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Review

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Progress in the Study of Coastal Storm Deposits

Haixian Xiong[1,3], Guangqing Huang[2]*, Shuqing Fu[2], and Peng Qian[4]

[1]*Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China*
[2]*Guangzhou Institute of Geography, Chinese Academy of Sciences, Guangzhou 510070, China*
[3]*University of Chinese Academy of Sciences, Beijing 100049, China*
[4]*School of Geography, Nantong University, Nantong 226007, China*

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Abstract – Numerous studies have been carried out to identify storm deposits and decipher storm-induced sedimentary processes in coastal and shallow-marine areas. This study aims to provide an in-depth review on the study of coastal storm deposits from the following five aspects. 1) The formation of storm deposits is a function of hydrodynamic and sedimentary processes under the constraints of local geological and ecological factors. Many questions remain to demonstrate the genetic links between storm-related processes and a variety of resulting deposits such as overwash deposits, underwater deposits and hummocky cross-stratification (HCS). Future research into the formation of storm deposits should combine flume experiments, field observations and numerical simulations, and make full use of sediment source tracing methods. 2) Recently there has been rapid growth in the number of studies utilizing sediment provenance analysis to investigate the source of storm deposits. The development of source tracing techniques, such as mineral composition, magnetic susceptibility, microfossil and geochemical property, has allowed for better understanding of the depositional processes and environmental changes associated with coastal storms. 3) The role of extreme storms in the sedimentation of low-lying coastal wetlands with diverse ecosystem services has also drawn a great deal of attention. Many investigations have attempted to quantify widespread land loss, vertical marsh sediment accumulation and wetland elevation change induced by major hurricanes. 4) Paleostorm reconstructions based on storm sedimentary proxies have shown many advantages over the instrumental records and historic documents as they allow for the reconstruction of storm activities on millennial or longer time scales. Storm deposits having been used to establish proxies mainly include beach ridges and shelly cheniers, coral reefs, estuary-deltaic storm sequences and overwash deposits. Particularly over the past few decades, the proxies developed from overwash deposits have successfully retrieved many records of storm activities during the mid to late Holocene worldwide. 5) Distinguishing sediments deposited by storms and tsunamis is one of the most difficult issues among the many aspects of storm deposit studies. Comparative studies have investigated numerous diagnostic evidences including hydrodynamic condition, landward extent, grain property, texture and grading, thickness, microfossil assemblage and landscape conformity. Perhaps integrating physical, biological and geochemical evidences will, in the future, allow unambiguous identification of tsunami deposits and storm deposits.

Keywords – storm deposits, depositional process, sediment provenance, paleostorm reconstruction, coastal wetland, tsunami deposits

*Corresponding author. E-mail: hgq@gdas.ac.cn

1. Introduction

Coastal storms such as tropical cyclones (hurricane or typhoon), winter fronts and sea storms, previously perceived as disturbances based on anecdotal reports, have been recognized as major agents in coastal and shallow-marine sedimentation, resulting in storm deposits. As the products of meteorologic, hydrodynamic, sedimentary and ecologic processes, storm deposits have proven to be excellent research objects for studying coastal sedimentation dynamics (e.g. Hamblin et al. 1979; Dott and Bourgeois 1982; Walker 1984; Aigner 1985; Duke et al. 1991; Xu 1997; Li et al. 2002), for the management and restoration of coastal wetlands (e.g. Guntenspergen et al. 1995; Turner et al. 2006; Cahoon 2006; Elsey-Quirk 2016), for the reconstruction of paleoenvironment and paleostorms (e.g. Liu and Fearn 1993; Elsner et al. 2000; Donnelly et al. 2001a, 2004; Liu et al. 2001; Fan and Liu 2008; Lambert et al. 2008; Das et al. 2013; Degeai et al. 2015), and for the comparison of different event deposits (e.g. Dawson and Shi 2000; Nanayama et al. 2000; Morton et al. 2007; Pomar et al.

2012).

Numerous studies have been devoted to storm deposits since the 1960s when storms were first observed to transport shelf sediments (e.g. Hayes 1967; Ball et al. 1967; Perkings and Enos 1968). The 1970–1980s witnessed a research boom in the field of ancient tempestites with the focus on the morphology and origin of hummocky cross-stratification (HCS) (e.g. Harms 1975; Hamblin et al. 1979; Bourgeois 1980; Kreisa 1981; Dott and Bourgeois 1982; Leckie and Walker 1982; Walker et al. 1983; Swift et al. 1983; Aigner 1985; Brenchley 1985). The technical development of subaqueous observation and sampling after the mid-1980s facilitated the investigation of modern storm deposits, yet without finding the modern analogs of HCS-like sequences (e.g. Aigner 1985; Gagan et al. 1988; Snedden et al. 1988; Hill and Nadeau 1989; Hequette and Hill 1993; Siringan and Andersen 1994; Huang 2000). Meanwhile, the study of tsunami deposits gradually received attention from geologists, but they soon recognized that it was tough to distinguish between sediments deposited by storms and tsunamis (e.g. Atwater 1987; Nanayama et al. 1998, 2000; Dawson and Shi 2000; Goff et al. 2004; Morton et al. 2007). Over the past few decades, interdisciplinary methods, such as numerical simulations, flume experiments, microfossil assemblages, and geochemical indicators, were introduced to provide diverse information on the nature of storm deposition. The scope of these types of study also extended to include coastal wetland sedimentation (e.g. Guntenspergen et al. 1995; Turner et al. 2006; Cahoon 2006; Elsey-Quirk 2016), and paleotempestology which has become one of the most successful applications regarding storm deposits (e.g. Liu and Fearn 1993; Collins et al. 1999; Donnelly et al. 2001a; Liu 2004; Nott 2004; Lamb et al. 2006, 2008; Donnelly and Woodruff 2007; Fan and Liu 2008; Woodruff et al. 2009; Sabatier et al. 2010; Das et al. 2013; Degeai et al. 2015).

Despite the fact that two books have overviewed storm deposits in China (Xu 1997; Li et al. 2002) and several review papers were devoted to paleotempestology (Nott 2004; Fan and Liu 2008), storm effects on coral reefs (Harmelin-Vivien 1994), coastal wetlands (Cahoon 2006), tsunami deposits (Dawon and Shi 2000) and internal-wave deposits (Pomar et al. 2012), there has been no recent review specifically centered on storm deposits in the wake of large numbers of case studies having been published. In the future, the study of coastal storm deposits will remain a research focus since coastal areas located near highly populated cities will likely experience increasing cyclone activity and intensity under climate change and global warming conditions. The objective of this review is to provide a well-organized guide for those interested in coastal deposits associated with storm events. Here, the study of storm deposits and its recent progress are summarized in the following respects: issues related to the origin of storm deposits, sediment provenance analysis, the role of storms in coastal wetland sedimentation, paleostorm reconstruction based on storm deposits and distinguishing storm deposits from tsunami deposits.

