Tsunami sediments and their grain size characteristics

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Abstract. Characteristics of tsunami deposits are very complex as the deposition by tsunami is very complex processes. The grain size characteristics of tsunami deposits are simply generalized no matter the local condition in which the deposition took place. The general characteristics are fining upward and landward, poor sorting, and the grain size distribution is not unimodal. Here I review the grain size characteristics of tsunami deposit in various environments: swale, coastal marsh and lagoon/lake. Review results show that although there are similar characters in some environments and cases, but in detail the characteristics in each environment can be distinguished; therefore, the tsunami deposit in each environment has its own characteristic. The local geological and geomorphological condition of the environment may greatly affect the grain size characteristics.

1. Introduction

Grain size analysis is one of the main parameters for tsunami deposits identification [1]. Most of paleotsunami studies use grain size in the analysis. Although grain size characteristics alone cannot be used to directly identify the paleotsunami, the general grain size characteristics of the studied tsunami deposits or paleotsunami is the important analogue for identification. Grain size characteristics of paleotsunami deposits reflect both the origin of the displaced sediment and the hydrodynamic conditions of sedimentation; therefore, paleotsunami (and tsunami) deposits usually display common characteristics with normally graded sand layers related to the decrease of the hydrodynamic energy during sedimentation [1]. Another common characteristic of paleotsunami are fining landward [2], poorly sorted [3], and the grain size distribution must not be unimodal [4]. As the tsunami deposits were the result of a complex transport and deposition processes, these common characteristics are overly simplifying the actual characteristics. Furthermore, the local condition, including the tsunami depositional environment, greatly affects the tsunami deposit characteristics. Here I review the sedimentological characteristics of tsunami deposit in various environments: swale, coastal marsh and lagoon/lake. In addition to summarizing the tsunami geology literature that describes the sedimentology analysis, the aim of this paper is to obtain a specific grain size characteristic in every environment. Another aim is to review the gaps in our understanding of grain size within paleotsunami studies.

2. Studies of tsunami deposits/paleotsunami that report grain size

Selected literatures are reviewed and summarized in the tables according to the environmental deposition from which the tsunami sediments deposited. Table 1 provides comprehensive selected literatures that describe sedimentology and grain size of tsunami deposits/paleotsunami in the coastal marsh environment. Literatures of the coastal lagoon/lake and in the ridge and swale environments are summarized in the Table 2 and 3, respectively. Besides the fact that the grain size characteristics of tsunami deposits are simply generalized no matter the local condition on which the deposition took place.
place, the study of grain size may be grouped into two. The first group is the grain size characteristics which are only visually observed without any laboratory analysis. The second group is the studies which performed grain size analysis.

| Table 1. Tsunami deposits/paleotsunami studies in the coastal marshes that report grain size. |
|-----------------|----------------|----------------------------------|
| No | Reference | Tsunami Age | Grain size characteristics |
|----|----------|--------------|-----------------------------|
| 1  | [2]      | 2010, 1960, 1835, 1751, 1445 CE | Laterally extensive and tabular sand beds, which thin or abruptly terminate landward. The deposits show fine upward, and well-sorted. |
| 2  | [3]      | older than 1769 | Chaotic sand, but the matrix shows a fining upward trend, extremely poorly sorted. Extend up to 400 m. |
| 3  | [4]      | 1929 tsunami | The deposit is bimodal distributed, fining upward and landward. |
| 4  | [5]      | Holocene tsunamis 6200 and 3600 BP | Upward fining sequences, significant lateral extent, uniform thickness, sharp lower and upper contacts. |
| 5  | [6]      | Holocene tsunamis | Thin and fine landward with local variation. |
| 6  | [7]      | Holocene tsunamis 13 layers up to 7300 years ago | Composed of medium to fine sand, silt, and clay. Thin landward trend. Normally graded. The sand sheets are often continuous or form sand lens. |
| 7  | [8]      | Six paleotsunami up to 3000 ya | Contain several distinct layers and rip-up clasts. |
| 8  | [9]      | 2010, 1960, 1751, 1575 tsunamis | The 2010 sand layer is mainly massive, with occasional weak, 1-cm-scale horizontal bedding. Distributed up to 2 km inland, thins inland. The older layers are composed of well-sorted, sand rip-up clasts. |
| 9  | [10]     | tsunamis during 5500 years ago 15 sand layers | Consist mainly of sand, muddy sand and mud cap. The sand includes granules and pebbles sized shell, sharp lower contact. The tsunami deposit commonly contains granules and pebbles. Consist of multiple beds. |
| 10 | [11]     | 0.3, 1.1, 1.3, 1.7, 2.5 Ka tsunamis | The sand sheets vary in thickness from 0.2 to 25 cm. Thin in the landward direction, consist of well-sorted sand, fining upward. Mud cap, rip-up. |
| 11 | [12]     | 4 tsunami up to 2100 BP | All four layers display internal stratification in the form of multiple sand-mud couplets. Progressively finer landward, fining upward. |
| 12 | [13]     | 1700, 1.2, 1.7 Ka 1960, 1575 | Deposits fine upward and landward. No rip-up clast. |
| 13 | [14]     | | The tsunami deposits seem thinning and fining landward, no analysis. |

