension and appreciation, and better management of coastal resources.

Environmental Management and Governance: Advances in Coastal and Marine Resources is subdivided into five parts: Part I, Coastal Hazards and Beach Management-Certification Schemes; Part II, Ocean Governance, Fisheries and

Aquaculture: Advances in the Production of Marine Resources; Part III, Exploration and Management of Coastal Karst; Part IV, Coastal Marine Environmental Conflicts: Advances in Conflict Resolution; and Part V, Examples of Advances in Environmental Management: Analyses and Applications that collectively contain 17 chapters. These subdivision are, of course, artificial and meant only to help organize the material into convenient study groups. Chapters in each part are briefly described in what follows.

Part I contains three chapters that deal with coastal hazards and beach management. In Chap. 1 ("Geological Recognition of Onshore Tsunamis Deposits"), Costa, Andrade, and Dawson discuss enhancements of our abilities to recognize (paleo) tsunami specific signatures in coastal sediments through the application of diverse sedimentological techniques. They show in this chapter how it is possible, through the use of diverse sedimentological proxies, to obtain information about the presence or absence of tsunami indicators, establish their likely source, and collect valuable information about tsunami run-up, backwash or wave penetration inland. Botero, Williams, and Cabrera, in Chap. 2 ("Advances in Beach Management in Latin America: Overview from Certification Schemes"), analyze beach certification schemes as part of beach management in Latin America. These authors highlight advances in beach management in Latin America by pointing out main conceptual, methodological, and practical challenges to be achieved for scientific and decision makers of the continent. Chapter 3 ("New Methods to Assess Fecal Contamination in Beach Water Quality") by Sarva Mangala Praveena, Kwan Soo Chen, and Sharifah Norkhadijah Syed Ismail deals with an emerging paradigm for assessment of recreational water quality impacted by microbial contamination. Advances in this topic are important because recreational water is susceptible to fecal contamination, which may increase health risk associated with swimming in polluted water.

Part II also contains two chapters, but these efforts focus on broader issues of advances in ocean governance that involve new developments in coastal marine management and fisheries and aquaculture production. Chapter 4 ("New Approaches in Coastal and Marine Management: Developing Frameworks of Ocean Services in Governance") by Paramio, Alves, and Vieira delves into aspects of "Modern" and "post-Modern" views of ocean uses as a source of resources and space; for example, how economic development is now supplemented by functions the marine environment provides, such as human life and well-being. Ocean governance remains a current focus of discussion for policymakers aiming to address sustainability principles and perspectives in a more effective way. Chapter 5 ("Interaction of Fisheries and Aquaculture in the Production of Marine Resources: Advances and Perspectives in Mexico"), by the Pérez-Castañeda team (Roberto Pérez-Castañeda, Jesús Genaro Sánchez-Martínez, Gabriel Aguirrte-Guzmán, Jaime Luis Rábago-Castro, and Maria de la Luz Vázquez-Sauceda) indicates advances that are indicative of the potential value of aquaculture as a complementary productive activity that will meet the growing human demand for food from the sea. This advanced understanding is critical because, in terms of global fisheries production, the maximum fisheries catch potential from the oceans around the world has apparently been reached.

Part III contains Chap. 6 ("Advances in the Exploration and Management of Coastal Karst in the Caribbean") by Michael J. Lace. This chapter is important because it explains that significant karst areas remain to be explored while illustrating associated landform vulnerabilities, anthropogenic effects, and range of coastal resource management and preservation initiatives that should be applied. These advances highlight unreported field research in selected island settings that support an emerging view of complex karst development.

Four chapters that deal with advances in coastal resources conflict resolution comprise Part IV. Chapter 7 ("Mud Crab Culture as an Adaptive Measure for the Climatically Stressed Coastal Fisher-Folks of Bangladesh") by Khandaker Anisul Huq, S. M. Bazlur Rahaman, and A. F. M. Hasanuzzaman is an example of new adaptive measures for ensuring the security of food and livelihood of coastal poor people. Highlighted here is on-farm adaptive research on crab fattening/culture as a livelihood option for the fisher folks. This chapter shows how to recommend and carry out comprehensive crab culture extension programs for building capacity and improving economic conditions in climatically stressed coastal communities. Chapter 8 ("The Guadalquivir Estuary: A Hot Spot for Environmental and Human Conflicts) by the Ruiz team (Javier Ruiz, Mª José Polo, Manuel Díez-Minguito, Gabriel Navarro, Edward P. Morris, Emma Huertas, Isabel Caballero, Eva Contreras, and Miguel A. Losada) demonstrates how the application of robust and cost-efficient technology to estuarine monitoring can generate the scientific foundations necessary to meet societal and legal demands while providing a suitable tool by which the cost-effectiveness of remedial solutions can quickly be evaluated. A holistic approach to understanding the estuarine ecosystem, including its physical and biogeochemical dynamics and how these control biodiversity, is identified as the first step towards making knowledge-based decisions for sustainable use. Chapter 9 ("Shrimp Farming as a Coastal Zone Challenge in Sergipe State, Brazil: Balancing Goals of Conservation and Social Justice") by Juliana Schober Gonçalves Lima and Conner Bailey discusses marine shrimp farming in Brazil from the perspective of both social justice and environmental conservation. Conflicts arose here because the rearing of marine shrimp became an important local economic activity that increasingly occupied large areas on the coast. Shrimp farming is practiced mainly through extensive family-based production systems in mangrove areas that were subsequently declared Permanent Preservation Areas by Brazilian law. As a result, these family shrimp farms are considered illegal, but the farms themselves long predate promulgation of the law and represent an important source of livelihood for hundreds of families. Chapter 10 ("Regional Environmental Assessment of Marine Aggregate Dredging Effects: The UK Approach") by Dafydd Lloyd Jones, Joni Backstrom, and Ian Reach describes the MAREA (Aggregate Regional Environmental Assessment) methodology, and shows how similar regional assessment exercises could contextualize the effects and impacts of multiple marine dredging activities in other parts of the world. Each MAREA assesses the cumulative impacts of marine dredging activities using regional-scale hydrodynamic and sediment transport models linked to regional-scale mapping of sensitive receptors.

