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COASTAL TSUNAMI GEOMORPHOLOGICAL IMPACTS AND SEDIMENTATION PROCESSES: CASE STUDIES OF MODERN AND PREHISTORICAL EVENTS

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Abstract: The study of coastal flood risk is of considerable interest to engineers, planners and politicians. Tsunami represents one of the most potentially serious forms of coastal flood risk. This paper reviews recent advances in research into geomorphological impacts and sedimentation processes associated with tsunami inundation. Detailed geomorphological and sedimentological investigations made in the cases of the Flores Tsunami generated by 1992 Indonesian earthquake, the 1998 Papa New Guinea tsunami and the Holocene Storegga Tsunami caused by a catastrophic submarine landslide off Storegga, Norway at circa 8,000 yrs B.P. are selected here. Although much is known on occurrence of this type of catastrophic coastal flooding which may cause loss of life, widespread destruction of property, and of infrastructure and industrial installations, it is not widely known, as these case studies show that the extent of flooding and geomorphological impact vary significantly along a coastline. Estimating the impact of tsunami and the vulnerability of coastlines to these phenomena may assist in coastal zone planning and management decisions. This paper also presents a conceptual model of coastal tsunami sedimentation processes deduced from the case studies and outlines diagnostic features of tsunami deposits.

Key words: Tsunami, stratigraphy, Geomorphology, Sedimentation, Particle size distribution, Conceptual model

1. INTRODUCTION

"Tsunami" is the Japanese pronunciation of two iconographic characters of Chinese origin, namely "Jin" and "Bo", which stand for "harbour" and "wave" respectively. In the Chinese-speaking world, it is also known as "Haixiao", meaning "sea roaring". As Japan is strongly associated with this type of coastal phenomenon, the use of the term "tsunami" has been on a steady increase within the scientific community to describe a series of waves that travel across the ocean with exceptionally long wavelengths (up to several hundred kilometres between the wave crests in the open ocean). As the waves approach a coastline, the speed of the waves decreases as they are deformed within shallower water depths. During this process of wave deformation, the height of the wave increases significantly and as the waves strike the coastline they often cause widespread flooding across low-lying coastal areas and on many occasions cause loss of life and widespread destruction of property. Tsunami is frequently described in the media as tidal waves. However this term is completely wrong since tsunami has nothing to do with tides or weather.

2. METHODS

The case studies reviewed here are based on the detailed field and laboratory investigations, as outlined in a number of previously published accounts (see below). In the case of Flores and Papa New Guinea tsunamis, post-disaster field investigations were undertaken to observe and record geomorphological and sedimentological effects of the tsunami, whilst in the case of the Holocene Storegga Tsunami, observations by the authors and by a number of other researchers have provided the information for the accounts here. Field studies have included geomorphological mapping and coring, whilst laboratory work has included microfossil analysis, radiocarbon dating and particle size analysis made at fine-resolution contiguous intervals using a Malvern Laser Granulometer (Malvern Instruments, 1990).

3. CASE STUDIES

3.1 CASE STUDY 1. FLORES TSUNAMI

On 12th December 1992, 1:30 pm (05:30 GMT), a major back-arc thrust earthquake of magnitude Ms 7.5 took place offshore approximately 50 km north of Maumere, the capital of Flores Island (Fig. 1). Several minutes later, a large tsunami struck the northern coastline of