2. Issues Concerning the Origin of Storm Deposits

Storm deposition varies widely among different coastal environments. From backshore, tidal flat, estuary, shallow sea to inner shelf, storm deposits have different forms and are generated by distinct hydrodynamic and sedimentary processes interlinked with multiple geological and ecological factors (see Fig.1a). Therefore, complexities and uncertainties surround the origin of storm deposits. Many questions remain to be answered regarding the genetic link between storm agents and storm deposits from these environments.

In backshore, beach ridges and shelly cheniers (Wang 1998; Li et al. 2002), overwash deposits in coastal depression settings (Liu and Fearn 1993) and storm deposits in coral reefs (Yu et al. 2004; Fig. 1b) are generally attributed to storm surge-induced set-ups, overwash and inundation processes under the constraints of coastal configuration and sediment material. Onshore storm surges may deposit anomalous sediments characterized by coarser grain size and marine material above local high-tide level, which can be directly observed. Morton et al. (2007) described overwash processes in sandy coasts as: (1) gradual inundation of the beach with attendant beach and dune erosion, (2) overtopping of dunes or berm crest where dunes are absent, and (3) deposition of perched fans or an overwash terrace. Nevertheless, several coastal high-energy events may induce overwash processes, including winter storms, tropical cyclones, tsunamis, or other hydrodynamic agents. This means that there usually exist non-unique explanations regarding the origin of ancient overwash deposits. Comparative studies of common event deposits will help resolve these ambiguities (see Section 6).

Storm sequences formed on tidal flats are prone to late tidal reworking and are less likely to be preserved. Even when preserved, the sequences are always incomplete. Many field investigations immediately after storms have attempted to unveil the intact storm-generated stratigraphy on tidal flats.

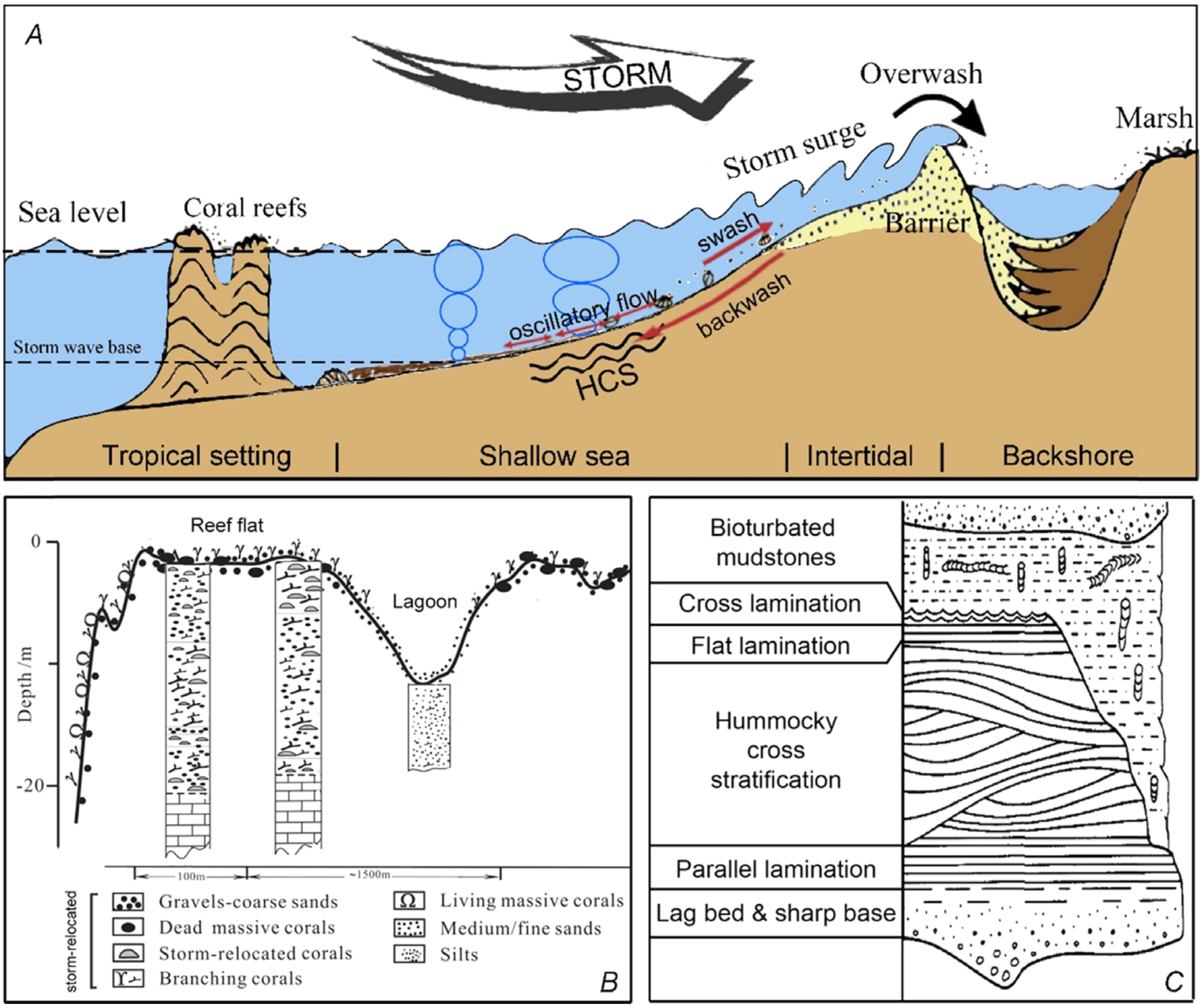

Fig. 1. (A) shows several sedimentation dynamics of storm deposits from backshore to shallow marine environments and in tropical coral reefs (modified from Liu 2007). (B) describes typical storm deposits in an atoll reef (modified from Yu et al. 2004). (C) displays a representative model of vertical storm sequence in underwater setting proposed by Walker et al. (1983)

Li and Li (1995) set up observation piles along high, middle and low tidal flats on the southern Yangtze Delta, China, to observe sedimentary processes during fair weather conditions and typhoons. The results indicated that micro- and small-scale sequences are both basic units of tidal flat deposits. A small-scale sequence consisting of a sand layer and a mud layer represents a storm sequence, with a sand layer indicating a storm event and a mud layer presenting fair weather. After a series of observations before and after a strong typhoon within the Caojing shoal in the northern Hangzhou Bay, China, Xu et al. (1984) proposed a sedimentation model: when a typhoon arrives, the storm surge entrains numerous solid materials, violently eroding the seabed and forming a sharp basal contact overlain by a lag deposit. After the landfall, the hydrodynamic energy gradually dissipates, successively forming parallel stratification or reverse sand-wave cross-bedding, HCS, ripple cross-bedding and traction bedding. Measurement of slope profiles after a winter storm from an open-coast tidal flat, South Korea, showed that the HCS became smaller onshore (Yang et al. 2006). This study confirmed that HCS was formed by a type of orbital wave ripple and HCS wavelength was controlled by the bottom orbital diameter (Yang et al. 2006). Unfortunately, these field observations did not actually observe during-storm sedimentation but compared sedimentary characteristics before and after a storm, with the formation mechanisms being inferred.

