Sedimentary features of tsunami deposits – their origin, recognition and discrimination: an introduction

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Abstract
The occurrence of numerous, recent, large tsunami suggests that they are a common natural event, yet tsunami deposits in the geological record are rare. This apparent anomaly may be due to a real infrequency of events and/or poor preservation potential but alternatively may be due to misidentification. Robust criteria for the discrimination of tsunami deposits from other sources such as storms is still lacking, establishing these criteria is essential if we are to improve our understanding of tsunami frequency over geological timescales. By this means we will improve the identification of tsunami hazard and improve risk assessment. This special issue focuses on tsunami deposits, identifying their characteristics and their discriminating features from other sources such as storms. Although perhaps not as common as other 'event' sediments, it is considered likely that a reappraisal of the geological record is required to place them in their representative context.

Keywords: *Tsunami, sediments, geological record, risk assessment*

Recent catastrophic tsunamis such as that of Papua New Guinea in 1998 when over 2,000 people died and the more recent devastating Indian Ocean event when the losses were an almost unbelievable 237,000 have focussed attention on tsunami and their hazard. One impact of the recent catastrophic events is the increased scientific attention on tsunami hazard, with studies on the resulting sediments providing an improved understanding of their distinctive sedimentary character that is applied to the identification of historic and prehistoric events.

Deposits laid down from tsunami are one type of episodic or 'event' sediment the most common of which are turbidites with other, less common, examples being storm deposits and tempestites. Of these event sediments those from tsunami are perhaps most uncommon, and there are a number of explanations for this. It may be that they are indeed infrequent. Their rarity may also be explained by their limited preservation potential because of the coastal environment in which they are laid down. Alternatively, it may be because of the continuing problem of their recognition because of their similarity to sediments laid down by other mechanisms such as storms.

When we consider the number of recent tsunami events, their rarity over geological timescales becomes somewhat suspect. Most notable recent events are those of Krakatoa volcano in 1883 when 60,000 lives were lost, Sanriku, Japan in 1896 when over 30,000 died, Peru in 2000 when 2,500 died, 1992 on Flores Island (close by to the recent July 2006 Java event) with fatalities of 2,000, Papua New Guinea in 1998 when over 2,000 people died and the more recent devastating Indian Ocean event when the losses were 237,000. These events resulted in a recognisable sedimentary signature supporting the contention that our interpretation of the geological record may be suspect. Consideration of the various causative mechanisms of tsunami, which include, earthquakes, volcanic collapses and eruptions, as well as submarine and subaerial landslides, supports this view. These processes take place in different geological environments, which range from passive to convergent margins, and from deep to shallow waters. There are thus numerous and geographical widespread tsunami sources, which might be expected to result in a more common long-term record.

Because of their scarcity, the contribution of tsunami deposits to the sedimentary record is considered to be very limited, and their real importance today lies in their use in hazard mitigation. Although we recognise the hazard from tsunami, without reliable data on event frequency it is impossible to develop realistic scenarios of risk and thus hazard mitigation. Mitigation strategies are obviously based on the nature and location of the hazard but to assess risk we also need to know event frequency. As noted by Morton et al in this issue, tsunami sediments may be subdivided into modern examples, those from the historic record and those from prehistory. Modern examples provide direct evidence of tsunami sedimentation, as the source is known. Historic records at best extend back only several thousands of years and only in certain countries such as Japan and Turkey where they may only be useful in identifying earthquakes (a common tsunami source) and sometimes, by association, tsunami. In most places however, records are far shorter, thus prehistoric data is essential and is only available by geological investigation. Even so prehistoric examples are mostly confined to the Holocene.

Thus to address the 'rarity' of tsunamis in the geological record, to better comprehend their contribution to the geological record and to improve our ability to discriminate them from other sources, thereby to improve hazard mitigation, we present this special issue. Here we bring together a collection of 16 papers contributed by scientists active in the field. These papers describe a variety of tsunami deposits from different geological locations, of different ages and in different environments. The idea for the issue predated the Indian Ocean event of December 2004 and thus has been a long time in preparation, most contributors being involved in fieldwork after the tsunami. Included here are field and modelling studies from Bermuda, New Zealand, Japan, North America, Papua New Guinea, Scotland and Portugal. Many focus on the critical issue of the discrimination of tsunami deposits from other causes such as storms, criteria essential in the identification of ancient examples in the geological record. The papers advance our understanding of the sedimentary processes of deposition by both observation and modelling.