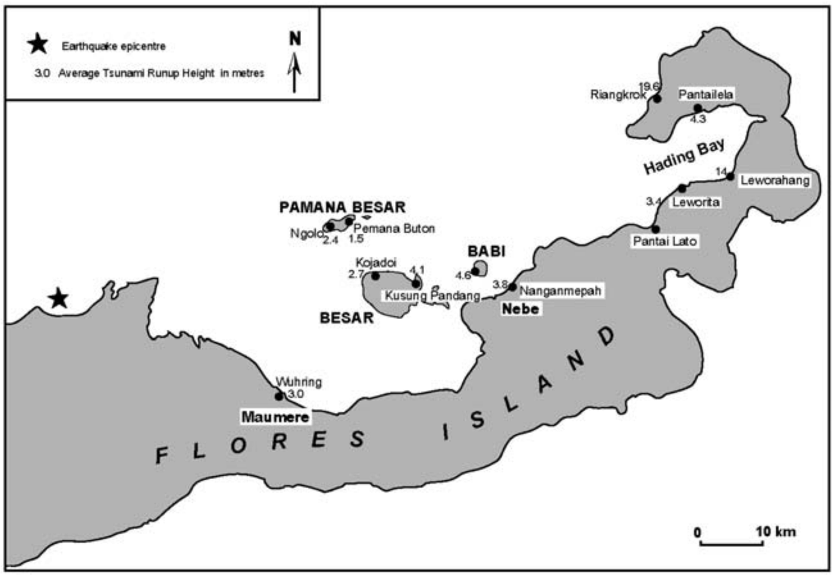

Fig. 1. Map of eastern Flores, Indonesia showing the sites where field observations were made. The numerical values denote the altitudes of mean tsunami runup (in metres) as measured by the International Survey Team (Yeh, et al., 1993)

Flores. The earthquake and associated tsunami caused significant morphological changes to northern coastal areas of Flores and adjacent islands. Most affected areas of the coastline were flooded by tsunami with runup values ranging between 1.5 and 4 m, whereas the runup was as high as 26m at Riangkrok due to underwater bathymetry and coastline configuration and the runup was 14 meters as a result of a local coastal landslide at Leworahang (Yeh, Imamura, Synolakis, Tsuji, Liu and Shi, 1993). Significant and widespread changes in the coastal lowland landscape are visually prominent and include destruction of properties, industrial facilities and natural landscape components such as mangrove and coconut trees by the hydraulic dragging forces of the tsunami currents and impacts from floating objects such as fishing boats and dislodged and transported artefacts. Large areas of vegetation including trees, bushes and grasses were destroyed by the tsunami waves. At most locations, the destruction is mainly attributable to the stripping-away of the soil surface as well as to the effects of saline water intrusion. Most severely affected areas of coastal lowland were the areas where incident tsunami waves concentrated. In areas where the tsunami currents were particularly strong (eg. Riangkrok and Babi Island), groups of trees were snapped off due to the hydraulic dragging force of the tsunami and only tree stumps remain visible. At Riangkrok, a "trim-line" between the vegetated hill-top and the bare lower slopes defines the upper limit of erosion, which is observed to be exceeded by the maximum level of run-up (26m). Hundreds of coral boulders (typically 1m in diameter) were deposited as far as 200 m inland (Yeh et al., 1993) while the maximum inundation distance extended as far as approximately 600 m along one river valley. Numerous coconut trees and ground vegetation were eroded during the tsunami runup and some debarked trees accumulated along the coast. At Babi Island, villages at the lee side of incident tsunami waves were destroyed and geomorphological and sedimentological effects were pronounced. The north shore which faces incident tsunami waves is protected by a wide coral reef. The south shore where the destroyed villages were located has a much narrower reef. Snapped off trees were deposited in a forested depression inland. At the other severely affected coastal areas where the runup values range between 1.5 and 4 m, geomorphological and sedimentological effects included dislodgement/erosion, transport and deposition of coral boulders, artefacts, broken slabs, uprooted trees and continuous and discontinuous sediment sheets. The tsunami resulted in very extensive coastal erosion and deposition.

Evidence of remarkable coastal erosion and retreat occurred at places along the northern coastal line of Flores Island. Coastal retreat, multiple sets of ephemeral erosional cliffs and lowered dark sandy soil ground surfaces due to erosion were frequently observable. The scale of geomorphological changes was found to be related to runup heights over a wide area. The extent of erosion was found to be conspicuously related to runup height. Where runup values ranged between 1 and 4 m, severe erosion was confined to a narrow strip along the coast, whilst erosion was much more extensive upon coastal lands in areas around Riangkrok where the average runup height was 26 m (Yeh et al., 1993). Superimposed upon the modified coastal land surface is an extensive sheet of coarse via medium to fine coralline sand that is succeeded farther inland by a discontinuous sand cover. Transported sporadic coral boulders and concrete slabs are also present and rest within the sediment. The distribution of the tsunami sediment is partly controlled by the sediment supply on the fringing coral reef coast and partly controlled by the topography of the coastal lowland. The maximum flood level indicated by affected vegetation is in general much higher than the upper limit of the sediment lain down by the tsunami.

