Scientific Research Publishing

Open Journal of Earthquake Research, 2017, 6, 89-97
http://www.scirp.org/journal/ojer
ISSN Online: 2169-9631
ISSN Print: 2169-9623

Converting Tsunami Wave Heights to Earthquake Magnitudes

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How to cite this paper: Mörner, N.-A. (2017) Converting Tsunami Wave Heights to Earthquake Magnitudes. *Open Journal of Earthquake Research*, **6**, 89-97.
https://doi.org/10.4236/ojer.2017.62005

Received: April 24, 2017
Accepted: May 12, 2017
Published: May 15, 2017

Abstract

There is a fairly strict relation between maximum tsunami wave heights and causation earthquake magnitudes. This provides a new tool for estimating the magnitude of past earthquakes from the observed wave heights of related paleo-tsunami events. The method is subjected to a test versus two paleoseismic events with multiple independent estimates of corresponding earthquake magnitude. The agreement to the tsunami wave height conversion is good, confirming very high magnitudes of M 8.5 - 9.0 and M 8.4 - 8.5. Applying the same method to two Late Holocene events of methane venting tectonics indicates a ground shaking of forces equivalent to a M 8.0 earthquake, seriously changing previous long-term crustal hazard assessments.

Keywords

Tsunamis, Wave Height, Earthquakes, Magnitudes, Paleo-Tsunamis, Methane Venting Tectonics, Hazard Assessment

1. Introduction

Major tsunami events are primarily generated by submarine earthquakes [1] [2]. In principle, there is a relation between earthquake magnitude and tsunami wave height. During the last 13 years, there has been eight high-amplitude tsunami wave events |3]; viz. 1) the 2004 Indian Ocean event with a tsunami wave height of 20 m (a statement of a 30 m height is considered to represent a run-up height, not an actual wave height) and a Mw 9.1 earthquake magnitude, 2) the Java 2006 event with a wave height of 8.6 m and a magnitude of Mw 7.7, 3) the Benkula 2007 event with a wave height of 1.65 m and a magnitude of Mw 8.5, 4) the Peru 2007 event with a wave height of 3 - 4 m and a magnitude of Mw 8.0, 5) the Samoa 2009 event with a wave height of 11.9 m and a magnitude of Mw 8.1, 6) the Mentawai 2010 event with a wave height of 10 m and a magnitude of Mw 7.7, 7) the Chile 2010 event with a wave height of 17.2 m and a magnitude of Mw 8.8

and 8) the Tihoku-oki 2011 event with a wave height of 19.5 m and a magnitude of Mw 9.0. Because these 8 events are known both to tsunami wave height and causation earthquake magnitude, they can be used to establish the relationship between tsunami wave height and seismic magnitude [3] [4]. This is illustrated in **Figure 1** (modified from [4]). Events 3 and 4 obviously never reached a maximum wave height, and are excluded in establishing the red line relation. Value 1a is superseded by the better 1b value.

2. Paleo-Tsunamis

Paleo-tsunamis can rarely be evaluated with respect to earthquake magnitudes [5] [6] [7] [8]. Having established the tsunami height/seismic magnitude relation in **Figure 1**, we now have a new tool for estimating the corresponding earthquake magnitudes [4].

Even the reverse may apply; *i.e.* knowing the seismic magnitude of a paleoseismic event, one may estimate the maximum tsunami height. This is the case with the Crete AD 365 paleoseismic event; its magnitude has been estimated to "at least 8.5" [6] or "8.3 - 8.5" [7]. It set up a major tsunami, which hit and destroyed the Library at Alexandria, destroyed 50,000 homes, and killed about 5000 persons [7]. It also left a "mega-turbidite" [7]. The tsunami height is less well known. From **Figure 1**, it is easy to read that an Mw 8.5 earthquake may set up a tsunami with a maximum wave height of about 15 m. This seems to fit well with observed records [7].