| Table 2. Tsunami deposits/paleotsunami studies in the coastal lagoon/lake that report grain size. |
|-----------------|----------------|
| No | Reference |
|----|----------|
| 1  | [2]      |
| 2  | [3]      |
| 3  | [4]      |
| 4  | [5]      |
| 5  | [6]      |
| 6  | [7]      |
| 7  | [8]      |
| 8  | [9]      |
| 9  | [10]     |
| 10 | [11]     |
| 11 | [12]     |
| 12 | [13]     |
| 13 | [14]     |
|    |   |                                                                 |                                                                 |                                                                 |                                                                 |
|----|---|-----------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|
| 1  | [15] | 6 tsunamis                                                      | Two layers have been identified as relatively thin (about 10 cm)  | single massive and                                             | Structureless bed, abrupt erosional lower contact. The other layers are chaotic beds. |
|    |     | during 4000 BP                                                  | No clear result of grain size analysis.                           |                                                                  |                                                                 |
| 2  | [16] | 16 tsunamis                                                    | Mud rip-up clasts in a sandy matrix. Massive sand, well to        | moderately well sand is                                          | The most abundant facies within the facies association of sandy layers. This facies consists of brown mud cap. |
|    |     | during 5500 years                                              |                                                                  |                                                                  |                                                                 |
| 3  | [17] | tsunami ~1100                                                   | Sediment size varied so dramatically over short distances (both   | vertically and                                                  |                                                                 |
|    |     |                                                                |                                                                  | horizontally). Sediment size was determined visually.           |                                                                 |
| 4  | [18] | BP tsunami                                                      | Tsunami shell bed was more poorly sorted, heterogeneous than the  | lagoon sediments.                                              | Thinning and fining landward.                                    |
|    |     | 1945 tsunami                                                   |                                                                  |                                                                  |                                                                 |
| 5  | [19] | 740, 967, 1509                                                 | Fining upward and landward, but no clear or no quantitative grain size analysis.     |                                                                  |                                                                 |
| 6  | [20] | 6400 and 7300                                                  | The tsunami deposit ranges from sand and sandy gyttja, with rip-up clasts, wood   |                                                                  |                                                                 |
|    |     | BP tsunami                                                     | Fragments and thin sand layers. The graded sand tsunami deposit is 2–25 cm thick, and grades from coarse sand or gravel to medium and fine sand. The lower contact is sharp and discordant. The upper boundary is gradational. The massive sand is a 2–3 cm thick bed of moderately to poorly sorted with clasts. |                                                |
| 7  | [21] | AD 1960                                                        | Sandy layer with mud rip-up and a mud cap. Tsunami sands in the lake cores are well to moderately well sorted. The grain size distribution shows of a narrow symmetrical peak around 205 μm; 6 out of 11 samples have a very low secondary peak of silt size. Often have a sharp and erosional contact to the underlying gyttja. Unimodal silt and unimodal sand distributions. Landward fining and thinning ~ 2.5 km |                                                                  |                                                                 |
| 8  | [22] | 2004 tsunami                                                   | The tsunami deposits are 9 cm thick on average (up to 35 cm in the lagoon and up to 66 cm on the shore) and are composed mainly of medium sand with low mud content. The distribution of the tsunami deposits was limited to within 1 km from inlet. The deposits become thinner and finer grained with increasing distance from the inlets. Most of the tsunami deposits are massive, some show single/multiple graded bedding, parallel laminations defined by layers of heavy minerals, well-sorted sediment. |                                                                  |                                                                 |
| 9  | [23] | ~ 7000 BP                                                      | The tsunami deposits consist of sand or muddy sand, massive mud and finely laminated mud. The sand or muddy sand is fining upward and landward. |                                                                  |                                                                 |
| 10 | [24] | 7000 BP                                                        | The sand thins and decreases in grain size in a landward direction. Massive sand and |                                                                  |                                                                 |
Tsunami also graded. Moderately to poorly sorted sand with erosional base. The deposit is also in the form of coarse organic detritus with rip-up clasts, termed 'organic conglomerate'. The clasts of the organic conglomerate normally have an irregular form and are commonly from 0.5-6 cm across, but may also be larger (at least 20 cm).