Part V contains seven chapters that consider various aspects of advances in environmental management based on examples of analyses and applications. Chapter 11 ("Advances in Large-Scale Mudflat Surveying: The Roebuck Bay and Eighty Mile Beach, Western Australia) by Robert J. Hickey, Grant B. Pearson, and Theunis Piersma deals with advances in mudflat surveying using the example of shores along Roebuck Bay and Eighty Mile Beach in northwestern Australia, the richest known intertidal mudflats in the world. Chapter 12 ("Sea-Level Indicators") by Niki Evelpidou and Paolo A. Pirazzoli illustrates how the study of relative sea-level changes is an essential element of ocean observation and technological advances that are necessary to improve the determination of levels (elevation or depth), chronological estimations, and the identification of appropriate sea-level indicators. Although levels are determined with satellites, oceanographic vessels, geophysical equipments, leveling techniques, tide-gauge devices, or even direct measurement by an observer, chronological estimations may result from radiometric analysis of samples, comparison with stratigraphic sequences, archaeological or historical data, assumptions on erosion or deposition processes, or even from glacio-isostatic or climate modeling. Indicators of fossil or present-day sea-level positions are nevertheless the most important elements for a sea-level reconstruction, because they provide information not only on the former level but also on the accuracy of the reconstruction. In Chap. 13 ("Advancement of Technology for Detecting Shoreline Changes in East Coast of India and Comparison with Prototype Behavior) by R. Manivanan, various aspects of intake/outfall of nuclear power plant on the coast, especially the dispersion of warm water discharges under different environmental conditions, is simulated using mathematical modeling techniques and suitable locations of intake and outfall with the minimum recirculation. This chapters discusses advances for optimizing the efficiency of power plants by locating the intake/outfall so there is minimum recirculation of warm water in the intake under the prevailing coastal environmental conditions. Chapter 14 ("Coastal Dunes: Changes of Their Perception and Environmental Management") by Tomasz A. Łabuz outlines coastal dune types and conditions for their development, while considering functions and practical use of coastal dunes. Of special interest here are advancing and changing attitudes to environmental management of coastal dunes that include various new approaches to use and perception of dunes that result from cultural and societal development. Chapter 15 ("Advances in Brine Disposal and Dispersion in the Coastal Ecosystem from Desalination Plants") by R. Manivanan observes brine water plume behavior in the vicinity of coastal areas with different outfall locations. This study indicates that higher velocity and larger port diameter enhances dispersion rates and minimizes adverse effects on the marine ecosystem. Chapter 16 ("Estuaries Ecosystems Health Status – Profiling the Advancements in Metal Analysis") by Ahmad Zaharin Aris and Looi Ley Juen demonstrates advanced analytical methods and detection techniques available for metals analyses. Environmental forensic approaches and application of various metal pollution indicators, indices, modeling, and statistical analysis are used to assess estuarine ecosystem health status. Chapter 17 ("Floating Offshore Wind Farms and Their

Application in Galicia (NW Spain)") by Laura Castro-Santos and Vicente Diaz-Casas provides a methodology for calculating the life-cycle costs of developing a floating offshore wind farm. This example was developed for a semisubmersible floating offshore wind platform and a general offshore wind turbine of 5 MW. The farm will be composed of 21 offshore wind turbines, with a total power of 107 MW.

While it is understood this volume does not include all advancements in the management and governance of environmental systems, a thorough selection of topics have been addressed. From coastal hazards, to ocean services, to aquaculture, this book presents a diverse cross-section of studies that provide innovative environmental stewardship on an international scale. However, these studies are only the beginning. From these new ideas spring forth new ways of thinking to effectively protect, manage, and govern fragile coastal ecosystems found around the world. By delving into original, pioneering methods and practices, as illustrated throughout this volume, true advancements are then achieved.