Today Sweden is an area of low to moderately low seismic activity. Due to the very high rate of glacial isostatic uplift at the time of deglaciation it was, at that time, an area of very high paleoseismic activity in frequency as well as in magni-

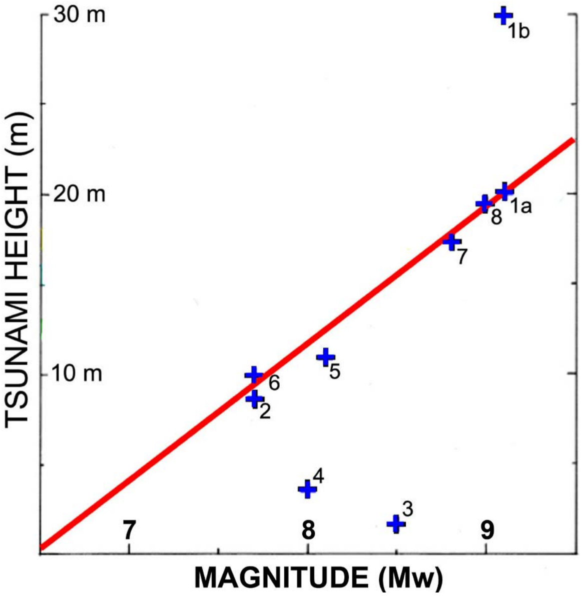

Figure 1. Relation between observed maximum tsunami heights and magnitudes of causational earthquakes (events 1 - 8). Having established this relation, observed tsunami heights of paleoseismic events can be converted to corresponding earthquake magnitudes [4]. The red line gives a ratio of 0.133 Mw per 1.0 m tsunami wave height.

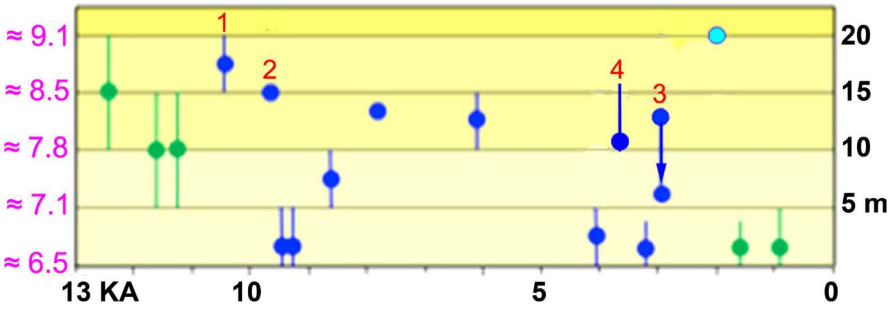

Figure 2. The Swedish paleoseismic database [10] [11] includes 17 tsunami events [4] [14]; 5 in the Kattegatt Sea (green) and 12 in the Baltic (blue) plotted chronologically with respect to observed wave heights. Purple figures to the left give corresponding earthquake magnitudes as read from **Figure 1** relation (modified from [4]). The four events further discussed in section 3 are marked in red (1 - 4).

tude [8]-[13]. In total, 62 paleoseismic events have been documented [13], out of which 17 events generated tsunamis [5] [11] [12] [13] [14].

In **Figure 2**, the Swedish database of tsunami events and wave heights is converted to magnitudes using **Figure 1** relations.

Figure 2 demonstrates that the corresponding paleoseismic event must have been of considerable magnitudes (viz. 7 between M 6.5 - 7.5, 6 between M 7.6 - 8.4, and 3 of M > 8.4). In some of the events (1 and 2 in **Figure 2**), there are independent magnitude estimates from liquefaction, fault movements and bedrock deformation [8] [10] [11], which can be used for testing the relations among wave heights and magnitudes as given in **Figure 1**.

3. Application on Some Swedish Paleo-Tsunami Events

The first Paleoseismic Catalogue of Sweden [10] included 52 paleoseismic events, and the second Paleoseismic Catalogue 62 events [11]. All events entering the catalogues were documented by multiple criteria [8] [10] [11] and well dated; often by varve chronology with an annual resolution [10] [13] (varve ages are assigned vBP, for distinction to conventional C14-dates in BP). All the events in the catalogues were assigned a magnitude estimate [10] [11], based on a number of different criteria [5].

Two of the Swedish paleoseismic events will be analyzed as a test of **Figure 1** tsunami/magnitude relations in comparison with independent estimates based on other criteria presented in [5] [8] [10] and [11].

3.1. The 10,430 vBP Paleoseismic Event

Stockholm is traversed by an old Permian fault that extends in west-east direction for about 400 km, and which may continue into the Bay of Finland and Lake Ladoga for another 300 - 400 km. The fault was reactivated in deglacial time some 10,500 - 10,400 vBP. The frequency of paleoseismic events was very high with 7 independent events recorded and dated with in 102 varve years from 10,490 to 10,388 vBP [8].