Cores and surface samples of the tsunami sediments as well as local sediments were obtained at selected sites (Nebe and Pantai Lato) and studied with the laser granulometer in the laboratory. At Pantai Lato, the sediment sheet is restricted close to the coastline and its thickness is as thin as a few centimetres. Surface samples analysed demonstrate a general landward fining. At Nebe, the local soil is composed of a mixture of sand, silt and clay and is characterised by multi-modal and broad particle size distributions. The tsunami sediment is composed of grey medium sand near the coast to grey fine sand farther inland forming extensive sediment sheets ranging in thickness from as much as 0.5 m down to a few centimetres. The mean particle size shows a general landward fining trend (Fig. 2). The tsunami sand sediment is very coarse and contains grit and pebbles at the base but does not display distinctive grading. Coarse clasts including sandy intraclasts or grits occur intermittently marking base levels of each fining upward sequence. The intraclasts are composed of friable dark sandy soil that closely resembles the local soil in appearance (Fig. 3). The analysis of contiguous samples (0.3 cm interval) of sediment cores shows that there are episodic fining-upward sequences and that the characteristics of particle size distribution change progressively from poorly-sorted multi-modal distributions to better sorted distributions within each fining upward sequence (Fig. 4 and 5). Within these, persistent subpopulations are identifiable within these compositional progressions and correspond to the particle size subpopulations of the local sandy soil.

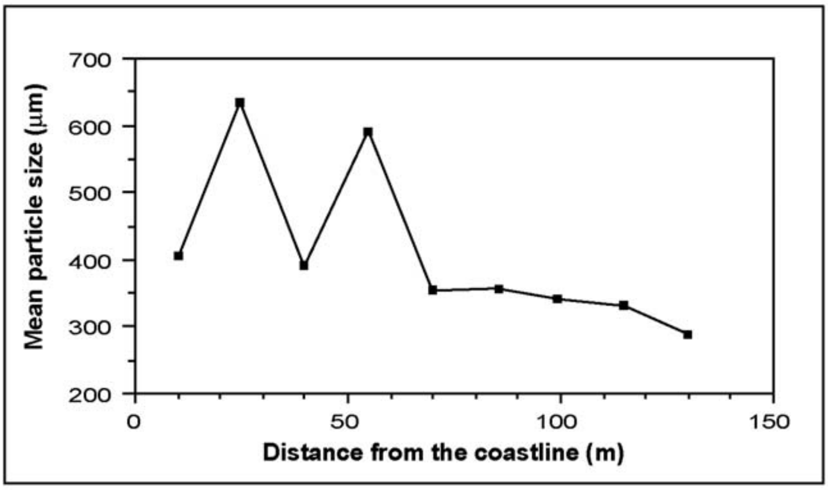

Fig. 2. Variations in mean particle size along a 130 m traverse perpendicular to the coastline at Nebe