Hydrodynamic conditions are complex within estuarine bays with land-sea interactive processes from tides, waves, ocean currents and fluvial discharge. The wide combination of these processes hampers the interpretation of estuarine storm sedimentation, which has been examined in relatively few estuaries (e.g. Davis et al. 1989; Xu et al. 1997; Huang 2000). The Holocene stratigraphy of two estuaries from the Gulf coast of Florida presents hurricane-related facies in three types: A) fining upward layers formed by landward transport of shelly sediment; B) thin homogenous shell layers formed primarily by reworking bay sediments; C) fluvial facies by runoff due to extreme rainfall (Davis et al. 1989). Sedimentological and foraminiferal records presented by Huang (2000) suggest that the storm sedimentation within the Pearl River Estuary is a complex process including: (1) wave-induced erosion and resuspension of the estuarine substrate that cause shell gravel concentration on the sea bed forming bioclastic storm beds; (2) widespread exchange of suspended sediments between the estuary and the open shelf by wind-induced currents, and (3) offshore bed-load transport of terrigenous sediments by storm-surge ebbing currents that form siliciclastic storm beds. Although the author argued the preservation of storm beds is better in estuarine-deltaic environments than in deep water because the sedimentation outpaces bioturbation, storm beds are seldom found in the Holocene sequence of the Pearl River Estuary compared to the historical record and instrumental record, suggesting that many storm deposits are not preserved. Furthermore, no modern case of the formation model described by Huang (2000) has ever been found in the estuary. For this reason, many cores will have to be examined from the estuary to obtain a better understanding of the formation and distribution of storm deposits.

Since Harms et al. (1975) first described and defined HCS (see Fig. 1c), it has become one of the most recognized storm-related structures from intertidal or shallow subtidal to outer-shelf settings. Much has been studied about its morphology and origin from the late 1970s to the 1990s (e.g., Dott and Bourgeois 1982; Brenchley 1985; Duke et al. 1991; Cheel and Leckie 1993). Because HCS has not actually been observed to form, the question of what sedimentary processes lead to the formation of HCS remains controversial. The form that of HCS takes is highly variable, as noted by Cheel and Leckie (1993), and has been divided into three types (scour-and-drape, accretionary, and migrating), suggesting that there are possibly several different formation mechanisms required for HCS to form. The mechanisms proposed can be categorized into three types: pure oscillatory flow (Dott and Bourgeois 1982; Walker et al. 1983), unidirectional-dominated combined flow (Allen 1985; Southard et al. 1990), and oscillatory dominated combined flow (Harms 1975; Duke 1985). It is generally believed that HCS originates from oscillatory currents under large storm waves. The extent to which unidirectional currents are dominant in the formation has been the focus of considerable speculation (e.g. Southard et al. 1990; Duke et al. 1991; Cheel and Leckie 1993), but flume experiments suggest that the conditions required for HCS formation must be oscillation dominated (Arnott and Southard 1990; Dumas et al. 2005). HCS varies enormously in form and size due to many environmental factors including water depth, slope gradient, grain size or bedform, which have not been evaluated systematically.

Despite the fact that the role of hydrodynamics in HCS formation has been fully recognized, we still need more evidences to determine whether the HCS formative cause is a tropical cyclone, tsunami or other coastal events, all of which may generate similar processes required for HCS formation. For example, Pomar et al. (2012) postulated internal waves as one of the most plausible processes to cause the formation of HCS and HCS-like structures because they fit with the HCS depositional model proposed by Duke et al. (1991) and meet the formative conditions postulated by Dott and Bourgeois (1982) in terms of bathymetric position, large waves and relative event frequency.

HCS is not the only type of subaqueous storm deposit formed in shallow-marine or shelf environments, due to the spatial variability of hydrodynamic conditions and sediment availability. Further studies have presented several storm-driven depositional processes different from that of HCS. By the comparison of observations and simulations, Fan et al. (2004) proposed two shelf regimes on the northern California shelf: high-concentration regime and low-concentration regime. High-concentration regime occurs as a flood pulse passes seaward during successive storm resuspensions. During the low-concentration regime, fine sediments are winnowed out of the inner and central shelf and are mainly bypassed seaward. By measuring wave and suspended sediment concentration on the muddy inner shelf fronting Atchafalaya Bay, Louisiana, during Hurricane Claudette, Sheremet et al. (2005) found that storm waves and currents could resuspend large quantities of sediment and form a high-density fluid mud layer in the waning phase of the storm. Re-surveys of long-shelf sediment transport on the Great Barrier Reef shelf after the passage of Cyclone Winifred showed that mud was still settling from suspension five days after the cyclone, and large parts of the inner shelf were bathed in muddy river plumes, some of which reached 30 km seaward (Carter et al. 2009). These studies jointly indicate that fine-grained sedimentary dynamics is one of the major storm-related underwater depositional processes and plays a significant role in the sedimentation of continental shelves.

We are still left with the ongoing questions of how various storm deposits form. Future research into the formation issues needs to employ innovative ideas and improved techniques. Flume experiments can provide controllable conditions to test the variability of factors responsible for HCS formation. The next phase of flume studies needs to develop general depositional models to approximate storm-driven processes, and examine the effects of grain material and size. Numerical simulations can reproduce storm-related hydrodynamic and sedimentary processes on a regional scale. Field observations are indispensable to collect real data of storm processes and sample the storm deposits, which serve as definitive evidences to verify formation mechanisms proposed. The combination of simulations and field observations may help better understand how storm processes are linked to the resultant storm sediments. On the other hand, because many coastal hydrodynamic events can originate similar processes required for the formation of storm deposits, there exist uncertainties in the reconstruction of paleostorm activity from ancient sediments. Hopefully, sedimentary processes induced by any event are always accompanied by distinct geological and ecological effects which will leave imprints in the resultant deposits. By tracing and comparing these sedimentary imprints, it is likely that storm deposits can be distinguished from other event deposits (see Section 3 and 6).