In varve year 10,430 vBP a giant earthquake occurred [10]. A lateral to sympathetic fault located 1 km north of the main fault was displaced by 6 - 8 m, indicating a very high magnitude of the causation earthquake. Heavy bedrock fracturing is documented over an area of 50 × 100 km. Liquefaction has been recorded over an area of 320 km, which is indicative of an earthquake magnitude of about M 9.1 [5] [10] [11]. Liquefaction of gravel is another indicator of a very high magnitude event. An intra-varve turbidite is recorded over an area of 200 × 320 km. Magnetic grain rotation is recorded over an area of 500 × 600 km [10] [15]. At present we have no means of converting this value into a magnitude estimate. One thing is clear, however, the magnitude must have been very high, *i.e.* ≫ 8 [5] [8].

This event also set up a gigantic tsunami event, which invaded several lake basins and washed the strait across southern Sweden (the so-called Närke Straight) free of pack-ice and ice-bergs so that entire Baltic became marine (the Yoldia Stage) within one year [10] [12] [16]. The tsunami wave must have had a wave height of 15 - 20 m.

In **Figure 3**, we compare the magnitude estimated from the observed tsunami wave height, with the estimates obtained previously on the bases of other criteria [5] [8] [10] [11].

In principle, there is a very good agreement between all the different and independent means of estimating seismic magnitude. No doubt, the 10,430 vBP paleoseismic event was a very strong event of a magnitude of about M 8.5 - 9.0, which implies that it was a "mega-earthquake". It also means that the test of the

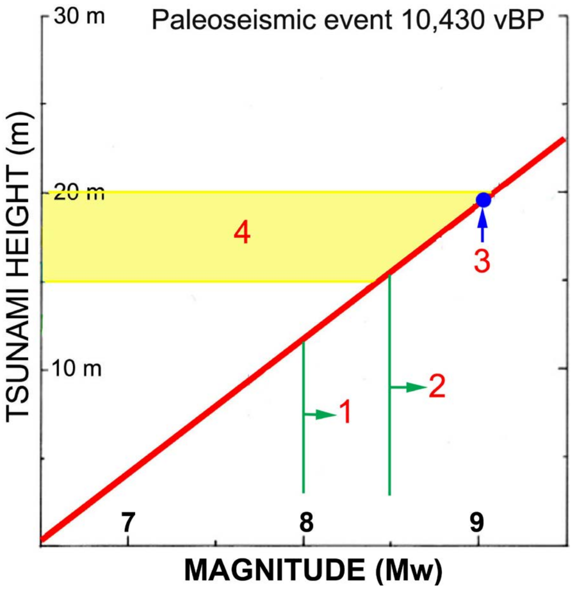

Figure 3. Comparision between previous magnitude estimates (1 - 3) and the present one (4) obtained via the tsunami wave height and earthquake magnitude relation in Figure 1. Group 1 refers to M > 8 suggested by liquefaction of gravel, fracturing opening of 10 - 20 cm, and turbidite spread. Group 2 refers to M ≫ 8 suggested by 6 - 8 m lateral fault displacement 1 km away from the main fault, spatial distribution of bedrock fracturing, seismic recurrence frequence, and rotation of magnetic grains over an immense area. Point 3 refers to the magnitude (M ~ 9.0) obtained from the spatial distribution of liquefaction. Point 4 represents the magnitude (M 8.5 - 9.0) converted from the tsunami height.

tsunami vs. magnitude relation of **Figure 1** seems to work very well.

3.2. The 9663 vBP Paleoseismic Event

This paleoseismic event is known as the Hudiksvall or Iggesund paleoseismic event [10]. It occurred in varve 9663 vBP (or 9150 C14-years BP). It is one of the ever best investigated paleoseismic events [10], documented by primary fault, bedrock deformations over an area of 50 × 50 km (with 49 sites investigated in details), recorded and dated in 31 varve sequences with a distinct turbidite extending for 320 km along the coast, recorded by liquefaction in 15 sited over an area of 40 × 80 km, and documented as a tsunami event in 14 lakes (and 43 sediment cores) covering an area of 30 × 125 km. At two sites 35 km apart, the liquefaction event is composed of 5 different phases, interpreted as shock and after-shock signals, which calls for a very strong event [5] [8] [10] [11].

The tsunami wave height can be very closely fixed at a minimum of 15 m [10] [12] [14], providing a magnitude of about M 8.5 according to **Figure 1** relation [5].