Coconut Creek, FL, USA Charles W. Finkl
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Part I
Coastal Hazards and Beach Management-Certification Schemes

Chapter 1
Geological Recognition of Onshore Tsunami Deposits

Pedro J.M. Costa, César Andrade, and Sue Dawson

Abstract The study and understanding of coastal hazards is a fundamental aspect for most modern societies. The consequences of extreme events such as tsunamis are being regarded as major threats for coastal regions. The sedimentological record provides a database useful to characterize and evaluate recurrence of tsunamis, which contributes to assessing the vulnerability of any coastal area to this natural hazard. Thus, the enhancement of our ability to recognize (palaeo) tsunami specific signatures in coastal sediments, through the application of diverse sedimentological techniques, is of unquestionable interest.

This work reviews and discusses contributions provided by developments in the study of onshore tsunami deposits based on a group of sedimentological attributes\characteristics.

1.1 Introduction

In addition to the long-term processes operating in a region, catastrophic inundation events such as tsunamis (and storms) can contribute significantly to the stratigraphy of any given area. In contrast to contemporary tsunami events, for which eyewitness descriptions and instrumental and field measurements of both erosional and depositional effects are utilized in modelling studies (e.g. Finkl et al. 2012), (palaeo) tsunami recognition depends on the identification of ancient tsunami deposits

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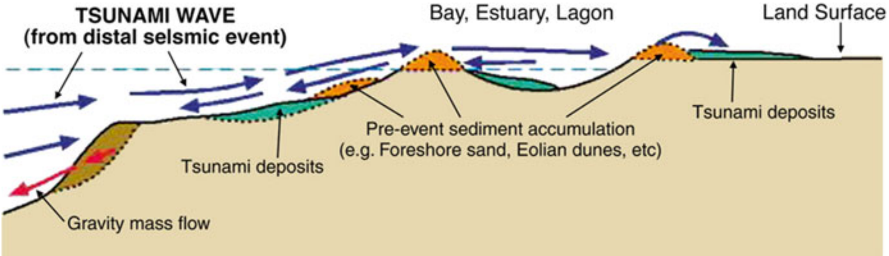

Fig. 1.1 Schematic illustration of principal pathways of tsunami sediment transport and deposition (Dawson and Stewart 2007 after Einsele et al. 1996)

(e.g. Bourgeois et al. 1988; Long et al. 1989; Smit et al. 1992; Bondevik et al. 1997; Clague et al. 2000; Dawson and Stewart 2007; Morton et al. 2011; Chagué-Goff et al. 2011; Goff et al. 2012; Goto et al. 2011a).

Tsunami deposition is usually characterized by the re-deposition of coarse shallow marine or coastal sediments in terrestrial and/or transitional (e.g. lagoonal, estuarine) environments (Fig. 1.1). Recognition of these deposits is the primary method for reconstructing tsunami minimum inundation distance and run-up, although patterns of erosion and deposition by both landward- and seaward-directed flows are complex, these patterns being further complicated by the existence of more than one wave associated with the same tsunami (Moore and Moore 1984; Synolakis et al. 1995; Bondevik et al. 1997; Le Roux and Vargas 2005; Nanayama and Shigeno 2006; Paris et al. 2007), thus introducing uncertainties in those reconstructions. In particular, because the maximum altitude at which tsunami sediments are deposited in the coastal zone is nearly always lower than the height reached by the tsunami. In fact, the upper sediment limit is generally regarded as a minimum level reached by the tsunami waves (this assumption is of crucial importance for hazard and physical and numerical modelling because sediment evidence might underestimate the maximum inland flooding penetration).

The nature of tsunami deposits varies greatly with coastal and nearshore morphology, the height of tsunami waves at the coast and run-up, and with the nature and amount of existing sediment in any coastal setting when affected by such an event. Consequently, the possible variations in sedimentary processes and products during these complex events remains poorly understood but in general a tsunami deposit will only be produced if there is a suitable supply of sediment and accommodation space in the coastal zone. More recently, the subsequent backwash has been regarded as a process of significant geomorphic and sedimentologic consequences (e.g. Hindson and Andrade 1999; Le Roux and Vargas 2005; Paris et al. 2010b), though the spatial extension of the correspondent signature is usually more restricted due to channelling effects. However, recent studies conducted in the nearshore area demonstrate the importance of the backwash process within tsunamigenic sediment transport (e.g. Goff et al. 2012). The geomorphological consequences and difficulty in differentiating tsunamis and storms in coastal dunes or barrier islands have also been addressed (e.g. Andrade 1990; Andrade et al. 2004; Regnauld et al. 2008; Goff et al. 2010b).

Due to their specific physics and particular sediment transport processes tsunami (and extreme storms) tend to leave their sediment imprint in a wide range of environments (e.g. alluvial plains, estuaries, coastal lagoons, embayments, nearshore and offshore areas) although storms usually exhibit a smaller amount of inland penetration. However, many of these environments display a low preservation potential for event deposits (Einsele et al. 1996) and the recognition of tsunami and storm deposits is constrained by the poor preservation of those deposits (or absence) in the stratigraphic record. In many cases, subsequent anthropogenic activity, the erosion characteristics of the event, the relative changes in sea level in a millennium timescale and the absence of lithological differentiation makes palaetsunami deposits difficult to identify and therefore also makes it difficult to make inferences regarding the return intervals of such events (Szczucinski 2012; Yawsangratt et al. 2012).

