Reply to Bridge (2008) Discussion of articles in “Sedimentary features of tsunami deposits”

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Bridge (2008) draws attention to interesting issues and complications for identifying and interpreting tsunami deposits that were presented in several papers in Sedimentary Geology volume 200. Bridge first challenges the discrimination between tsunami and storm deposits (Morton et al., 2007a; Kortekaas and Dawson, 2007) and then questions the reconstruction of tsunami flow speed (Jaffe and Gelfenbaum, 2007) and depth (Smith et al., 2007) from deposit attributes. Our replies are presented in the same order that the papers are first mentioned by Bridge.

The comments and criticisms of Bridge (2008) regarding the guidelines presented by Morton et al. (2007a) are based largely on misrepresentations and invalid assumptions. Bridge narrowly focuses his discussion on a few trench-scale criteria, pointing out that there are exceptions to the criteria presented to distinguish between tsunami and storm deposits. However, he did not present quantitative data that would invalidate our conclusions. It is acknowledged that relatively thick tsunami deposits can exhibit planar stratification (Morton et al., 2007b, 2008) and storm deposits can contain mud intraclasts, but those are not the most common attributes observed and reported either from our investigations or in the published literature. Language such as “tends to be” and “may be” was deliberately used by Morton et al. (2007a) to connote caution and to make it clear that because of possible variability, no single criterion can be used unequivocally to distinguish between sandy tsunami and storm deposits. It was also specifically stated that a probabilistic approach based on average values or most-likely occurrences and the preponderance of evidence from multiple lines of inquiry would be necessary to make a reasonable interpretation regarding the origin of a deposit

Bridge (2008) incorrectly assumes that no peels were made of the tsunami trenches. Of the peels that were made of the 2001 tsunami deposits in Peru and 2004 tsunami deposits in Sumatra, some showed layering or planar stratification and others did not. The likelihood of stratification in tsunami deposits increases as bed thickness increases.

Bridge (2008) provides no evidence to support his statement that “There is absolutely no reason why storm-surge deposits should not contain mud intraclasts...” There must be a physical explanation why low muddy coasts are commonly lined with washover deposits composed of sand or sand and shell that rarely contain mud intraclasts. Two of the Hurricane Carla deposits (Matagorda Peninsula and Bolivar Peninsula, Texas) and one of the Hurricane Isabel deposits (Rodanthe, North Carolina) illustrated in Morton et al. (2007a) are located where the lower beach and upper shoreface are composed of mud, but the washover deposits contain no observable mud rip-up clasts. The muddy coast of the Mississippi delta is another well-known example where washover deposits rarely contain mud (Penland and Boyd, 1985). The ancient storm deposits with mud clasts that Bridge alludes to are interpretations, not unequivocal examples of storm-wave deposits like we and many others have investigated and described. In our opinion, clear differences between the hydrodynamics of tsunami and storm waves involve the number of waves and duration of erosion, transportation, and deposition. The few tsunami waves may erode, entrain, and deposit mud clasts because there is little time (minutes) for reworking and dispersion of mud. In contrast, storms generate many waves and the wave action persists for long periods (days), allowing for complete reworking and dispersion of eroded mud.

Bridge (2008) correctly points out that Morton et al. (2007a) only presented data for two hurricanes and two tsunamis, but he incorrectly implies that our database was limited to those four events. Together Morton, Gelfenbaum, and Jaffe have examined hundreds of trenches, exposures, and cores of modern storm and tsunami deposits. Furthermore, there is a vast body of literature on modern storm deposits and a growing body of literature on modern tsunami deposits that we have contributed to and that we incorporated into our summary statements and conclusions. We consider the results presented in our Table 2 to be representative of sandy deposits formed by extreme-wave events because they are consistent with attributes of deposits generated by other tsunamis and storms we have investigated and those published in the literature. Our view is that the comparisons we made are only the beginning of quantitative analysis relying on only the basic physical properties of sedimentary deposits. We can easily imagine future advances that incorporate other parameters and quantitative attributes from modern extreme-wave events to improve criteria for distinguishing between sandy storm and tsunami deposits.

Bridge continues by questioning the criteria used by Kortekaas and Dawson (2007) to discriminate between tsunami and storm deposits. Some of the observations that form the basis for the interpretation that the sediments most likely owe their origin to tsunami are a) the stratigraphic relationships with older and younger sediments along the Portuguese Algarve coast (Dawson et al., 1995b; Hindson et al., 1996) b) the occurrence of similar extensive sheets of sediment in the same stratigraphic position in every inlet that we have examined along the Algarve coastline c) the occurrence within the deposits of isolated boulders some of which exhibit bioerosional pits across their surfaces within which are found marine mollusca. While we do not expect Bridge to have been aware of conference presentations where we have provided lacquer peels of inferred (AD 1755) tsunami deposits in Portugal, we can verify that all lacquer peels plus all sedimentological investigations have shown that the tsunami deposits everywhere consist of massive sands (often containing isolated boulders) while nowhere that we have examined is there any trace of planar bedding (Dawson et al., 1995a; Andrade et al., 1998; Kortekaas et al., 1999).