The various independent means of estimating seismic magnitude are compared in **Figure 4** to test the new tsunami vs. magnitude relation, and to provide a combined estimate of the corresponding magnitude.

Even for this event, there is a reasonably good agreement between all the different and independent means of estimating seismic magnitude. No doubt, the 9663 vBP paleoseismic event was a very strong event of a magnitude of about M

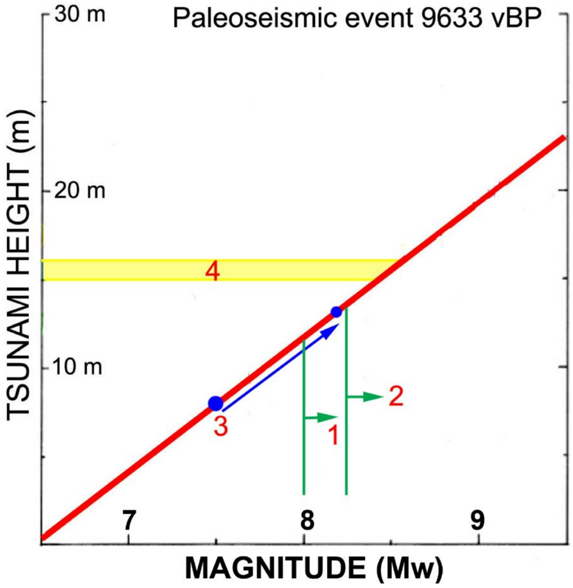

Figure 4. Comparison between previous magnitude estimates (1 - 3) and the present one (4) obtained via the tsunami wave height and earthquake magnitude relation in **Figure 1**. Group 1 refers to M > 8 suggested primary fault displacement, mode of bedrock deformations, slide volumes, spatial distribution of turbidities, liquefaction of gravel, and methane venting. Group 2 refers to M ≫ 8 suggested by spatial distribution of bedrock deformation, and mode of liquefaction in 5 phases. Point 3 refers to spatial distribution of liquefaction. Point 4 represents the magnitude (M 8.5 - 8.6) converted from the tsunami height.

8.4 - 8.5. The test of the tsunami vs. magnitude relation of **Figure 1** seems to work very well.

3.3. The 2900 BP Methane Venting Tectonics Event

Methane venting tectonics is a novel factor, which it has taken time to evolve from the first idea [17] [18] [19] to observational confirmation [10] and finally to full presentation [20] [21], summarized in [22]. It implies the sudden phase transition from methane hydrate stored in voids and fractures in the bedrock to methane gas venting explosively to the surface, by that causing severe bedrock deformation.

This event set up a major tsunami, recorded in nearby bogs and lakes [10] [12]. It was later found to be coincidental with a tsunami event recorded 160 km to the south [4] [14] with an age of 2900 C14-years BP. At the nearby sites the tsunami wave must have had a height of at least 12 m, and at southern sites a height of at least 6 m. At both sites, the wave had a submarine trimming depth of at least 18 m.

The bedrock is severely deformed in a huge cone of angular block torn out of the bedrock beneath. The cone is 20 - 25 m high and 100 × 150 m wide (*i.e.* elliptic). It is surrounded by a depression (compensating the rock masses of the cone). At the top of the cone, there are gigantic blocks of 10 m to >10 m diameters.

Methane venting tectonics is, of course, something quite different from earthquake deformational magnitudes. The deformation was so violent, however, that it was compared to a magnitude M ~7 earthquake event [10] [11].