1.2 Nearshore and Offshore Deposits

Nearshore and offshore deposits have been described essentially in association with several specific tsunami events worldwide (Smit et al. 1992; Cita et al. 1996; Fujiwara et al. 2000; van den Bergh et al. 2003; Terrinha et al. 2003; Abrantes et al. 2005, 2008; Noda et al. 2007; Gracia et al. 2010) and were considered by Dawson and Stewart (2008) a "very much neglected research area" within tsunami sedimentary recognition. Weiss and Bahlburg (2006) considered that offshore tsunami deposition in deep marine environments well below the wave base of severe storms are theoretically much more likely to preserve tsunami deposits than shallow settings. Despite of that fact, these authors noted that there are only a few descriptions in the literature of marine, and particularly subtidal, tsunami deposits (Pratt 2001, 2002; Bussert and Aberhan 2004; Cantalamessa and Di Celma 2005; Schnyder et al. 2005).

In the offshore area, the term "deep-sea homogenite" has been used to define a massive, poorly sorted, grain-supported unit that contains large reworked shallow-marine fossils and occasional large intraclasts that have been described in association with the Bronze Age Santorini tsunami event (Cita et al. 1996). Other tsunamigenic deposits were discussed in an offshore sedimentary context and related with events such as the K/T meteoric tsunami (e.g. Smit et al. 1992; Albertão and Martins 1996), the AD 1755 tsunami (Terrinha et al. 2003; Abrantes et al. 2005, 2008; Gracia et al. 2010), the 2003 Tokashioki earthquake (Noda et al. 2007) or to try and match earthquake-triggered turbidites with tsunamigenic events from the Saguenay (Eastern Canada) and Reloncavi (Chilean margin) (St Onge et al. 2012). In fact, another peculiar note in terms of offshore tsunami deposits is that some have been specifically attributed to processes of tsunami backwash and the generation of gravity-driven flows of turbid water from nearshore to deep water (e.g. Abrantes et al. 2008; Paris et al. 2007).

1.3 Onshore Boulder Deposits

There are two main types of onshore sedimentary evidences associated with tsunami and storms: one consisting in deposits of large boulders and the other in the deposition of finer (typically sand-sized) sediments in coastal areas.

To facilitate the classification of larger particles Blair and McPherson (1999) revised the Udden-Wentworth scale (Wentworth 1922) to describe in greater detail the size of boulders and other larger particles. The grain size of fine, medium, coarse, and very coarse boulders range from 25.6 to 51.2 cm, 51.2–102.4 cm, 102.4–204.8 cm, and 204.8–409.6 cm, respectively. Larger rocks or megaclasts, include fine (4.1–8.2 m) and medium (8.2–16.4 m) blocks.

In the case of larger particles, the differentiation between tsunami and storm deposits is firstly based on the identification of boulders that have been transported inland and\or upward from or within the coastal zone, and against gravity. In some cases, these boulders appear simply overturned a few m inland from their original source area. The recognition of boulder deposits associated with both tsunami and storms has been intensely debated in the literature (e.g. Bryant et al. 1992; Young et al. 1996; Nott 1997; Bryant and Nott 2001; Noormets et al. 2002; Goff et al. 2004, 2006, 2007; Williams and Hall. 2004; Scheffers and Kelletat 2005; Hall et al. 2006; Bourrouilh-Le Jan et al. 2007; Scheffers and Scheffers 2007; Kelletat 2008; Paris et al. 2010b; Scheffers 2008; Scheffers et al. 2008; Etienne and Paris 2010; Fichaut and Suanez 2010; Goto et al. 2010a, b, 2011b; Nandasena et al. 2011). From the many examples in the literature a few deserve special notice because of their specific lithological, geological, geomorphological or oceanographic significance.

In terms of boulder deposits there are many examples worldwide attributed to deposition by storms and tsunami (compiled by e.g. Sheffers and Kelletat 2003; Scheffers 2008). They range from over 10 up to 1,000 m^3 and, depending on the bulk rock density their mass can exceed 2,000 t (Scheffers and Kelletat 2003). They have been found at various elevations from the intertidal zone to a few tens of meters above the present sea level. Shi et al. (1995) reported that hundreds of boulders were deposited as far as 200 m inland by the December 12, 1992 tsunami in Flores (Indonesia), especially in the area of Riangkroko where waves reached 26 m. The deposition of boulders in association with tsunamigenic events were discussed essentially after the 1990s (e.g. Paskoff 1991; Dawson 1994; Hindson and Andrade 1999). For instance, Hindson and Andrade (1999) noted that at several locations on the Algarve coastline the AD 1755 tsunami was associated with the deposition of both continuous and discontinuous sand sheets, some of which contain boulders. The individual boulders were frequently pitted and sculptured by bioerosion and in hollows marine endolithic mollusca were found and used to indicate the marine provenance of the boulders (Fig. 1.2 for example).