The organisation of the papers is somewhat anecdotal and is designed to provide a context for the science. The first paper, by Dawson and Stewart, provides an introduction to the processes of tsunami deposition, identifying the three main aspects of tsunami generation that makes the depositional process unique, source, propagation and runup. These authors also identify and discuss the little known process of traction flow, due to the return flow of the tsunami wave. They also identify the problems of identifying tsunami deposits in the geological record, due to both their limited preservation potential or an inability to differentiate tsunami from storm deposits.

The following papers by Morton et al and Kortekaas and Dawson identify and describe sedimentary criteria for distinguishing sandy tsunami deposits from those laid down by storms. Morton et al use four recent examples, two storm deposits from North America and two tsunami deposits, one from the Papua New Guinea event of 1998 and one from Peru 2001, to address this perennial problem. The paper is an excellent introduction to the hydrodynamic differences between tsunami and storm processes and relates these to the physical nature of the sediments. Although there are significant similarities between tsunami and storm sediments, there are also significant differences, particularly of internal stratification that both relate directly to the mechanisms of deposition and allow discrimination. A surprising aspect of the paper is the acknowledgement that few storm deposits are recognised in the geological record, and few published articles on recognition of storm deposits (e.g. Sedgewick and Davis, 2002). Kortekaas and Dawson discriminate between tsunami and storm deposits from the south coast of Portugal using grain size analyses and micropaleontology. The tsunami sand identified is the result of the Lisbon earthquake generated tsunami of 1755.

There follow four papers from New Zealand. The origin of large coastal boulders has been the source of much recent discussion, with the most likely sources storms or more controversially, tsunami. Kennedy et al present evidence, based upon field survey and optical luminescence dating, for a tsunami origin of boulders on the Otago coast of South Island, New Zealand emplaced during Marine Isotope Stage 5. De Lange and Moon present a field study from North Island, New Zealand based on a sand body that, by comparison with the adjacent beach sand, local geomorphology and an absence of alternative sediment sources, demonstrates the likelihood of deposition by a tsunami in the 15^{th} century. The dating is based on a combination of evidence from the deposit together with associated archaeological remains from dated Maori settlement activity and pumice from dated volcanic eruptions. The paper is innovative in that it uses ground-penetrating radar for the first time in mapping a tsunami sand body. Nichol et al describe another tsunami deposit from South Island also from the 15th century age. Their paper develops a conceptual model of earthquake related geomorphic change including subsidence, tsunami generation and renewed sedimentation caused by change in base levels. McFadgen and Goff continue the emphasis on New Zealand in the following paper in which they identify archaeological criteria that may be used to identify tsunamis in the temporal gap between the present and prehistoric past. In New Zealand the presence of the Maoris for over 700 years, with their abundant legends provides an opportunity for this approach. The use of archaeological evidence in these New Zealand studies provides a new methodology in its early stages of development.

There is a change in emphasis in the following two papers that address tsunami sedimentation along the convergent margin off eastern Japan. Nanyama et al present evidence for late Holocene tsunami inundation along the east coast of Hokkaido Island in northern Japan. The objective is to a gain an improved understanding of the recurrence of tsunamis in the region, and hence earthquake and tsunami hazard, preserved in sediment cores from a low-lying marsh area. They apply standard field procedures followed up by laboratory analysis of grain size, radiography and sediment peels together with environmental analysis based on pollen and diatoms with the age dating using tephrachronology and C^{14}. The tectonic background is complex and reflects the interesting interplay of long term subsidence, intermittent uplift and sea level fall from the mid-Holocene highstand at about 5-6,000 years; all taking place in a typical subduction zone environment in which there is intermittent rupture resulting in large earthquakes which create tsunami that inundate the local coast.

Fujiwara and Kamataki describe examples of submarine tsunami deposits from eastern Japan. As noted by Dawson and Stewart descriptions of these type of sediments are rare. The paper develops previous work in eastern Japan on a series of deposits preserved on coseismically uplifted terraces. Originally the sediment's tsunami origin was based on the relationship to the terraces (by age dating), coseismic uplift being the result of large earthquakes that caused tsunami. Here the author's base their interpretations of the sediments origin on a combination of internal features including, mud drapes, opposing palaeocurrent directions and coarse-grained interbeds. A lack of bioturbation is another criterion applied. The sediments are correlated with a tsunami waveform developed from a tide gauge record in the area of the deposits that the authors suggest explains the features observed. Although all the features described can be attributed to other causes such as storms or debris flows, it is their combination that leads the authors to their conclusion that they were laid down from tsunami.