3. Sediment Provenance Analysis of Storm Deposits

Source, transport and fate of sediment provide essential information to decipher sedimentary environments, deposition dynamics and ecological changes associated with storms. Recent years have seen a rapid growth in the number of studies that have utilized sediment provenance analysis to investigate the source and movement of storm deposits (e.g. Huang and Yim 1997; Hippensteel and Martin 1999; Lambert et al. 2008; Liu et al. 2008; Sabatier et al. 2010, 2012; Das et al. 2013; Degeai et al. 2015). Sediment provenance analysis, or sediment source tracing and fingerprinting in some contexts, is an approach to identify sediment sources and allocate the amount of sediment contributed by each source through the use of physical, chemical and biological properties as tracers, fingerprints or indicators with a combination of field data collection, laboratory analyses of sediments, and statistical modeling techniques (Walling 2005; Davis et al. 2009; Owens et al. 2016). In the study of storm deposits, the development of the source indicators, such as mineral composition (e.g. Sabatier et al. 2010), magnetic susceptibility (e.g. Degeai et al. 2015), microfossils (e.g. Huang and Yim 1997; Collins et al. 1999; Hippensteel and Martin 1999; Scott et al. 2003; Hippensteel et al. 2005; Liu et al. 2008; Hawkes and Horton 2012; Pilarczyk et al. 2014, 2016), inorganic geochemical indices (e.g. Sabatier et al. 2010, 2012; Degeai et al. 2015) and organic geochemical indices (e.g. Das et al. 2013; Lambert et al. 2008), has allowed for better understanding of depositional processes and environmental changes associated with storms.

For example, Sabatier et al. (2010) reported that the main sediment origin areas of the Lyon Bay lagoon are (1) the Mosson drainage basin with a high concentration of smectite reflecting erosion and reworking processes of ancient formations, and (2) the sandy barrier characterized by high contents of illite, chlorite. Using the clay mineral composition, this study showed that the ratio of smectite/(illite+chlorite) of storm layers in the lagoon is low, indicating that material of storm deposits was mainly derived from the sand barriers by overwash events likely induced by storm tides (Sabatier et al. 2010).

The magnetic susceptibility of sediment is related to the ferromagnetic mineral content in the sediment. Storm sandy layers in Salerno Bay, Italy, show high magnetic susceptibility, indicating that storm currents may transport magnetic minerals to this area (Budillon et al. 2006). In contrast, storm overwash layers in the Bagnas Lagoon display very low magnetic susceptibility because coastal dune barriers among the four source areas of sediments deposited in the lagoon show the lowest magnetic susceptibility (Degeai et al. 2015). To sum up, the sedimentary meaning of magnetic susceptibility of any storm deposit cannot be demonstrated without site-specific investigation of sediment sources.

The identification of storm sediments is commonly based on the recognition of anomalous deposits using diverse microfossils indicative of sediment provenance and sedimentary environments (e.g., Collins et al. 1999; Hippensteel and Martin 1999; Scott et al. 2003; Hippensteel et al. 2005; Hawkes and Horton 2012; Pilarczyk et al. 2014, 2016). Marine microfossils, such as foraminifera and halophilous diatom, are often present in overwash sediments due to the landward storm surge (e.g. Hippensteel and Martin 1999; Lane et al. 2011). While pollen (e.g. Liu et al. 2008) and phytolith (e.g. Lu and Liu 2005), commonly found in land environments, have potential as indicators of terrestrial impacts and environmental changes by storms.

For example, the foraminifera in the fair-weather sediment layers in the Pearl River Estuary primarily belong to an in-situ burial community (Huang and Yim 1997). In contrast, storm layers are presented by abundant allochthonous benthic and planktonic foraminifera from shallow or deep sea, indicating that storm sediments were transported over substantial distances (Huang and Yim 1997). Lane et al. (2011) inferred a storm origin for microfossil-bearing sands within a coastal sinkhole in Florida based on unusually high abundances of radiolarians and calcareous foraminifera that originated from at least 5 km offshore and were transported landward. Hawkes and Horton (2012) also inferred a nearshore to inner shelf provenance for the overwash sand layer generated by Hurricane Ike in 2008 on the coast of Texas. Diatom-based studies of storm overwash include Parsons (1998), who reported a multi-source origin for sediments deposited by Hurricane Andrew 1992 in Louisiana. The hurricane deposit consisted of diverse assemblages and a mixture of diatoms from marine, brackish, and freshwater settings, making it easily distinguishable from underlying autochthonous salt-marsh taxa. A pollen record of vegetation response to hurricanes over the past 1200 yr from a coastal lake in Alabama suggest that populations of halophytic plants (Chenopodiaceae) and heliophytic shrubs (Myrica) expanded after the hurricane strikes, probably due to saltwater intrusion into the marshes and soil salinization caused by overwash processes (Liu et al. 2008). The investigation of phytolith from a variety of coastal plant communities or depositional environments in the southeastern USA suggest that different coastal subenvironments can be distinguished by their modern phytolith assemblages, thus supporting the contention that the prehistoric sand layers characterized by phytolith assemblage of the sand dunes from Western Lake, northwestern Florida, were deposited from overwash flows eroding the sand dunes (Lu and Liu 2005).

Geochemical properties are generally more sensitive indicators of sediment sources, particularly where storm sequences are indistinguishable or absent (Sabatier et al. 2010; Das et al. 2013). Recent development of X-ray fluorescence spectrometry (XRF) has allowed the rapid detection and analysis of major and trace elements which allow for the spatial characterization of sediment sources to identify storm deposits through the use of multivariate data analysis such as principal component analysis and cluster analysis (e.g. Woodruff et al. 2009; Sabatier et al. 2010, 2012; Degeai et al. 2015; Raji et al. 2015). For example, principal component analysis of a geochemical dataset that consisted of sixteen elements established a very good method to distinguish between the coastal sandbars, which are characterized by higher contents in Sr and Cl, and the terrestrial sediments sampled in the watershed of the Bagnas lagoon or in the Holocene floodplain of the Herault River (Degeai et al. 2015). Therefore, the strontium may represent a tracer element of detrital flux from the coastal barriers by storm surges (e.g. Woodruff et al. 2009; Degeai et al. 2015). Based on a similar analytical approach, Raji et al. (2015) identified extreme sea events (storm or tsunami) from lagoonal sedimentary layers in the northeast of Morocco with high Sr/Fe ratios and coarser grain size indicating marine intrusions into the lagoon.