The imbrication of boulders (at certain altitudes and distances from the coastal edge), coupled with the presence of shell and debris inclusions, were used as a diagnostic criteria of tsunami deposits (Bryant and Nott 2001). Hall et al. (2006) focused exclusively in storm wave impacts on boulders sitting at the top of cliffs in Aran and

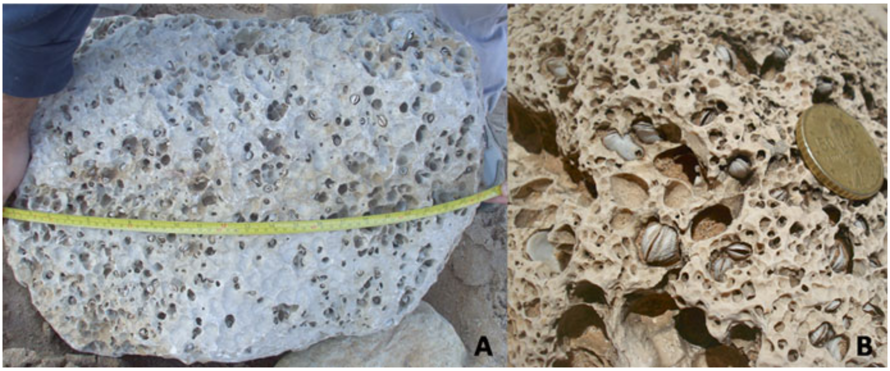

Fig. 1.2 Boulders exhibiting endolithic shells (Praia do Barranco, Portugal). *Left image* – Boulder measuring approximately 0.5 m (long axis – A) on *top* of other boulders. *Right images* – Detailed view of in situ shells, within the borings (Costa et al. 2011)

Shetland Islands (North Sea), and identified inverted boulders exclusively transported by storms. Saltation of these boulders during transport was implied by the presence of shatter marks on the upper limestone ramps on Aran (Williams and Hall 2004) and by trails of impact marks and chipped edges visible on otherwise weathered and lichen-covered surfaces. Hansom et al. (2008) provide modelled solutions for the forces of wave impact and subsequent lift at those sites. According to Hall et al. (2006), the characteristics and distribution of cliff top storm deposits allows the definition of wave properties that could generate those boulder accumulations. According to these authors, cliff top storm deposits require full exposure to storm waves and limited nearshore attenuation. Switzer and Burston (2010) stated that the imbrication, mixed lithology and sedimentary characteristics of boulder deposits at Little Beecroft Head and Greenfields Beach (Australia) provided compelling evidence for large-scale movement attributed to washover by single or multiple events. If the deposits were late-Holocene in age then hypothesise of higher Holocene sea level must be discarded and it is likely that storms and tsunami may have both played a role in the development of the high elevation boulder deposits. However, as in many other sites where boulder deposits transported against gravity have been found, it remains unclear which (i.e. tsunami or storms) was the exact mechanism of emplacement.

1.4 Onshore Cobble and Gravel Deposits

Different size-ranged clasts associated with tsunamis and storms are also described in the literature. In terms of cobble and peeble deposits (2–256 mm diameter – Krumbein and Sloss 1963) a few studies have been conducted over recent years. For example, Morton et al. (2008) analysed coastal gravel-ridge complexes deposited either by tsunamis or hurricanes on islands in the Caribbean Sea. The ridge complexes of Bonaire, Jamaica, Puerto Rico (Isla de Mona) and Guadeloupe consisted of clasts ranging in size from sand to coarse boulders derived from the adjacent coral reefs or subjacent rock platforms. The authors observed that the ridge complexes were internally organized, displayed textural sorting and a broad range of ages indicative of several historical events. Some of the cobble deposits displayed seaward-dipping beds and ridge-and-swale topography, whereas other terminated in fans or steep avalanche slopes. Together, the morphologic, sedimentologic, lithostratigraphic, and chronostratigraphic evidence indicated that ridge complexes were not entirely the result of one or a few tsunamis as previously reported (e.g. Scheffers and Kelletat 2003) but resulted from several events including not only tsunamigenic but also storm/hurricane events. Furthermore, in a nearby region (French West Indies) Caron (2011) used samples from beachrock and non-cemented coarse-grained coastal deposits and applied quantitative textural and taphonomic analysis to discriminate different depositional processes associated with storm and tsunami waves.

Research in Hawaii identified three distinct coarse-clastic depositional assemblages that could be recognized based on clast size, composition, angularity, orientation, packing, elevation and inland distance of each accumulation (Richmond et al. 2011). These deposits were characterized as:

1. Gravel fields of isolated clasts, primarily boulder-sized, and scattered pockets of sand and gravel in topographic lows.
2. Shore-parallel and cuspate ridges composed mostly of rounded basalt gravel and sand with small amounts of shell or other biogenic carbonate. The ridges ranged in height from about 1–3 m.
3. Cliff-top deposits of scattered angular and sub-angular (cobble and gravel) clasts along sea cliffs that were generally greater than 5 m elevation.

The authors concluded that the gravel fields were primarily of tsunami origin from either the 1975 Kalapana event, or a combination of tsunamis during 1868 and 1975. The ridge deposits were presently active and sediment continues to be added during high wave events. The cliff-top deposits contained evidences of deposition by both tsunami and storm processes.