| No | Reference | Tsunami Age | Grain size characteristics |
|----|-----------|-------------|----------------------------|
| 1  | [25]      | 2004, 1000-1200 BP | The 2004 tsunami deposit is more widely distributed and covers the whole coastal plain in the form of decimeters thick sand sheet. The older layers are more restricted in the distribution. The 2004 deposit is graded. No sorting information. |
| 2  | [26]      | 2004 tsunami | The tsunami deposits show a generally fining-inland trend along the 3.4 km long transect. Normal grading is common, with pebble-sized clasts and mud cap. In some locations, parallel and cross-laminations occur in the upper part, with a massive in the lower part. Unimodal and bimodal grain size distributions. The thick tsunami deposits were observed at sites immediately landward of beach ridges. The deposits mostly poorly sorted. |
| 3  | [27]      | 2004 tsunami | The tsunami deposited a sand sheet, ranged from 0–30 cm in thickness, with an average thickness of approximately 10 cm. Sedimentary structures include ripples, graded bedding, parallel lamination, and double-layered deposits. |
| 4  | [28]      | 2004 tsunami | A discontinuous sand-dominated sheet was prevalent to about 2800 m from the shoreline where mud content then gradually increased further landward resulting in a mud-dominated deposit ranging from 3.5 cm to a few mm thickness. The overall thinning and fining of the deposit was often interrupted by localized features that led to complex sedimentological relationships over short distances. The deposits are poorly sorted inland. The 2004 tsunami deposits thickness ranged from 8 to 12 cm, composed mostly of medium to very coarse sand, moderately to poorly sorted, fining upward. Sharp lower contact with the soil. The older deposits were generally composed from medium to very coarse sand, in some parts the most of the sediments consisted of laminated. No sorting information. |
| 5  | [29]      | 2004 tsunami (late Holocene) | The 2004 tsunami deposits thickness ranged from 8 to 12 cm, composed mostly of medium to very coarse sand, moderately to poorly sorted, fining upward. Sharp lower contact with the soil. The older deposits were generally composed from medium to very coarse sand, in some parts the most of the sediments consisted of laminated. No sorting information. |
| 6  | [30]      | 1000 - 1200 BP tsunami | The sediment size ranges from fine-to-medium, moderately well-sorted-to-well-sorted, and exhibit positive skewness with platykurtic-to-leptokurtic nature. Abrupt winnowing or back and forth motion including unidirectional transport of these sediments with positive skewness. |
Fining upward and landward. The deposits were also thinning landward with bimodal distribution. Immediately landward of the coastal dunes the tsunami deposit was more than 20 cm thick, but thinned markedly inland from this point. At sites more than half the inundation distance inland, the thinner tsunami deposit consisted mainly of fine sand with some upward fining. The deposit massive at most sites, and showed lamination and bedding only at those near the sea. The deposit thinned inland. No apparent laminae or grading were observed at the sites more than half the inundation distance. Tsunami sediments are generally fine inland, well to moderately sorted.

The sediments are thick in the swale and thinned across the ridges. The tsunami deposit is coarser better sorted sand compared with the soil. Two normally graded sublayers dominated by rather homogeneous sand. Fining upward, rip-up clasts no fining inland. Moderately to poorly sorted.

The 2004 tsunami deposit varies in thickness, structure and preservation potential. The deposit shows no internal structure and contains one fining upward sequence. More fining upward in the swale. The 2004 tsunami sediments show prominent bimodal distribution.

The fining-inland tsunami deposits consisted of poorly to moderately sorted medium to coarse sand within 2 km of the coastline and very poorly to poorly sorted mud farther inland. There was a slight fining upward and coupled coarsening-fining upward trends.