We are familiar with scepticism from sedimentologists unfamiliar with the stratigraphy of tsunami deposits. However, we would point out that the suite of tsunami deposits associated with the AD 1755 Great Lisbon earthquake located along the Portuguese Algarve coast are, in the Kortekaas and Dawson's experience, some of the finest examples to be found anywhere. The differences in storm and tsunami deposits described in the paper are indeed found at Martinhal, SW Portugal. As stated in the paper, the characteristics of both tsunami and storm deposits in this area (as elsewhere) are dependent on local factors, such as available source material, bathymetry, coastal geomorphology and the depositional environment. All of these factors determine the sediment preservation potential.

Kortekaas and Dawson (2007) showed that distinguishing tsunami and storm deposits at Martinhal is indeed a challenge. Both microfossils and grain size analysis were inconclusive. At this particular site the only difference found were the boulders and intraclasts within the tsunami deposits. This does not mean that boulders and intraclasts cannot occur in storm deposits elsewhere (see Table 1 in Kortekaas and Dawson, 2007). It may indicate, however, that this particular site is sufficiently protected by its berm, dunes and beach for erosion to inhibit the deposition of boulders during storm events.

Bridge (2008) continues by questioning the approach of estimating tsunami flow speed from deposits using a simplified model (Jaffe and Gelfenbaum, 2007) and the reliance of the modeled portion of the deposit having formed by sediment settling out of suspension. Both theory and field observations support using the model for some reconstructions, but certainly not all.

Implicit in the Jaffe and Gelfenbaum (2007) model's ability to successfully produce deposits from suspension is that the sediment was suspended. Bridge points out that an explicit test was not performed—"Jaffe and Gelfenbaum do not attempt to check that all the sediment was in suspension, by calculating a suspension threshold criterion (ratio of shear velocity to grain settling velocity: Bridge, 2003)". We agree, that for clarity, such a test should be performed. A ratio of the shear velocity (U*) to the settling velocity (Ws) above 2.5 suggests that sediment will predominantly be transported in suspension, assuming that the coefficient of anisotropy reaches a maximum of 0.1 to 0.2 near the bed (Bridge, 2003). U*/Ws ranged from 6 to 75 for the curves in Figures 4 and 5 (Jaffe and Gelfenbaum, 2007) that show the relationship between grain size, tsunami deposit thickness, and tsunami flow speed. For the Papua New Guinea tsunami deposit, this ratio for the coarsest grains in the deposit (those most likely to be transported as bedload) was everywhere greater than 4. The range of shear to settling velocities is consistent with the sediment in both the idealized single grain size plots of Jaffe and Gelfenbaum (2007) and the observed field data being suspended.

A more rigorous test of whether a tsunami deposit formed from sediment settling out of suspension is to compare the measured vertical variation in grain size of deposits with those reconstructed by the model. This is an independent test in the sense that, although the model matches the sediment suspended in the water column with observed bulk grain size distribution for the normally graded portion at the top of the deposit (or for the normally graded portion at the top of a layer if the deposit is composed of multiple layers), the vertical distribution of suspended sediment settling need not create the observed grading. A good match between the reconstructed and observed normal grading is evidence for the deposit forming from sediment settling out of suspension. Figure 9 of Jaffe and Gelfenbaum (2007) shows that the upward fining of the reconstructed mean grain size matches well with the measured grading for a deposit created in the 1998 Papua New Guinea tsunami approximately 400 m landward of the shoreline (Gelfenbaum and Jaffe, 2003). The trends and magnitudes in vertical variation of predicted and observed sorting (average difference of 0.1 phi) and skewness (average difference of 0.2 phi) are also similar. The vertical variation in grain size is consistent with formation by settling from suspension. Deposition by bedload would not create a normally graded deposit with the same decrease in grain size higher in the deposit as observed unless the sediment source was fining with time in a complex manner that mimicked the observed grading.

This is not to say that normal grading cannot be created by bedload processes (Bridge, 2003; Bridge and Demicco, 2008a). However, the scale (lamina, layer, sequence) and details (tail grading or distribution grading [Middleton, 1967]) of grading can, and should, be used to further constrain the process of tsunami deposit formation (bedload vs. suspend load deposition). A very specific form of distribution grading is created when a deposit is formed by sediment settling out of suspension. This characteristic should be evaluated before applying the model to estimate tsunami flow speed from the normally graded portion of a tsunami deposit. As stated in Jaffe and Gelfenbaum (2007), “This model is not applicable under conditions where a deposit is not formed from suspension and should not be applied to such locations.”