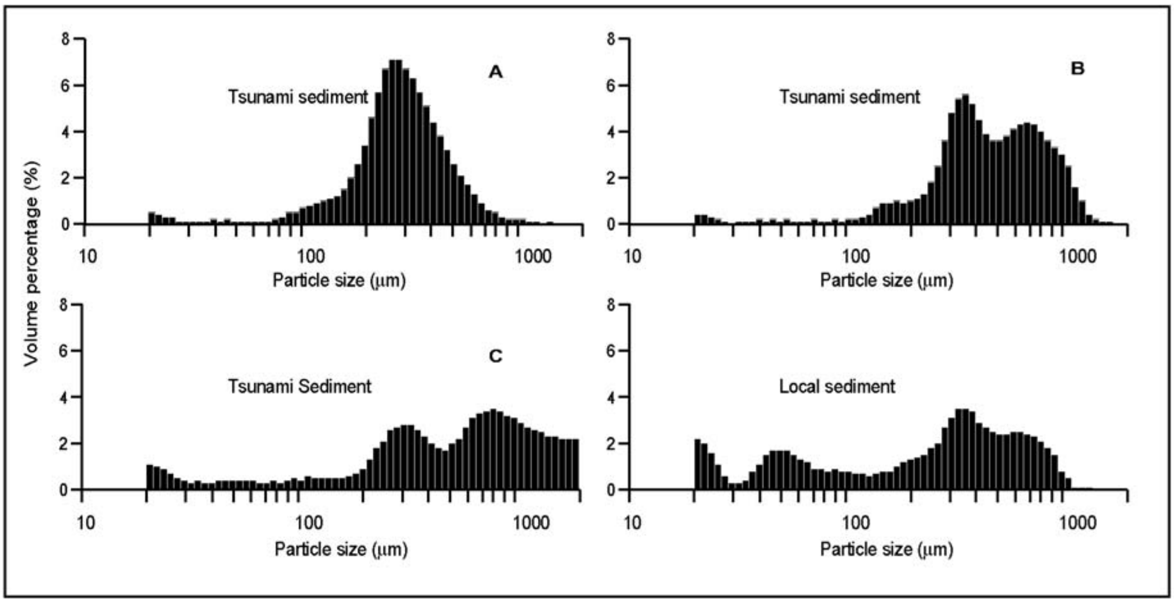

Fig. 3. Particle size characteristics of tsunami sediment and local source sediment within a core at Nebe. The positions of the samples are shown in Fig. 4

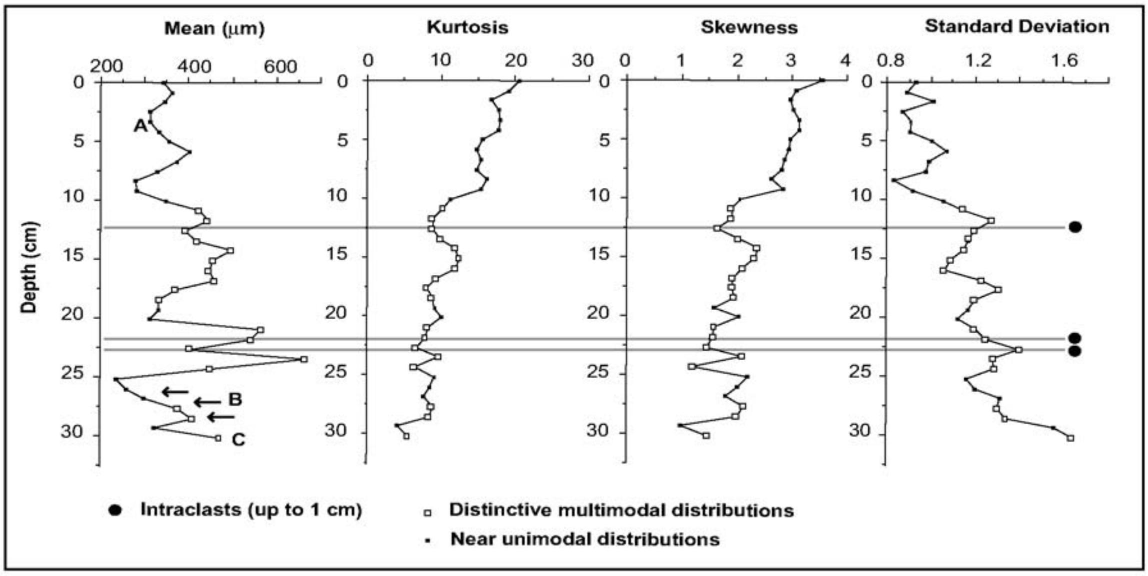

Fig. 4. Upcore variations in the parameters of tsunami sediment particle size distribution at Nebe. Letters A, B and C denote particle size distribution histograms shown in Fig. 3. The arrows point to positions of particle size histograms shown in Fig. 5

3.2 CASE STUDY 2. PAPUA NEW GUINEA TSUNAMI

The 17 July 1998 Papua New Guinea tsunami followed an earthquake offshore northern Papua New Guinea, and mainly affected an 80 km stretch of coastline from west of Sissano to east of Aitape. The greatest waves affected the coastline between the villages of Sissano and Wairapu (Fig. 6). Detailed geomorphological studies undertaken one year later between Wairapu and Arop examined the effects of the tsunami on this area of barrier coastline. Broadly, the main effects of the tsunami were in the transport of sand from the beach and nearshore areas, inland to form sand sheets of up to 20cm thick covering much of the landward side of the barrier. Additionally, sand accumulated on the seaward edges of trees but was often removed from the landward areas of the same trees. Observations on the height to which epiphytes were removed from trees indicate that tsunami waters reached heights of at least 7 metres above the sand sheets. Similarly, a separate study found that sand sheets deposited by the tsunami vary in thickness from 1 to 16cm and extend up to 700m inland (Gelfenbaum, Jaffe, Nongkas and Davies, 2001). In this study, surface samples were analysed and the result shows that the mean particle size decreased gradually inland from about 2-2.5 phi close to the shoreline to 3.5-4phi at the landward extent of the deposit. Skewness changed from negative to positive and increased with distance inland. This change suggests that the coarser sand was deposited closer to shore, whereas the finer material was uniformly deposited across the transect (Gelfenbaum et al., 2001).