In another paper from Japan, Noda et al investigate whether a moderate-sized tsunami left a discernable sedimentary signature on shallow marine sediments off of Hokkaido Island in Japan. The study is based on a pre- and post tsunami sediment samples which are analysed for grain size and microfossils (diatoms and forams). A tsunami hydrodynamic model is used to estimate flow velocities during the tsunami, which are then used to estimate bottom shear velocity and sediment entrainment. These data and numerical results are used to attribute the identified changes in bottom sediment to a tsunami origin. The data set presented is unique and of high quality and the modelling adds much to the paper.

As demonstrated by the previous studies, the biostratigraphy of tsunami sediments contributes significantly to the identification of depositional environment. Dawson present a local study that uses diatoms sampled from a known tsunami sand laid down by the 1998 event in Papua New Guinea to 'type' its marine origin. It compares the faunas laid down by the tsunami to intertidal species from the same location. The paper is brief and to the point and is an addition to similar studies from previous recent tsunami events. The faunas are sparse but seem to allow identification of the environments and are representative.

One on the seminal tsunami events is that of the Grand Banks in 1929 and in Moore et al analysis of sediment grain size of tsunami deposits from Newfoundland reveals interesting aspects of their generation and in detail provide evidence of sediment source and tsunami flow velocity and depth. A bimodal grain size distribution of the tsunami deposit that is attributed to two sediment sources, a finer-grained offshore source and a coarser grained one on the coast. Based on the shear stress required to transport the coarsest grains the tsunami flow velocity and flow depth have been calculated. Because the event is historical with survivor's accounts of these parameters, there is control on the accuracy of these figures.

Following on from Moore et al, the modelling approach is continued in Jaffe et al, who present a mathematical model for estimating tsunami flow speed based on the thickness and grain size of the sediment deposited by the tsunami. It validates the approach by using an example from the Papua New Guinea tsunami of 1998 and the result is a better understanding of tsunami impact for hazard mitigation. Historical and pre-historical field examples can be used to develop local scenarios. Several interesting conclusions fall out of the study; tsunami sediment thickness is not a reliable criterium for estimating tsunami flow depth, but sediment grain size and bulk grain size distribution both affect flow velocity. Deposit grain size is a better predictor of flow speed than deposit thickness. The model is a beginning, it is simple, and the authors suggest ways of improving it.

Smith et al present interesting new observations on relating tsunami flow depth to the settling velocity of sediment grains, based on an analysis of sediments laid down in northeast Scotland by the tsunami resulting from the Storegga landslide, 8,000 years ago. The paper also considers the reasons for the consistent nature of the sediment, including its' grain size, geographic distribution, stratigraphy and thickness. These characteristics are attributed to a number of factors including; a local sediment source, focussing of the wave within gullies, a heavily sediment laden water mass, decreasing turbulence with inland penetration, deposition only during run-up and a tsunami inundation depth of between 7.2 m.

Morton et al present a review of tsunami deposits along the Cascadia subduction zone, research into which has been seminal in developing our understanding of the origin of these sediments and their relationship to the Great earthquakes that occur in the region. This understanding forms the basis of tsunami sediment research globally.

The final paper by McMurtry et al addresses two controversies, the potential of tsunami generation from the collapse of intraoceanic volcanoes (such as the Hawaiian and Canary islands) together with the possibility that sea levels during Marine Interglacial Stage 11 (360,000 to 420,00 years BP) were significantly higher than those of today. The study is of intriguing deposits of calcareous conglomerates on Bermuda, in the western Atlantic Ocean, preserved in caves up to 21m above present sea level. Bermuda is regarded as stable over geological time scales and a 'dipstick' for measuring eustatic sea level. Facies analysis of the sediments indicates that, rather than being formed at sealevel (when this was much higher) their final deposition was due to a massive wave. As cyclones are not considered to be capable reaching such heights in the Bermuda region, the only alternative source is a tsunami. The most likely source is from eastern Atlantic, probably one of the intraoceanic island groups, probably the Canary Islands.

Acknowledgements
Thanks are due to all the authors who submitted papers and the reviewers who spent their time in painstaking effort improving the papers. Dave Tappin acknowledges the British Geological Survey (NERC) for their continued support in his work on tsunami hazard. He published by permission of the Executive Director of the British Geological Survey (NERC).

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