In contrast to inorganic properties, organic geochemical indicators such as C%, N%, C/N, $\delta^{13}C$ and $\delta^{15}N$, have also been utilized to provide a more comprehensive and detailed assessment of organic matter (OM) sources and post-storm ecological changes in depositional environments. The variability of C% and N% in sediments probably results from changes in lake productivity, which is mainly controlled by temperature fluctuations and nutrient flux (e.g. Meyers 1994, 1997; Lamb et al. 2006). Changes in C/N ratios, $\delta^{13}C$ and $\delta^{15}N$ likely reflect variations in the proportion of OM derived from terrestrial versus freshwater versus marine environments (e.g. Meyers 1994, 1997; Lamb et al. 2006; Lambert et al. 2008; Das et al. 2013). In the Holocene strata of the Yangtze River delta, $\delta^{13}C$ of sand-dominated layers was more positive than that of overlying mud-dominated layers and C/N ratio was smaller, suggesting that sand-dominated layers of storm origin have higher marine organic matter component of storm-surge input than the overlying post-storm muddy deposits of normal estuarine facies (Fan and Liu 2008). The most common method for reconstructing paleostorm history is to identify and count overwash deposits in sheltered coastal lakes which are presented usually by readily recognizable sandy layers (e.g. Liu and Fearn 1993; Liu et al. 2008), or by less visible storm laminae which are distinguishable from organic geochemical proxies (e.g. Lambert et al. 2008; Das et al. 2013). To interpret the potential of organic geochemical proxies to identify storm signals in the lake sediment, Lambert et al. (2008) proposed a model stating that a coastal lake has two contrasting states: (1) an "isolated" state under which the lake system is isolated from the adjacent sea and characterized by the normal lake environment with low nutrients and low $\delta^{13}C$ and $\delta^{15}N$; and (2) a "flooded" state under which the lake is subject to marine flooding caused by storm waves washing over the coastal barrier and characterized by a marine-like environment with higher $\delta^{13}C$ and $\delta^{15}N$. The organic geochemical approach was further tested and applied to similar coastal lakes in the Gulf of Mexico by Lambert et al. (2008) and Das et al. (2013) who noted that using any single geochemical parameter alone will lead to equivocal interpretations, but examining the patterns of the indicators can help ameliorate the ambiguity.

It is apparently, therefore, concluded that sediment provenance analysis has only been qualitatively applied in the above case studies of storm sediments. These studies have only answered where the storm deposits originated but rarely estimated how much each source contributed to the deposits. Plus, few researchers have provided insights into how storm sequences form with the rapidly changing sediment sources under storm processes. Sediment provenance analysis, or sediment fingerprinting, has served as an established quantitative approach in many studies of earth sciences (Walling 2005; Yellen et al. 2015; Owens et al. 2016), which will inspire the solution of many scientific issues in the study of storm deposits, such as the formational mechanisms and storm-induced environmental changes.

4. Role of Storms in Coastal Wetland Sedimentation

Coastal wetlands such as marshes and mangrove swamps provide diverse ecosystem functions including coastline stabilization, protection from storm surge and flooding, water purification, carbon sequestration, as well as having aesthetic, recreational and tourism value. Since coastal wetlands are vulnerable to impacts from sea level change and high-energy events, especially increasing hurricane landfalls, many studies have tried to assess the role of extreme storms in driving sedimentary processes and shaping coastal wetlands (e.g. Cahoon 2006; Turner et al. 2006; Smith et al. 2015; Leonardi et al. 2016; Elsey-Quirk 2016). The effects of storms on low-lying wetlands are often temporally and spatially variable depending on coupling factors of storm intensity, track, coastline elevation, landscape features and vegetation types (e.g. Guntenspergen et al. 1995; Donnelly et al. 2001b; Howes et al. 2010). Key effects include uprooting and removal of vegetation (e.g. Guntenspergen et al. 1995), scouring and erosion (e.g. Howes et al. 2010), deposition of sediments (e.g. Cahoon et al.1995) and organic debris (e.g. Mckee and Cherry 2009) onto the wetland surface, folding, tearing, and compression of the marsh (e.g. Guntenspergen et al. 1995; Cahoon 2006), and changing wetland elevations (e.g. Cahoon 2006).

Hurricane-induced sedimentation on coastal marshes in the Mississippi River delta has attracted great attention. It is reported that individual storms can deposit sediments three orders of magnitude higher than pre-storm deposition (Cahoon et al. 1995). Hurricane Katrina was implicated in leaving behind a 50-cm thick coarse-grained sand layer in a marsh along Bay Champagne (Naquin et al. 2014). River flooding and storm inundation are two contrasting pathways of sediments accreting onto coastal wetlands. It is important to know the quantities delivered by each pathway in order to understand how storms contribute to wetland accretion and stability. Rejmanek et al. (1988) reported that storm reworking often results in net sedimentation to the marsh surface while normal river flooding contributes little to the marsh accretion rate. Similarly, Turner et al. (2006) showed that the dominant pathway of inorganic sediments into the Louisiana coastal wetlands is from offshore to inshore during hurricanes, and not from overbank flooding of the Mississippi River, smaller storm events, or tidal inundations. Hurricane Katrina deposited 3-8 cm of organic sediment in two subsiding salt marshes in the Mississippi River delta, and this deposition aided in a net elevation gain of 0.7–1.7 cm when recorded two years after the event (Mckee and Cherry 2009). Therefore, sedimentation from hurricanes can often be greater than long-term annual accretion and may lead to long-term elevation changes (Nyman et al. 1995). However, hurricanes have been paradoxically identified as both substantial agents of widespread land loss, and vertical marsh sediment accumulation in the Mississippi River delta. Smith et al. (2016) indicated that over multi-decadal timescales, hurricane-induced sediment delivery may be an important contributor for deltaic wetland vertical accretion, but the contribution from hurricanes to long-term sediment accumulation is substantially less than present river-sediment delivery. Locally, vegetation structure can influence spatial variation in storm deposition. During

Hurricane Andrew in 1992, sediment accumulation in stands of *Juncus roemerianus* was almost two times greater than in stands of *Spartina alterniflora* associated with a greater stem density (Nyman et al. 1995). During the 2005 hurricane season, low salinity wetlands were preferentially eroded by the storm surge and wave field associated with Hurricanes Katrina and Rita, while higher salinity wetlands remained robust and largely unchanged because high salinity wetlands with deeper rooting have higher shear strength (Howes et al. 2010). Furthermore, it was reported that hurricane storm surges moved, tore and folded the intact marsh root mat along the coast of Louisiana as a result of Hurricane Lili in 2002 (Cahoon 2006). Apparently, much of what we study about the storm effects on coastal marshes is from the rapidly subsiding deltaic marshes of the northern Gulf of Mexico, especially the Mississippi River delta. Understanding such effects along other coastlines with frequent storm strikes is equally important as they are regionally variable and thus need site-specific study.