3. General characteristics of the sedimentology
There are similar grain size characters in some environments and cases, but in detail the grain size characteristics in each environment can be distinguished. Therefore, the tsunami deposit in each environment has its own characteristic. As described above, the common characteristics are that the deposits tend to be fining upward with single or multiple bedding, thinning and fining landward, see e.g. [2, 4, 5, 8, 18, 21, 26, 28] and relatively poorly sorted [3, 18, 20, 36]. From the literature reviewed here (Table 1 to 3) it is undeniable that those characteristics are observed in each environment. The occurrence of rip-up clasts and mud cap may also be considered to be the common characteristics, e.g. [7, 9, 11, 20, 21, 24]. Specifically, the most visible characteristic that characterizes the tsunami deposits in the ridge/swale environment is the occurrence of parallel lamination that cannot be observed in another environment (e.g. [27, 31], Table 3). It is also observed that the sedimentary structures in the ridge/swale environment are the most complex as many sedimentary structures can be observed, such as current ripple and cross bedding [26, 27]. Parallel lamination is also observed in the lagoon [22], but it is only presence as a minor structure and only in one location. Similar to parallel lamination, coarsening upward or inverse grading is intensively observed in the tsunami deposits in ridge/swale environment (Table 3). In this environment, the thickest tsunami deposits are observed and their occurrence is in relation to the parallel lamination that can be observed in immediate landward of the coastal dune. This condition is probably as a result of the bedload transport of tsunami [27]. The sediment type (clay, silt, sand or coarser materials) highly depends on the available source materials [1]. Thus, it is not applicable to distinguish the type of sediment in every environment. However, the occurrence of mud deposits (as rip-up mud and/or mud cap) is mostly visible when it is observed in the lagoon or lake environment. The tsunami deposits in the swale also commonly show this rip-up and mud
cap, although the bigger rip-up is found in the tsunami deposits in the lagoon [24]. This characteristic is probably due to the soft and very fine lagoon sediments that could be easily lifted up and eroded by the tsunami waves. The sorting of the deposits is also connected to the available sediments source. If the available sources are in highly grain size variations, the resulting grain size might be relatively poorly sorted. In such case, we cannot differentiate the sorting of the deposits from each different depositional environment. From the reviewed literatures, however, the sorting of the deposits ranges from relatively well sorted to poorly sorted. It means that not all tsunami deposits are poorly sorted. For the grain size distribution, the controlling factors, whether the deposits distributed unimodal or not, is related to the types of source sediments and the tsunami transport and deposition processes. In general, the thickness of the deposits is thinning inland with some local variations, due to the local micro scale topography as an example. This characteristic is observed in every depositional environment.

4. Summary
In detail, the characteristics of tsunami deposits/paleotsunami in each environment can be distinguished, even though only based on the minor parameter, such as the occurrence of rip-up clasts that is the most common in the lagoon/lake environment, and based on the occurrence of a specific sedimentary structure. Although the sedimentological proxy is the main method for paleotsunami identification, there is no consistency in the sampling and methodology used. As described above (refer to Section 2), many literatures only visually describe the grain size characteristics. This approach is not recommended, because if it is from the visual observation only, the obtained information is very limited. On the other hand, most of the literatures that used grain size analysis only stated and described the mean grain size of the deposits. Some of them calculated the sorting of the deposit; however, there are many literatures that only visually observed the sorting. Then, the resulting sorting condition is not really valid. The other grain size parameters: skewness and kurtosis, are very rarely calculated. The complete calculation of grain size parameters, on the other hand, would give detail and complete grain size characteristics that not only will give more specific sediment characteristics but will also make it easier to identify paleotsunami. In addition, there is no consistency on the sampling resolution both horizontally along transect or vertically, that will be used for laboratory analysis. It is highly recommended that tsunami geologists make a scientific agreement on the deposits sampling and analysis methods. This scientific agreement will lead us to characterize the deposits more accurately and be able to compare the deposits from site to site and or event to event.

Acknowledgments
The author would like to thank the Director of Research Center for Geotechnology, Indonesian Institute of Sciences (LIPI) and the GCGE committee for the opportunity to publish this paper. I acknowledged comments and reviews from the reviewer and the editor.