In **Figure 5** the original magnitude estimate is compared to the magnitude es-

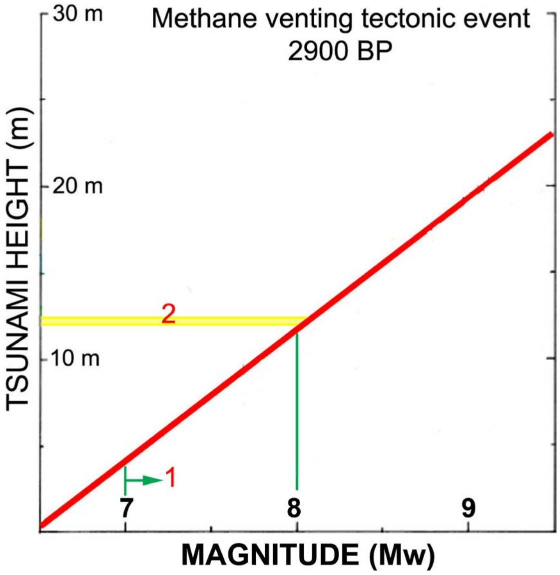

Figure 5. Comparing estimated earthquake magnitude equivalent (1) and observed tsunami wave height (2) of the methane venting tectonic event at 2900 BP [10] [14] [20], indicating that the ground shaking associated with methane venting tectonics may reach very high magnitudes comparable to M 8.0 earthquake magnitudes. A quite similar situation applies to the 3000 - 4000 BP methane venting tectonic event documented south of Stockholm [20] [21].

timate according to **Figure 1** relation between tsunami height and earthquake magnitude. It reveals that the 2900 BP methane venting event set up a ground shaking comparable to a magnitude M 8.0 earthquake. This is, of course, quite remarkable because it seems to verify that methane venting tectonics imply ground deformations comparable to very high magnitude earthquakes.

3.4. The 3000 - 4000 BP Methane Venting Tectonic Event

A major methane venting tectonics event is recorded south of Stockholm [20]. It occurred sometime between 4000 and 3000 BP. The deformational structures indicate that the event must have been quite violent [20] [21]; a 25 m high cone of 150 × 230 m width, and with gigantic blocks at the top. It seems that a tsunami event with a run-up of about 11 - 21 m can be associated with this event [10] [20]. The field data referring to the tsunami need to be revisited and checked before a serious magnitude estimate can be done. If an 11 m height is taken as wave height, we would be dealing with a ground-shaking magnitude of M 7.9 by applying **Figure 1** relations. The situation is quite similar to that of the 2900 BP event (**Figure 5**), in basic structure as well as in tsunami height.

4. Discussion

Figure 1 relations between tsunami wave height and earthquake magnitude [3] [4] implies an improved and simplified tool of converting observed tsunami wave height into corresponding earthquake magnitude as compared to preceding graphic relations [23].

Sweden has a database of 17 postglacial tsunami events [10] [12] [14]. The wave heights documented is consistent with a very high seismicity, not only in Late Glacial time, but also in Mid-Holocene and Late Holocene time (**Figure 1**).

Two paleoseismic events were selected for a test of the significance of **Figure 1** relations established; *viz.* the 10,430 vBP and the 9663 vBP events, because both of these event were established by means of a multiple criteria [10] [11], besides they both represent very strong events with well-established tsunami heights. This implies the comparison between multiple independent parameters. The data referring to the 10,430 vBP event are consistent with a mega-event of a magnitude of about M 8.5 - 9.0 (**Figure 3**) and the data referring to the 9663 vBP event to an event of magnitude of M 8.4 - 8.5 (**Figure 4**).

In the Late Holocene, there were two major tsunami events (**Figure 1**). Both of those events were generated by methane venting tectonics, however [10] [20]. Hence, there is no straightforward application of **Figure 1** relations. In order to obtain some sort of quantification of the forces involved and magnitude of the ground shaking, **Figure 5** was drawn. The tsunami height of the 2900 BP event is consistent to a magnitude (rather magnitude equivalent) ground shaking of M 8.0, which seems to harmonize with the violence of the structures observed (**Figure 5**). The 3000 - 4000 BP event from the Stockholm area give a similar picture.

The process of methane venting tectonics [20] has by this (**Figure 5**) obtained a first serious quantification as to corresponding ground shaking, and both events were found to be consistent with a magnitude M 8.0 equivalent. This makes it a very dangerous factor for long-term stability and must be considered seriously in hazard assessment [5] [11].

5. Conclusions

A new tool for the conversion of observed tsunami heights to corresponding causation earthquake magnitude is presented (**Figure 1**).

It is quite successfully tested on multiple independent magnitude estimates from two paleoseismic events in Sweden (**Figure 3**, **Figure 4**). The general agreement is very good.

Methane venting tectonics is a novel process of severe bedrock deformation [10] [20]. Big tsunami events were generated at an event occurring 2900 BP (the Skålboberget event in central Sweden) and at 3000 - 4000 BP (the Kvarnberget event in the Stockholm area). The tsunami heights documented correspond to an earthquake equivalent magnitude of about M 8.0 (**Figure 5**), indicating that methane venting tectonics implies violent deformation and ground shaking equivalent to high-magnitude seismic events.

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