Mangrove swamps occupy a large area of the world's coastlines within tropical regions and have long been recognized for the many ecosystem services they provide. Soil build-up and sediment accretion under mangrove forests will occur as long as root production exceeds organic matter decomposition and thick mangrove peat can develop when sediment elevation continues to keep pace with local sea-level rise (Cahoon et al. 2003). Thus, their long-term stability depends on sustained favorable conditions for root production and organic matter accumulation. Frequent storm strikes will cause mass mortality of mangroves and collapse of substrates peat due to decomposition of dead root material and sediment compaction, leading to sediment elevation decreases (Cahoon et al. 2003). Descriptions of hurricane impacts on mangrove sediments have been reported many times in the literature (e.g. Cahoon et al. 2003; Smith et al. 2009; Smoak et al. 2013). But the role of storm-induced mass tree mortality and subsequent peat collapse in the sedimentation of mangrove swamps is unknown and requires further investigation.

In the short term, storms destroying coastal wetland deposits are often regarded as anomalous events. However, repeating storm attacks year after year may be perceived as regular geologic forces that result in the present nature of coastal wetlands. The recognition that storms play a pivotal role in sedimentation dynamics of coastal wetlands will help to develop better management and restoration guidelines.

5. Paleostorm Reconstruction Based on Storm Deposits

Paleostorm reconstruction based on proxies developed from storm deposits has numerous advantages over the instrumental record and historic documents as it allows for the reconstruction of storm activities on millennial or longer time scales and thus provides a longer-term picture of storm activities (e.g. Liu and Fearn 1993; Elsner et al. 2000; Donnelly et al. 2001a, 2004; Liu et al. 2001; Lambert et al. 2008; Das et al. 2013; Degeai et al. 2015). Development of paleotempestology has seen the methodology evolving from a single geologic proxy technique to multi-proxy techniques by integrating physical, chemical and biological properties to increase the diagnosis of storm deposits (e.g. Collins et al. 1999; Hippensteel and Martian 1999; Lu and Liu 2005; Lambert et al. 2008; Liu et al. 2008; Das et al. 2013). Storm deposits that can serve as agents to establish proxies mainly include beach ridges and shelly cheniers, coral reefs, estuarine-deltaic storm sequences and overwash deposits.

Beach ridges and shelly cheniers

A beach ridge or chenier is an elongated sand body running parallel to a shoreline that is composed predominantly of sand, mixed sand and shell, and shell fragments (Fan and Liu 2008). Although beach ridges are susceptible to late reworking by storm waves or regular waves, storm deposits accumulated above the storm erosion base may cement to form beach rocks (e.g. Wang 1998; Li et al. 2002), which may indicate paleo-storm activities. Many beach ridges are distributed along the coast of the Great Barrier Reef. The living reefs were struck and broken by storm waves, with many detritus transported shoreward and forming storm beach ridges (Nott 2004). The new ridge is deposited seaward of the previously emplaced ridge, separated with distinct sedimentary break from each other. Coral detritus derived from living reef are reliable material to date storm events (Nott 2004; Hayne and Chappell 2001). The intensity of paleostorms may be estimated through comparison of the height of an individual storm ridge with modern analogues plus numerical simulations (Nott 2003, 2004).

Storm deposits in coral reefs

Within tropical areas, coral reefs frequently suffer from strong cyclone attacks, resulting in mass disturbances to the reef ecosystem that is somehow preserved in deposits (see

Fig. 1b). Transported large coral blocks on reef flats and increased sedimentation rates in atoll lagoons were demonstrated to be excellent proxies for past strong storms in the southern South China Sea (e.g. Yu et al. 2004, 2009). By recognizing coarse-fraction storm deposits in the cores from the flat and lagoon, it is possible to use ^{14}C or uranium series dating methods to reconstruct paleo-typhoon activities. Strong storms can relocate large coral blocks from the reef-front living coral zone to reef flat, thereby the ages of the storm-relocated coral blocks should date such storms (Yu et al. 2009). Two problems should be answered with regard to such dating: (1) whether the coral to be dated is alive before transported by storms, and (2) whether the coral block suffer from secondary erosion after transportation (Zhao et al. 2009).

Estuarine-deltaic storm sequences

It was previously thought that storm deposits were barely preserved above the normal wave base (Walker 1984), especially in estuaries with complex hydrodynamic conditions. However, in spite of late reworking, deposits resulting from strong storms are likely preserved within the estuary with a large delta due to the high sedimentation rate (e.g. Huang 1998; Fan et al. 2002; Keen et al. 2004; Allison et al. 2005), which offers an opportunity to reconstruct a high-resolution paleostorm history. Using foraminifera assemblage as an indicator of storm deposits, Li et al. (2002) identified 17 storm layers in cores drilled from the submarine delta in the Pearl River Estuary. According to ^{14}C dating, the return period of the paleo-typhoons suggested by the storm layers is approximately 350 years and the storms were potentially category 4–5 hurricanes by the Saffir-Simpson scale; however, this was only a pilot study and the storm layers identified still need further investigation and assessment based on robust evidences.

Overwash deposits

The most appropriate sites for paleostorm reconstruction seem to be backshore topographic depressions such as lakes, lagoons or marshes with coastal barriers, which provide relevant geomorphic settings for transport and deposition of overwash material induced by storm surges through geologic time (e.g. Liu and Fearn 1993, 2000; Woodruff et al. 2008; Yu et al. 2009; Dezileau et al. 2011; Das et al. 2013; Degeai et al. 2015). For a given coast, the occurrence and return period of storms can be calculated by identifying and counting overwash deposits over a chronostratigraphic frame (e.g. Liu and Fearn 2000; Donnelly et al. 2001). Diverse methods have been applied to detect these overwash deposits in sedimentary sequences, such as sedimentological signatures (e.g. Liu and Fearn 2000; Sabatier et al. 2008, 2012; Parris et al. 2010; Dezileau et al. 2011), clay minerals (e.g. Sabatier et al. 2010, 2012), microfossil indicators such as foraminifera (e.g. Collins et al. 1999; Hippensteel and Martin 1999; Pilarczyk et al. 2014), diatom (e.g. Parsons 1998), pollen (e.g. Liu et al. 2008), phytolith (e.g. Lu and Liu 2006) and geochemical indices (e.g. Lambert et al. 2008; Woodruff et al. 2009; Page et al. 2010; Sabatier et al. 2010, 2012; Das et al. 2013). Over the past few decades, application of overwash deposits have successfully facilitated the reconstruction of storm activities during mid to late Holocene in the Gulf coast (e.g. Liu and Fearn 2000; Lane et al. 2011; Das et al. 2013), the western North Atlantic (e.g. Donnelly and Woodruff 2007; Parris et al. 2010), the central Pacific (e.g. Toomey et al. 2013), Southern Japan (e.g. Woodruff et al. 2009, 2015), Western Australia (e.g. Nott 2011), Northeastern New Zealand (e.g. Page et al. 2010), Northern Europe (e.g. Sabatier et al. 2012) and the Northwestern Mediterranean (e.g. Sabatier et al. 2010; Degeai et al. 2015).