References
[1] Goff J, Chague-Goff C, Nichol S, Jaffe B and Sominey-Howes D 2012 Progress in paleotsunami research Sediment. Geol. 243-244 pp 70-88
[2] Hong I, Dura T, Ely L L, Horton B P, Nelson A R, Cisternas M, Nikitina D and Wesson R L 2017 Holocene 27 pp 1-13
[3] Cordova J 2014 Analysis of a potential paleotsunami deposit at Los Penasquitos marsh, San Diego County, USA Undergraduate Thesis Geological Science California State University, Fullerton p 27
[4] Moore A L, McAdoo B G and Ruffman A 2007 Landward fining from multiple sources in a sand sheet deposited by the 1929 Grand Banks tsunami, Newfoundland Sediment. Geol. 200 pp 336-46
[5] Dura T, Cisternas M, Horton B P, Ely L L, Nelson A R, Wesson R L and Pilarczyk J E 2014 Coastal evidence for Holocene subduction-zone earthquakes and tsunamis in central Chile Quaternary Sci. Rev. 113 pp 93-111
[6] Peterson C D, Cruikshank K M, Schlichting R B and Braunsten S 2010 Distal run-up records of Latest Holocene paleotsunami inundation in alluvial flood plains: Nesikowin and Beaver Greek, Oregon, Central Cascadia Margin, West Coast U.S.A J. Coastal Res. 264 pp 622-34

[7] Peters R, Jaffe B, Gelfenbaum G 2007 Distribution and sedimentary characteristics of tsunami deposits along the Cascadia margin of western North America Sediment. Geol. 200 pp 372-86

[8] Peterson C D, Carver G A, Cruikshank K M, Abramson H F, Garrison-Laney C E and Dengler L A 2011 Evaluation of the use of paleotsunami deposits to reconstruct inundation distance and runup heights associated with prehistoric inundation events, Crescent City, southern Cascadia margin Earth Surf. Proc. Land. 36 pp 967-80

[9] Ely L L, Cisternas M, Wesson R L and Dura T 2014 Five centuries of tsunamis and land-level changes in the overlapping rupture area of the 1960 and 2010 Chilean earthquakes Geology 42 pp 995-98

[10] Sawai Y, Kamataki T, Shishikura M, Nasu H, Okamura Y, Satake K, Thomson K H, Matsumoto D, Fujii Y, Komatsubara J and Aung T T 2009 Apriodic reccurrence of geologically recorded tsunamis during the past 5500 years in eastern Hokkaido, Japan J. Geophys. Res.-Solid 114 pp 1-20

[11] Schlichting R B and Peterson C D 2006 Mapped overland distance of paleotsunami high-velocity inundation on back-barrier wetlands of the central Cascadia Margin, U.S.A J. Geol. 114 pp 577-92

[12] Williams H and Hutchinson I 2000 Stratigraphic and microfossil evidence for Late Holocene tsunamis at Swantown marsh, Whidbey Island, Washington Quaternary Res. 54 pp 218-27

[13] Ritter R C, Hemphill-Haley E, Hart R and Gay L 2009 Tracking prehistoric Cascadia tsunami deposits at Nestucca Bay, Oregon Final Technical Report U.S. Geological Survey

[14] Garret E, Shennan I, Woodroffe S A, Cisternas M, Hocking E P and Gulliver P 2015 Reconstructing paleoseismic deformation, 2: 1000 years of great earthquakes at Chucalen, south central Chile Quaternary Sci. Rev. 113 pp 112-22

[15] de Martini P M, Barbano M S, Smedile A, Gerardi F, Pantosti D, Del Carlo P and Pirrotta C 2010 A unique 4000 year long geological record of multiple tsunami inundations in the Augusta Bay (eastern Sicily, Italy) Mar. Geol. 276 pp 42-57

[16] Kempf P, Moemaut J, Daele M V, Vandoorne W, Pino M, Urrutia R and De Batist M 2017 Coastal lake sediments reveal 5500 years of tsunami history in south central Chile Quaternary Sci. Rev. 161 pp 99-116

[17] McCloskey T A, Blanchette T A, Liu K 2015 Geological and sedimentological evidence of a large tsunami occurring ~1100 year BP from a small lake along the bay of La Paz in Baja California Sur, Mexico J. Mar. Sci. Eng. 3 pp 1544-67

[18] Donato S V, Reinhardt E G, Boyce J I, Pilarczyk J E and Jupp B P 2009 Particle-size distribution inferred tsunami deposits in Sur Lagoon, Sultanate of Oman Mar. Geol. 257 pp 54-56

[19] Bertrand S, Doner L, Akçer Ön S, Mischke S, Çagatay M N and Leroy S A G 2011 Sedimentary record of coseismic subsidence in Hersek coastal lagoon (Izmit Bay, Turkey) and the late Holocene activity of the North Anatolian fault Geochim. Geophys. 12 pp 1-17