Costa et al. (2011) observed spreads of cobbles and boulders (typically with an A-axis of *ca*. 0.30 m but some with smaller dimensions) that extended several hundred meters inland and well beyond the present landward limit of storm activity in a low-lying area of the Algarve (Portugal). The marine origin of the boulders was demonstrated by well-developed macro-bioerosion sculpturing and in situ skeletal remains of endolithic shallow marine bivalves. The authors associated (using radiocarbon age-estimation of *Petricola lithophaga* whole shells) the transport of these boulders with the desctructive Lisbon tsunami of AD 1755.

1.5 Sedimentological Characteristics of Onshore (Sand-Sized) (Palaeo) Tsunami Deposits

In this sub-chapter, the criteria used to recognize and differentiate tsunami deposits consisting of the finer fraction (i.e. typically sand) is presented. These features/criteria reflect the characteristics of tsunami waves, transport peculiarities, preservation potential and sedimentary sources. The first studies to use geological record to detect prehistoric tsunamis were conducted by Atwater (1987) and Dawson et al. (1988). Since then many papers have been published discussing several aspects concerning features associated with tsunami deposits. The study of modern deposits carried out during immediate post tsunami surveys provided the opportunity to refine palaeotsunami diagnostic criteria, without the uncertainty of the generating event and preservation issues due to natural and anthropogenic disturbance. Understandably, the number of studies on tsunami sedimentation increased exponentially since the 2004 Indian Ocean event, but care should be taken in adopting as of unquestionable universal applicability inferences derived from research on this particular event. Typically, tsunamis can leave sedimentary imprints on shores far from the event source, and usually less than a kilometre from the coastline. Tsunami deposits are usually thicker in topographic lows (areas of spatial deceleration of flows) and thin over topographic highs (areas of spatial acceleration of flows) (Gelfenbaum et al. 2007). In fact tsunami sediments can also be eroded during phases of backwash and have also been linked to new phases of sedimentation during backwash. The preservation of tsunami deposit is a fundamental factor in any sedimentological study focusing in recurrence intervals of such events.

Tappin (2007) discussed sedimentary features associated with tsunami, stressing that the development of realistic scenarios of risk requires reliable data on tsunami frequency, which is obviously constrained by the sporadic absence of deposit, to which we could add the eventual unability to recognize a particular tsunami-deposited layer as such in a given sedimentary sequence. In fact, Szczucinski (2012) conducted five yearly surveys after the 2004 Indian Ocean tsunami and concluded that the post-tsunami recovery of coastal zones was generally in the order of a few months to a few years. The study by Nichol and Kench (2008) in the Maldives found that within 2 years, significant reworking and bioturbation of the tsunami deposit occurred. The major macroscopic change observed was the fast removal of the thin layer of very fine sediments usually representing the top of the tsunami deposits, though such a thin layer consisting of very fine-grained material has not been reported as ubiquitous in other places worldwide and surveyed shortly after tsunami inundations. Szczucinski (2012) observed that almost all the near-surface structures of the tsunami deposits were removed with time (i.e. after at least one rainy season). Tsunami deposits thinner than 10 cm usually acquired a massive appearance after 1 or 2 years; the only remnants of the primary structures, for instance fining upward, having vanished out. This was attributed to bioturbation by growing roots and burrowing animals like crabs and rodents. A few years earlier Szczucinski et al. (2007) detected that tsunami deposits thinner than 1 cm were occasionally washed away, the depositional relief was flattened and deposits at the slopes were partially eroded; and yet, in other locations, the sedimentary bodies, including thin sand *laminae*, and sedimentary structures, such as lamination and size grading, persisted at century-long timescales (e.g. Washington State, Boca do Rio, Martinhal) following deposition. According to Yawsangratt et al. (2012) micropalaeontological evidences (i.e. carbonate foraminifera) may be subjected to significant dissolution 4.5 years after tsunami emplacement; again, this post depositional disturbance is not exclusive of tsunami deposits and rapid intrasediment dissolution or downwearing of carbonate foraminifera tests, ostracoda valves or diatom frustules is a common drawback micropaleontologists working in Holocene sediments of various facies are used to and aware of, and not exclusive of high-energy events of abrupt marine inundation. In this context, it is somewhat surprising that Lowe and de Lange (2000) suggested, based on a study from New Zealand, that a tsunami needs to raise a height of at least 5 m in order to leave any long-term, recognisable sedimentary signature (cf. Goff et al. 2010a). This statement disregards the effect of sediment concentration in tsunami waves in determining the size and preservation potential of the depositional signature, just as a number of other relevant variables, such as the presence of a compatible source, accommodation space, rapid capping of the inundation deposit, among other, which are completely independent of the tsunami amplitude.