Storm deposits have proved to be excellent information carriers of paleostorms for selected coasts to construct a record of storm events extending far beyond the instrumental and historical records. However, the attempts to infer the intensity of paleostorms from storm deposits are problematic and unconvincing due to the fact that storm deposits can only reflect the magnitude of storm surges, which is a function of various factors such as location relative to the storm track and coastal geomorphology besides storm intensity. Secondly, assessment of long-term storm variability using geological proxies such as microfossils may be limited by the lack of modern analogues. Thirdly, less is known and studied about post-storm reworking and preservation, which will decrease the reliability of paleostorm reconstruction. Lastly, but worthy of caution, storm deposits are readily mixed up with other event deposits. Accordingly, future studies should place an emphasis not only on the reconstruction of more paleostorm records but also on improving techniques such as (1) developing sedimentary proxies indicative of storm intensity, (2) understanding the origin, reworking and preservation mechanisms of storm deposits, (3) differentiating sediment deposited by different coastal events, especially for hurricanes and tsunamis.

6. Distinguishing Storm Deposits from Tsunamis Deposits

Cyclones and tsunamis are two of the most catastrophic and common coastal hydrodynamic events resulting in energetic and episodic sedimentation in coastal areas. As shown in Fig. 2, cyclones are the interactive products of the atmosphere and ocean, whereby cyclonic circulation and low barometric pressure combine to raise storm surges and generate destructive waves, leading to gradual and prolonged coastal inundation with storm flow depth commonly lower than 3 m and sediments transported primarily as tractive bed load that is deposited within a zone close to the beach (Morton et al. 2007). While in the subaqueous environment, storm-heightened waves and gravity-driven seaward flows can generate oscillatory-dominated combined flows that may form HCS-like structures (Duke et al. 1991) and high-concentration suspension loads that may deposit as mud beds in distal shelves (Fan et al. 2005). In contrast, tsunamis are generally generated by deep-ocean earthquakes, submarine landslides, volcanic eruptions, or asteroid impacts in the form of a chain of long-period, high-velocity waves that entrain sediment from coastal erosion zones to broad inland regions. Tsunami may have flow depth greater than 10 m, transport sediment primarily in suspension, and distribute the load over where sediment falls out of suspension when flow decelerates (Morton et al. 2007). In spite of their intrinsic difference, there are many resemblances in the hydrodynamic and depositional processes of storms and tsunamis, especially in areas above shoreface under flooding risks, making it one of the most awkward issues to distinguish between storm deposits and tsunami deposits (Dawson and Shi 2000).

Entering the 1990s, soon after numerous investigations of storm deposits, geologists started to pay attention to tsunami deposits and the comparison between tsunami deposits and storm deposits (e.g. Shi et al. 1995; Sato et al. 1995; Nishimura and Miyaji 1995; Dawson et al. 1996; Minoura et al. 1997). Liu and Fearn (1993) suggested that multiple sand layers in coastal lakes of Alabama were deposited by a series of hurricanes during late Holocene time. However, Davis et al. (1989) questioned whether hurricanes generated graded or homogeneous sediments of sand, shell, gravel and mud in Florida's lagoons with prominently clastic deposits. Dowson and Shi (2000) argued that tsunamis, in contrast to storms, generally deposit continuous and discontinuous sediment sheets over relatively wide areas and considerable distances inland, though storm surges in certain areas of the world (e.g. Bangladesh) reach many km inland (Hindson et al.

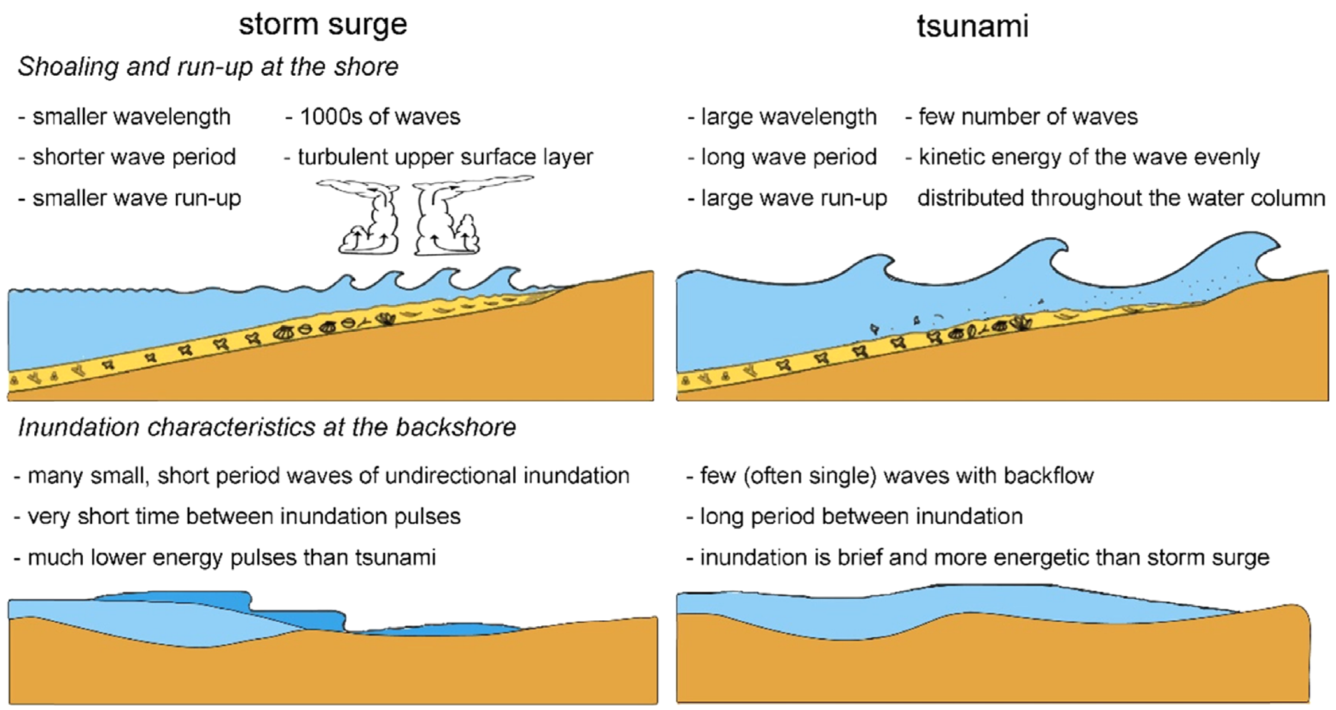

Fig. 2. Schematic summary diagram of different hydrodynamic characteristics of storm surge and tsunami at the shore and backshore (modified from Switzer and Jones 2008)