[20] Grauer J, Björck S and Bondevik S 2001 Storegga tsunami deposits in a coastal lake on Suduroy, the Faroe Islands Boreas 30 pp 263-71

[21] Kempf P, Moenmaut J, Van Daele M, Verrassen F, Vandoorne W, Pino M, Urrutia R, Schmidt S, Garret E and De Batist M 2015 The sedimentary record of the 1960 tsunami in two coastal lakes on Isla de Chiloe, south central Chile Sediment. Geol. 328, pp 73-88

[22] Matsumoto D, Shimamoto T, Hirose T, Gunatilake J, Wickramasooriya A, DeLile J, Young S, Rathnayake C, Ranasooriya J and Murayama M 2010 Thickness and grain-size distribution of the 2004 Indian Ocean tsunami deposits in Periya Kalapuwa Lagoon, eastern Sri Lanka Sediment. Geol 230, pp 95-104
[23] Kelsey H M, Nelson A R, Hemphill-Haley E, Witter R C 2005 Tsunami history of an Oregon coastal lake reveals a 4600 yr record of great earthquakes on the Cascadia subduction zone *GSA Bull.* **117** pp 1009-32

[24] Bondevik S, Svendsen J I and Mangerud J 1997 Tsunami sedimentary facies deposited by the Storrega tsunami in shallow marine basins and coastal lakes, western Norway *Sedimentology* **44** pp 1115-31

[25] Brill D, Jankaew K, Neubauer N-P, Kelletat D, Scheffers A, Vott A and Bruckner H 2014 Holocene coastal evolution of southwest Thailand - implications for the site-specific preservation of palaeotsunami deposit *Z. Geomorphol.* **58** pp 273-303

[26] Takeshimaizu Y, Urabe A, Suzuki K and Sato Y 2012 Deposition by the 2011 Tohoku-oki tsunami on coastal lowland controlled by beach ridges near Sendai, Japan *Sediment. Geol.* **282**, pp 124-141

[27] Choowong M, Murakoshi N, Hisada K, Charusiri P, Daoererk V, Charoentitirat T, Chutakositkanon V, Jankaew K and Kanjanapayont P 2007 Erosion and deposition by the 2004 Indian Ocean tsunami in Phuket and Phang-nga Provinces, Thailand *J. Coastal Res.* **23** pp 1270-76

[28] Richmond B, Szczucinski W, Chague-Goff C, Goto K, Sugawara D, Witter R, Tappin D R, Jaffe B, Fujino S, Nishimura Y and Goff J 2012 Erosion, deposition and landscape change on the Sendai coastal plain, Japan, resulting from the March, 11 2011 Tohoku-oki tsunami *Sediment. Geol.* **282**, pp 27-39

[29] Yawsangratt S, Szczucinski W, Chaimanee N, Chatprasert S, Majewski W and Lorenc S 2012 Evidence of probable paleotsunami deposits on Kho Khao Island, Phang Nga Province, Thailand *Nat. Hazard* **63** pp 151-163

[30] Lakhsmi C S V, Srinivasan P, Murthy S G N, Trivedi D and Nair R R 2010 Granularity and textural analysis as a proxy for extreme wave events in southeast coast of *India J. Earth Syst. Sci.* **119** pp 297-305

[31] Nakamura Y, Nishimura Y and Putra P S 2012 Local variation of inundation, sedimentary characteristics, and mineral assemblages of the 2011 Tohoku-oki tsunami on the Misawa coast, Aomori, Japan *Sediment. Geol.* **282** pp 216-27

[32] Brill D, Bruckner H, Jankaew K, Kelletat D, Scheffers A and Cheffers S 2011 Potential predecessors of the 2004 Indian Ocean tsunami - Sedimentary evidence of extreme wave *Jankaew K, Atwater B F, Choowong M, Charoentitirat T, Martin M E and Prendergast A 2008Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand *Nature* **455** pp 1228-31

[33] Jankaew K, Atwater B F, Choowong M, Charoentitirat T, Martin M E and Prendergast A 2008Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand *Nature* **455** pp 1228-31

[34] Szczucinski W, Kokocinski M, Rzeszewski M, Chague-Goff C, Cachao M, Goto K and Sugawara D 2012 Sediment sources and sedimentation processes of 2011 Tohoku-oki tsunami deposits on the Sendai Plain, Japan - insights from diatoms, nannoliths and grain size distribution *Sediment. Geol.* **282** pp 40-56