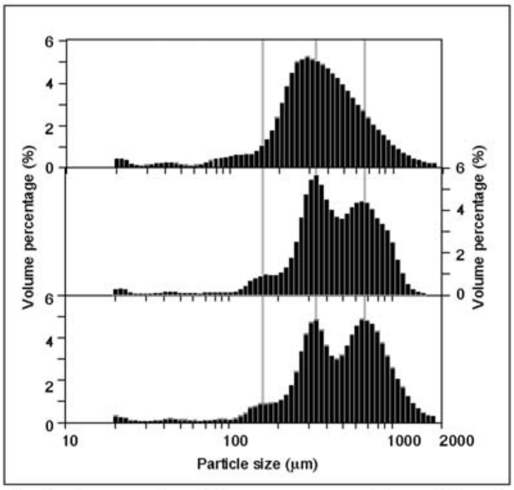

Fig. 5. An example of the upcore progressive variations in multi-modal distributions within tsunami sediment. Note that significant modification occurs at the coarsest end of the composite overall population

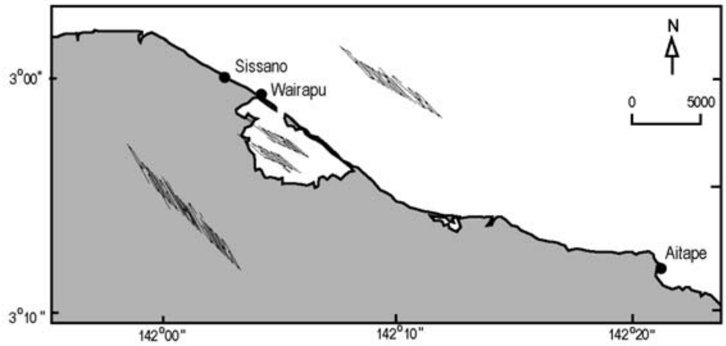

Fig. 6. Map of locations affected by the Papua New Guinea tsunami and mentioned in the text

3.3 CASE STUDY 3. HOLOCENE STOREGGA TSUNAMI

Approximately 8000 years ago, a submarine slide occurred on the continental slope and shelf off SW Norway (Bugge, 1983; Bugge et al., 1987; Jansen et al., 1987). This is believed to have generated a tsunami which inundated many coastal areas of Norway, the Faeroes, Iceland, N and E Scotland and NE England. Detailed studies of a widespread sand horizon in coastal sediments in Scotland provide evidence for the timing, magnitude and impact of the event. The evidence is so detailed that this palaeotsunami may actually provide information of value in assessing the vulnerability of modern coastlines to tsunami activity (Fig. 7).

Fig. 7. Location map of the sites where the Storegga Tsunami deposits are found

Stratigraphical evidence shows that a particular horizon of marine sand is intercalated within terrestrial coastal sediments and rises in elevation landwards. Along a long stretch of the NE coastline of Scotland and N England, this particular sand layer occurs persistently in estuarine silt and peat as discovered in various studies (Dawson et al., 1988; Long et al., 1989a and 1989b; Smith et al., 1992; Dawson and Smith, 1997 and 2000 and Smith et al., 1999). This sand layer occurs in a similar stratigraphical position at most coastal locations, as exemplified in Fig. 8. In the case of western Forth valley, this sand layer (*ca* 5 cm) can be traced over 1.5 km from the river towards the valley side (Sissons and Smith, 1965). Peat resting conformably upon the surface of the sand layer was dated at *ca* 6900-7500 radiocarbon years BP (Smith et al., 1980; Morrison et al., 1981; Haggart, 1982; Robinson, 1982; Smith et al., 1983). With many radiocarbon dates below and above the sand layer, these studies estimate that the age of the sand deposit falls into a broad agreement of dates within the range of 7000 – 7100 radiocarbon years BP (7800 – 8000 calibrated years BP). The microfossil content of the layer at sites examined (Dawson et al., 1996) shows that marine and brackish species predominate. The most prominent diatom is normally *Paralia sulcata*, which indicates the marine provenance of the sand layer. Several authors have remarked on the broken and eroded nature of the diatoms (e.g. Smith et al., 1985; Robinson, 1993; Dawson, 1999; Dawson and Smith, 1997; 2000). This characteristic contrasts with that for the diatom record in estuarine sediments below and above the layer where, although broken and eroded diatoms are often recorded in significant amounts in some horizons, such amounts are well below those in the sand layer. This is considered to be probably diagnostic of a high energy event.