During the last two decades, several authors (e.g. Shi et al. 1995; Goff et al. 1998; Gelfenbaum and Jaffe 2003; Dawson and Stewart 2007; Huntington et al. 2007; Shiki et al. 2008; Switzer and Jones 2008; Chagué-Goff et al. 2011) have postulated criteria to distinguish (palaeo) tsunami deposits. These are described below and summarized in Table 1.1. Dawson and Stewart (2007) discussed the processes of tsunami deposition, identifying the three main aspects that make the depositional process unique, tsunami source, propagation and inundation. The establishment of source material has been widely used (e.g. Moore and Moore 1986; Atwater and Moore 1992; Dawson et al. 1996a; Minoura et al. 1997; Bourgeois et al. 1999; Hindson and Andrade 1999; Gelfenbaum and Jaffe 2003; Switzer et al. 2005; Szczucinski et al. 2006; Babu et al. 2007; Morton et al. 2007, 2008; Narayana et al. 2007; Dahanayake and Kulasena 2008; Higman and Bourgeois 2008; Switzer and Jones 2008; Jagodzinski et al. 2009; Costa et al. 2009; Paris et al. 2009; Mahaney and Dohm 2011) because it allows one to reconstruct the origin and pathway of former tsunami waves. However, it has been commonly reported that tsunami waves transport essentially sediment that is available in the coastal fringe landward of the boundary defined by the seasonal depth of closure of the beach (and coastal) profile (e.g. Atwater and Moore 1992; Clague and Bobrowsky 1994; Dawson 1994, 2004; Moore et al. 1994; Hindson et al. 1996; Kortekaas and Dawson 2007; Paris et al. 2010b; Goff et al. 2010a; Costa et al. 2012a, b). In contrast with this, micropalaeontological evidences have indicated either relevant changes in the population of Nannoplankton, Foraminifera, Diatoms and Ostracods or that marine species from offshore/nearshore have been transported inland and deposited by tsunami (e.g. Hemphill-Haley 1996; Hindson et al. 1996; Patterson and Fowler 1996; Shennan et al. 1996; Clague et al. 1999; Dominey-Howes et al. 2000; Chagué-Goff et al. 2002; Dawson and Smith 2002; Abrantes et al. 2005; Dawson 2007; Kortekaas and

Table 1.1 Table summarizing the criteria to identify and differentiate tsunami deposits

Criteria	Features (from selected references)
Physics	Very long wave length
	Very high velocity and speed current
	Few waves but with backwash
	Swift inundation with high shear stress and erosion
Sedimentary structures (requires stratigraphic context/analysis)	Erosional/abrupt/sharp/unconformity basal contact
	Massive/chaotic unit
	Normal grading (in places repeated)
	Unit with several laminae
	Cross-stratification
	Soft-sediment deformation
	Loading structures
	Parallel lamination or cross-lamination
	Convolutions
	Ripple-marks
	Mud drapes
	Rip-up clasts
	Broken shells
Sediment source (requires multiple source analysis)	Typically reflects the material available in the coastal fringe (i.e. beaches and berms, aeolian, inner shelf landward of closure depth)
	Grain size range from mud to boulders
	Multi-modal grain-size distribution indicating multiple sources
	Increase of heavy mineral concentration in the base of the deposit
	Increase of platy minerals (i.e. micas) in the top of the deposit
	SEM microtextural imprints suggest increased presence of percussion/mechanic marks
Palaeontological features (requires stratigraphical, palaeoecological and source analysis)	Marked changes in diatoms, foraminifera, ostracods, nannoplankton, pollen (usually presenting either a chaotic assemblage or a wider range of species and, in cases, offshore/nearshore species)
Geochemical signatures (requires source analysis)	Increase inf Cl, Na, Mg, Ca, K, SiO2, CaO, Cr, MgO, I, Fe, S
	Increases in the ratios of SiO2/Al2O3, CaO/Al2O3
	Increase in carbonate content (shell)
	Subtle variations in source-sensitive elements: K/Rb, La/Sm and Hf/Ta
	Enrichment in Cu, Pb, Zn or, in contrast, dilution of anthropogenic elements
Geomorphological aspects (requires regional context)	Multiple breaching of dune systems or individual overwash fans
	Dune ridges and sand dune pedestals
	Landward sand sheets
	Hummocky topography
	Parabolic dunes

Dawson 2007; Mamo et al. 2009; Sawai et al. 2009; Paris et al. 2010a; Ruiz et al. 2010). Although a site-specific component might be a central feature of any tsunami deposits some generalizations are possible interrelated with sedimentary structures, sediment source, palaeontological, geochemical and geomorphological signatures (Table 1.1).