Similarly, Smith et al. (2007) do not maintain that "all deposition from tsunamis is from settling from suspension as velocity and turbulence were decreased over time" as Bridge stated. They simply said that the depth of water in a tsunami deposit might be estimated from the size of the smallest grains to have settled individually, taking account of the regular pattern of deposition evident in the detailed textural studies, which they undertook.

The statement by Bridge that “most deposition (from bed load or suspended load) in natural environments generally occurs from spatially decelerating flows, and temporal deceleration plays a very minor role in deposition” is certainly true for thick deposits because temporal deceleration, which result in a decrease in the volume of sediment in the water column, can only contribute as much sediment as in the water column. In contrast, the quantity of sediment deposited by spatial decelerations is only limited by the time that they act and the strength of the transport gradient (Paola and Voller, 2005). For tsunamis, however, the transport time is limited (at most 10s of minutes for each half wave) and, where the wave is large, the capacity to charge the water column with sediment is significant because of the high flow speeds. Application of standard sediment transport formula for steady flow (Jaffe and Gelfenbaum, 2007) results in deposits 15 cm thick from temporal deceleration when flow speeds are 7 to 21 m/s for 0.1 to 0.5 mm sediment, respectively. These are very fast flow speeds, but not unreasonable. A flow speed of 5 m/s was determined by Particle Image Velocimetry analysis of video shot approximately 3 km inland in Banda Aceh during inundation of the 2004 Indian Ocean tsunami (Fritz et al., 2006); flow speeds were likely higher closer to shore where the tsunami was larger (Borrero, 2005). Matsutomi (in Kawata et al., 1999; Matsutomi et al, 2001) also estimated that tsunami flow speeds can be high, ranging from 5 to 19 m/s for the 1996 Irian Jaya and 1998 Papua New Guinea tsunamis, using a technique combining field evidence and Bernoulli’s principle.

It should be noted that spatial decelerations do indeed create portions of tsunami deposits as evidenced by spatial variability in deposit thickness and inversely graded or massive intervals at the base of layers. Tsunami deposits near the coast, a zone where tsunamis change from erosional to depositional flows, vary in thickness (e.g.; Jaffe et al., 2003; Moore et al., 2006; Bahlburg and Weiss, 2006). Tsunami deposits observed in Sumatra were thicker than expected from temporal decelerations in flow and have inversely graded intervals (Jaffe et al, 2006). Tsunami deposits also are observed to thicken in topographic lows (areas of spatial deceleration of flows) and thin over topographic highs (areas of spatial acceleration of flows) (Gelfenbaum et al., 2007). However, the statement by Bridge that "There is absolutely no evidence for uniform flows in tsunamis" is not borne out by the evidence for remarkably regular patterns of deposition over large areas, and may be inferred from the observations by Smith et al. (2004), which is based on hundreds of boreholes over a number of sites in eastern Scotland. If the effect of spatial decelerations on deposit thickness were significant, the deposit would thicken and thin (and grain size would increase and decrease).

The model developed in Jaffe and Gelfenbaum (2007) is based on numerous field observations and an explicit suggestion that reconstruction of tsunami flow characteristics from deposited sediment can sometimes be performed with a simple approach if certain assumptions are valid. In cases where the deposit is formed by sediment falling out of suspension, the simple model has proven to be valuable for estimating tsunami flow speeds. We agree, however, that a comprehensive sediment transport model for tsunami inundation will, in the long run, improve the ability to extract flow information from tsunami deposits. In the discussion section of Jaffe and Gelfenbaum (2007), a similar approach was suggested to improve the simple model, “Adding the ability to use grain size and thickness of deposits from multiple locations will generalize the model. A next generation model that evaluates sediment transport convergences and flow unsteadiness from the inland change in grain size of deposits will allow calculation of tsunami flow speed at locations where TsuSedMod is not appropriate. The cross-shore distribution of the volume for each grain size of the sediment deposited can also be used to constrain sediment fluxes, which has the potential to give information about the period of the tsunami that formed the deposit. As with using deposits from a single location, coupling a multiple location sediment transport model with an inundation model is a promising area of research for expanding the ability to interpret tsunami characteristics from the deposit it leaves behind."

Indeed more sophisticated models are needed that are applicable in a variety of hydrodynamic and sediment transport settings. Testing of existing tsunami sediment transport models and development of new models were goals of a tsunami sedimentology benchmark workshop held in April 2007 (Huntington et al., 2007). A second benchmark workshop that is planned for the future will provide an opportunity for others to join in the testing and development of tsunami sedimentation models.

In conclusion, the comments in Bridge (2008) point towards the need for continued research in the identification and interpretation of tsunami deposits. Although we disagree with many of his comments, we do acknowledge this need for continued rigorous testing of field data and model results.

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