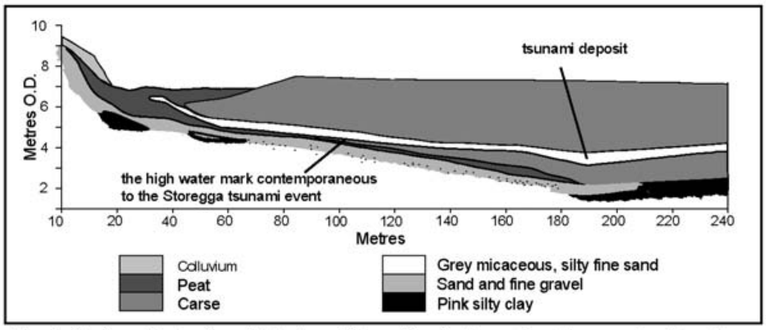

Fig. 8. Stratigraphical section at Fullerton, which contains the tsunami sand layer running through the former esturine deposit known as "carse" and up through into the peat deposit.

Studies of its sedimentology (e.g. Dawson et al., 1991; Shi, 1995; Bondevik et al., 1997b) revealed that the sand layer contains peat and silt intraclasts. Detailed particle size analysis undertaken by Shi (1995) revealed that there is a general landward fining of the sand deposit and progressive fining upward sequences of particle size. Andrade et al. (2000) and Smith et al. (2000) have maintained (on morphological and lithostratigraphical grounds) that the estuarine surface beneath the tsunami is inter-tidal and have maintained that the inner margin of this surface represents a shoreline. The sand layer of marine origin runs through the coastal sequences and its run-up values as calculated from the underlying former shoreline at the sites examined range up to 20 metres.

A corresponding sand layer has been found in isolation basins in southern Sunnmøre at Almestadmyra and Skolemyra, Norway (Svendsen and Mangerud, 1990; Bondevik, 1996 and Bondevik et al. 1997a and 1997b). In NW Iceland at Vestfirdir, a raised beach is attributed to the event (Hanson and Briggs, 1991). More recently, evidence for the tsunami has been described from an isolation basin on Suduroy in the Faeroe Islands (Grauert et al., 2001).

4. CONCLUSIONS

4.1 DIAGNOSTIC FEATURES OF TSUNAMI DEPOSITS

By drawing together the facts obtained in the case studies of modern and prehistorical tsunami events, diagnostic features of tsunami deposits are considered to include stratigraphical and granulometric evidence, conditions of microfossil preservation and presence of intraclasts of eroded sediment. These diagnostic features, as presented above, are considered to be of value for the identification of tsunami deposits in future studies.

4.2 CONCEPTUAL MODEL OF COASTAL TSUNAMI SEDIMENTATION PROCESSES

4.2.1 Coastal hydrodynamics of tsunami

Tsunami inundation is an ephemeral process and consists of several episodes of runup and backwash. The hydrodynamics of runup and backwash are characterised by turbulent flood currents rather than waves. During the runup phase of one episode of inundation, a large amount of energy transferred from the incident offshore wave is dissipated over the coastal topography through destroying, eroding and transporting solid materials as well as partly being reserved as a result of part of the water body being elevated. In the case of the Flores tsunami, examining the hydrodynamics of the runup processes further, there appears to be ample evidence, indicated by eyewitness accounts of the impact upon coastal areas, that tsunami waves broke far away from the coast (near the edge of fringing coral reefs), and turned into horizontal movements of turbulent water with great impetus, running across the near-shore zone to strike upon the coastal lowland. Theoretically, once a tsunami wave breaks, its impact can exert a tremendous force on objects and obstacles, scouring and carrying a large amount of material in its path.