1996). A comparison study of modern tsunami deposits and storm deposits by Nanayma et al. (1998) noted that the storm deposits show better sorting than the tsunami sediments and that storm deposits only exhibit evidence of onshore current direction, whereas tsunami deposits are transported by both runup and backwash flows. One of the major effects of tsunamis on rocky coasts is the displacement of boulders from near shore to further inland, but few studies have clearly indicated whether such displacements were the result of tsunamis or storm waves (e.g. Goto et al. 2007, 2009; Paris et al. 2009; Bourgeois and MacInnes 2010) or storm waves (e.g. Scheffers 2006; Goto et al. 2009). Furthermore, tsunami deposits may contain distinctive microfossil assemblages that can be differentiated from those produced by storm surges (e.g. Dawson 1994; Dawson et al. 1996).

Several studies have attempted to investigate the difference in detail of sediments deposited by modern or documented storms and tsunamis. Nanayama et al. (2000) described the deposit associated with the 1993 Japan Sea tsunami and the 1959 Miyakojima typhoon in the same trench on the Hokkaido coast. Both deposits have the same thickness of 50 cm and thin landward within the trench. The tsunami deposit consists of four beds, showing evidence of bidirectional currents associated with land- and seaward flow of the two main waves and contains marine sand, gravel, seashells and eroded soil. In contrast, the storm deposit shows a unidirectional current, contains foreset bedding and is better sorted than the tsunami deposit. Another comparison of the 1929 tsunami deposit in Newfoundland and the 1991 Halloween storm deposits in Massachusetts by Tuttle et al. (2004) showed differences in the sedimentology and position of the two deposits. The tsunami deposit can be traced farther inland at a higher elevation and consists of one to three subunits of massive or normal graded sand, while the storm deposit shows lamination, delta foreset stratification and subhorizontal, planar stratification with channels. Goff et al. (2004) compared a storm deposit with the inferred tsunami deposit at the same site in New Zealand and found that they were different in aerial extent, thickness, and grain-size characteristics. The storm deposit is better sorted and extends about 40 m inland compared to 200 m for the tsunami deposit. The storm deposit shows a highly variable grain-size distribution with a marked coarsening at its landward extent, while tsunami deposit thins and becomes fine as it moves landward.

With data accumulating, many studies are attempting to establish systematic criteria for diagnosing and distinguishing storm deposits and tsunami deposits. Nelson et al. (1996) summarized the principal stratigraphic, sedimentological and palaeontological evidence for the occurrence of tsunami deposits synchronous with episodes of coseismic submergence. Goff et al. (1999) established diagnostic criteria for tsunami deposits using paleo-tsunami interpretations due to the shortage of studies of modern tsunami deposits as an acceptable sample size. After investigating known tsunami deposits at several coastal sites, Kortekaas (2002) concluded that most of the criteria proposed by Goff et al. (1999) also apply to storm deposits. Similarly, Sedgwick and Davis (2003) used a geographically limited sample of modern overwash sites to develop criteria for identifying storm deposits, but nearly all the criteria also apply to tsunami deposits and thus are not uniquely diagnostic of storm deposits. Morton et al. (2007) emphasized the use of physical attributes to differentiate between tsunami-emplaced and storm-emplaced sand deposits including sediment composition, textures and grading, types and organization of stratification, thicknesses, geometry, and landscape conformity. Other studies have favored the use of microfossil assemblages, pollen, heavy mineral, microtexture of grain surface and geochemical signatures as evidence of sediment sources for marine inundation and onshore sediment transport caused by tsunamis (e.g. Dawson et al. 1996; Goff et al. 1998; Tuttle et al. 2004; Pilarczyk et al. 2014; Costa et al. 2014; Bellanova et al. 2016) and storms (see Section 3). Perhaps integrating physical, paleontological and geochemical data will someday allow for the unambiguous differentiation of tsunami deposits and storm deposits (e.g. Morton et al. 2007; Ramírez-Herrera et al. 2012; Donnelly et al. 2016).

7. Summary

A great number of studies have focused on coastal storm deposits and many remarkable findings have been detailed since the 1960s when storms were first observed transporting shelf sediments. The 1970–1980s witnessed a research boom in the field of ancient tempestites with the focus on characterizing and interpreting HCS. Technical developments in subaqueous observation and sampling after the mid-1980s enabled the extensive investigation of modern storm deposits, yet without finding any HCS-like or graded sequences indicative of tempestites. Meanwhile, although the study of tsunami deposits has commenced and developed very rapidly, but it remains difficult to distinguish between sediments deposited by storms and tsunamis. Over the past few decades, interdisciplinary methods have been applied in the study field of storm deposits while the study scope has expanded to include coastal wetland sedimentation and paleotempestology which has become one of the most successful application of storm deposits

Multiple factors are involved in the origin of storm deposits, which make it difficult to decipher storm-related sedimentations in different coastal environments. Further research into the formation mechanisms should put an emphasis on quantitative approaches, such as laboratory physical experiments, field observations and numerical simulations. Recent developments in source tracing techniques, such as mineral composition, magnetic susceptibility, microfossils, and geochemical properties, have led to rapid growth in the number of studies utilizing these indicators to investigate sediment sources of storm deposits. It is highly important to understand the role of extreme storms in the sedimentation of low-lying coastal wetlands that provide diverse ecosystem services. Many investigations have attempted to quantify widespread land loss, vertical marsh sediment accumulation and wetland elevation change induced by major hurricanes. Paleostorm reconstruction based on storm sedimentary proxies has many advantages over the instrumental record and historic documents as it allows reconstruction of storm activities on millennial or longer time scales. Storm deposits that have been used to establish proxies mainly include beach ridges and shelly cheniers, coral reefs, estuary-deltaic storm sequences and overwash deposits. Particularly over the past few decades, overwash deposits have successfully provided established proxies for recapturing storm activities during the mid to late Holocene worldwide. Distinguishing between sediments deposited by storms and tsunamis is one of the most awkward yet one of the most important issues in the study of storm deposits. Comparative studies have investigated numerous diagnostic evidences including hydrodynamic condition, landward extent, grain property, texture and grading, thickness, microfossil assemblage and landscape conformity. Perhaps integrating physical, biological and geochemical data will someday allow for the unambiguous identification of tsunami deposits and storm deposits.

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