1.5.1 Sedimentary Structures

In terms of sedimentological structures, an erosive/sharp/abrupt basal contact is a common feature and is symptomatic of the energy involved in the emplacement of tsunami deposits. However, this criterion was also recognized in storm deposits (Switzer 2008). The sharp/abrupt/erosive contact of tsunamigenic layers were firstly described by Dawson et al. (1988) and Minoura and Nakaya (1991). Bondevik et al. (1997), analysing evidences lay down by the Storegga tsunami in Norway, detected that the tsunami deposit rest on an erosional unconformity which in cases has removed more than 1 m of underlying sediment. Moreover, Nanayama et al. (2000) observed deposits that resulted from the 1993 Hokkaido-nansei-oki (Japan) tsunami and identified distinctive sharp erosional bases in the tsunamigenic unit. Gelfenbaum and Jaffe (2003) analysed the erosion and sedimentation associated with the 1998 Papua New Guinea tsunami and observed that the beach face and berm showed no evidence of deposition from the tsunami. However, on the berm, exposed roots and scour at the base of some palm trees indicated erosion of approx. 20–30 cm of back-beach sand and they observed that only erosional signatures had been left by this tsunami to the landward side of the berm, up to about 50 m from the shoreline. Chandrasekar (2005) described erosion of up to 2 m over large tracts of beach associated with the return flow of the 2004 Indian Ocean tsunami. In Thailand, Szczucinski et al. (2005) and (2006), Hori et al. (2007) and Fujino et al. (2009) observed an erosive sharp basal contact between the tsunamigenic and the underlying layers. Choowong et al. (2009) also noted that during the same event, erosion and deposition occurred mainly during two periods of inflow and that the return flow was mainly erosive. Paris et al. (2009) described erosion associated with the 2004 Indian Ocean Tsunami in Banda Aceh (Indonesia) that extended up to 500 m inland. These authors quantified the overall coastal retreat from Lampuuk to Leupung as of the order of 60 m (*ca.* 550,000 m^2) and locally in excess of 150 m. The erosional impact of tsunamis is still controversial, not only the recognition of associated patterns in the sedimentary record, other than the erosive base and quantification of the amount of sediment removed but also the mechanisms and processes associated and responsible for the erosional/depositional balance during a tsunami. In fact, Bahlburg and Spiske (2011) analysing the sedimentary record of the February 2010 tsunami at Isla Mocha (Chile) observed that the tsunamigenic unit was produced essentially (i.e. >90 %) by the backflow. These authors suggest that due to the lack of sedimentary structures, many previous studies of modern tsunami sediments assumed that most of the detritus were deposited during inflow and an uncritical use of this assumption may lead to erroneous interpretations of palaeotsunami magnitudes and sedimentary processes if unknowingly applied to backflow deposits. Typically tsunami deposits present sediment size that can vary from mud to boulders and, in many cases, grain-size variation in tsunami deposits is controlled by the size of sediment available for transport, rather than by flow capacity (Bourgeois 2009) or direction.

The detection of sedimentary structures is limited by sampling methods because coring (which is frequently used), in contrast to trench excavation, is in general destructive. Sedimentary structures are also difficult to identify in tsunami deposits due to the common deposition as massive deposit (e.g. Dawson et al. 1995; Dahanayake and Kulasena 2008). However, there has been several tsunami deposits where sedimentary structures including *laminae* (e.g. Reinhart 1991; Bondevik 2003), rip-up clasts (e.g. Dawson 1994; Shi et al. 1995; Hindson and Andrade 1999; Bondevik et al. 2003; Gelfenbaum and Jaffe 2003; Goff et al. 2004; Morton et al. 2007; Paris et al. 2009), cross-stratification (e.g. Choowong et al. 2008) and soft-sediment deformation (Matsumoto et al. 2008) have been observed. Muddy laminae or organic layers can represent evidence for multiple waves of the tsunami wave train (e.g. Reinhart 1991; Bondevik 2003). Furthermore, loading structures at the base of the deposit have been reported in literature (e.g. Dawson et al. 1991; Minoura and Nakaya 1991; Costa 2006; Martin and Bourgeois 2012).

Another peculiar feature observed in many tsunamigenic deposits worldwide is the enrichment in bioclasts or shells (many of them broken) when compared with the under and overlying layers (e.g. Bryant et al. 1992; Albertão and Martins 1996; Imamura et al. 1997; Clague et al. 1999; Donato et al. 2008) and in cases platy or prolate shell fragments occur aligned suggesting a ghosty lamination (e.g. Dawson et al. 1995; Hindson et al. 1996; Hindson and Andrade 1999). For example, Clague and Bobrowsky (1994) observed that tsunami sand deposits commonly include fragments of bark, twigs, branches, logs and other plant material. Moreover, Donato et al. (2008) showed that shell features could be used as useful indicators of tsunamigenic deposit due to their vertical and lateral extent, to the allochthonous mixing of articulated bivalve species (e.g. lagoonal and nearshore) out of life position, and to the high amount of fragmented valves, with angular breaks and stress fractures. The authors suggested that the taphonomic uniqueness of tsunami deposits should be considered as a valid tool for tsunamigenic recognition in the geological record.

The sedimentological fingerprint of currents associated with tsunami events have also been observed in the form of parallel lamination, cross-lamination, convolutions and ripple-marks (e.g. Shiki et al. 2008). Moreover, Morton et al. (2007) detected palaeocurrent indicators in tsunami deposits indicating seaward return flow. In deposits laid down by the 2004 Indian Ocean tsunami, in Thailand, Choowong et al. (2008) observed capping bedforms and parallel *laminae*, cross-lamination, rip-up mud and sand clasts. The authors also observed normal grading but some reverse grading was locally recognized. According to Choowong et al. (2008) reverse grading in tsunami deposits indicates a very high grain concentration within the tsunami flow, and was possibly formed at the initial stages of inundation in shallow water. Cross-bedding was seen as restricted to return-flow sediments