Immediately following the wave ebbing offshore, backwash taking place due to the gravity of the elevated water body (or a pressure gradient), is also erosive and transported materials offshore. Both processes of runup and backwash are turbulent in a strict hydrodynamic sense. As the backwash was weaker than the runup, accumulation of sand sheets on land takes place. However, where the runup is exceptionally high and the energy of the backwash flow particularly strong, there is little trace of deposition of sand deposits but extensive erosional features and deposition of boulders.

4.2.2 The Role of the Source Sediment

Although there is difficulty in quantifying and interpreting the relative contributions of specific sediment sources, there are ample indications that the source of sediment for tsunami deposition is largely drawn from local coastal sediment in these case studies. The particle size distributional characteristics of the sediment are found to be dependent on the characteristics of its source material and the processes of transportation and deposition. The source material is composed of particles, which cluster into several size ranges forming subpopulations. The subpopulations in the sand range are readily identifiable in the tsunami sediment and this compositional characteristic imposes significant controls upon the resulting characteristics of the tsunami sediment. Modification of the transported sediment has also conceivably occurred as a result of differential transportation and sedimentation of different sized grains. The significant difference in composition between the source sediment and tsunami sediment indicates that a large amount of clay and silt has been removed and transported into the sea. In addition to this, other modification or sorting processes of particle size composition associated with transportation and deposition are conceptually derived from the granulometric evidence and are given in the following respective sections.

4.2.3 Deposition Processes

The inherited multi-modal characteristics of the tsunami sediment clearly reflect that sedimentation takes place rapidly and that particles of different sizes settle out together but at different rates. Some of fine particles settle out with coarse particles together. This is well illustrated by some of the individual fining-upward sequences of typical multi-modal distributions which consist of consistent sand subpopulations. Progressive compositional variation of the sediment within such fining upwards sequences indicates that the modal positions of subpopulations occur within consistent size ranges and the coarsest fraction fines and decreases in proportion upwards. Such a variation trend registered in the sediment indicates that the coarsest particles were progressively decreasing in concentrations in the transporting water body when sedimentation took place.

4.2.4 Tsunami Runup and Backwash

Tsunami inundations consist of both run-up and backwash and both contribute to processes of reworking, transporting and depositing sediment. The occurrence of a multiple set of fining-upwards sediment sequences clearly indicates that there are net accumulations of sediment resulting from different episodes of run-up and backwash. Separate suites of sediment with different granulometric characteristics are identifiable.

4.2.5 Lateral Sorting

The general trend of fining landwards is undoubtedly a result of differential transport. Landwards dispersion of sediment produced a landwards fining trend. The compositional characteristics of the sediment vary laterally. This indicates particles were subject to differential transportation. Finer particles travelled further in the transporting water body than the coarser ones.

In summary, the sorting process of the source material can be conceptually understood as having occurred in two different ways. Primary sorting is represented by the removal of a large amount of clay and silt by tsunami backwash. Secondary sorting resulted in further modification of the material during the tsunami transportation and sedimentation. Variability in the particle size histograms is most pronounced at the coarsest end of particle size distribution within the tsunami sediment. At present, distinction between the sediments deposited by run-ups and backwashes is not fully understood.

5. ESTIMATING THE IMPACT OF TSUNAMI AND THE VULNERABILITY OF COASTLINES

The Flores study demonstrates that the vulnerability to coastal tsunami flooding and magnitude vary significantly along a coastline. Lowlying areas such as valley floors, areas where offshore protection is poor or where underwater bathymetry focuses flow tend to be prone to higher flooding impacts.

Mathematical modelling methods utilising wave equations and bathymetrical data have been applied to estimate the likely magnitude and run-up of the Storegga event (Harbitz, 1992; Henry and Murty, 1992) and preferred values provided by these authors for eastern Scotland only marginally exceed observed sediment run-up, especially when the effects of post-depositional sediment compaction are taken into account. Recently, a new approach involving estimation of sediment settling rates has been used to estimate Storegga tsunami run-up. This approach uses equations developed by Gibbs et al. (1971) for settling rates in still water, by taking into account the salinity and dynamic viscosity (which varies with temperature) of the water and the size and specific gravity of the sediment, likely settling rates for the range of particle sizes in the tsunami deposit. As tsunami is not still water, this method allows an estimate of the minimal possible flood level. It is concluded that tsunami run-up exceeded sediment run-up by several metres at the Scottish sites (Smith et al., 2003).

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