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Sedimentologic and geomorphologic tsunami imprints worldwide—a review

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Abstract

Tsunami events with extreme effects on sedimentary transport or considerable alterations of the coastal configuration are rather rare regarding human history, but considering geological timescales they occur frequently. At least 100 megatsunami in different parts of the world have been recorded in the past 2000 years—but presumably far more have failed to be noticed during historical times and are not mentioned either in written or oral ancient records. Therefore, the topic of paleotsunami requires inevitable sedimentological and geomorphological research. However, field research concerning paleotsunami is astonishingly rare within the scientific approach and only 5% of the existing tsunami literature is related to this subject. Future efforts in paleotsunami research should focus on the geological evidence of these mega-events to clarify their contribution to coastal forming processes. This paper reviews the state-of-the-art knowledge of sedimentologic and geomorphic imprints of tsunami along the world's coastlines in order to highlight the need for more detailed studies of paleotsunami depositional and geomorphological traces.

Keywords: Tsunami; Onshore tsunami deposits; Field evidences

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1. Introduction

Worldwide tsunami catalogues from different parts of the world (e.g. Lander and Whiteside, 1997; Tinti and Maramai, 1996; Nakata and Kawana, 1993, Iida et al., 1967a,b; Heck, 1947; Papadopoulos and Chalkis, 1984; Zhou and Adams, 1986; NGDC, 1997, 2001) list far more than 2000 tsunami events during the past 4000 years (Fig. 1). Yet, it is highly likely that going back in time weaker events might not occur in the historical record and the catalogues emphasize greater damage or loss of life. This trend is apparent in the rapid increase of tsunami registrations with the advanced measuring technology of the 19th century. Tsunami occurring prior to the period of direct and objective measurements have mostly been recorded only when they destroyed infrastructure or caused casualties. Changes of natural features like deposition or erosion of material or even alterations of the entire coastal landscape often have not been passed on to the following generations. Therefore, it is not surprising that most of the events mentioned below and docu-

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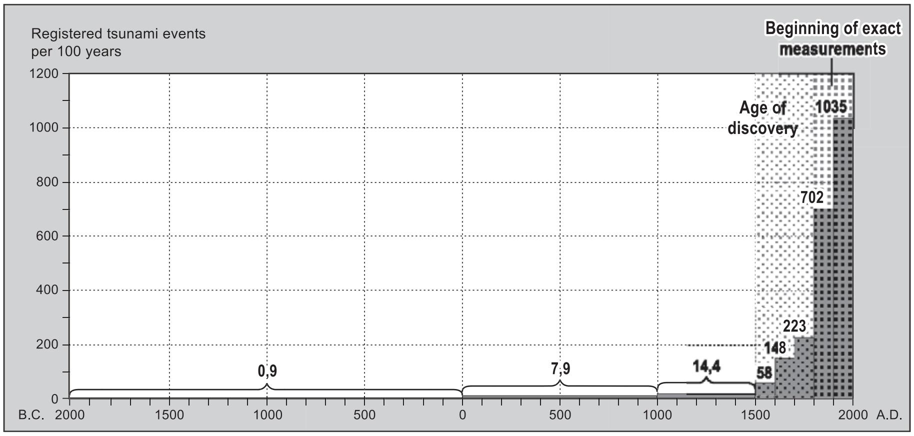

Fig. 1. Temporal distribution of 2341 tsunami events listed in the database of the National Geophysical Data Center, USA. The database contains the events of the past 4000 years until 2001 AD.

mented by sediments or geomorphological shapes are not reported in the extensive catalogues. Consequently, it can be assumed that the actual number of mega-tsunami might be highly underestimated in the existing databases.

Due to the possibility of exact measurements of sea-level variations caused by tsunami since the 19th century, the actual frequency of such impacts is known relatively well. However, it can be stated that predominantly tsunami of minor intensity occur. Tsunami reaching runup heights of more than 2 m and causing damage constitute only for 10% (of documented runups from over 6500 localities) while disastrous events with runups >10 m amount for merely 2% of the record (Fig. 2).

Assuming that our knowledge of tsunami occurrence during historical times is limited, the same counts all the more for prehistoric tsunami, in particular for several thousand years of the postglacial sea-level highstand. Since then at least 4000 years of tsunami records are missing. For most regions (e.g. the eastern, central and southwestern Pacific, the Indian Ocean or most of the African coastlines) the tsunami chronology is incomplete for at least 5500 years of the Holocene (Fig. 1). Almost nothing is known of the Pleistocene tsunami record during periods of high sea levels over the last hundred thousands of years.

Moreover, strikingly, research focusing on alterations of the natural landscape due to tsunami was almost neglected even for historical well-documented tsunami events. Curtis (1995) stated that "little has been published other than the theoretical analyses." Except for a few recent documented studies based upon field evidences many aspects of the nature and the occurrence of paleotsunami remain incomplete. Merely 5% of the more than 1000 publications of the past 50 years related to tsunami concentrate on the imprints of such events upon the landscape. Even in scientific literature especially dedicated to tsunami research such as the journal *Science of Tsunami Hazards*, research about geological traces of tsunami is rather rare. Since 1982, of the 177 articles published in this journal, only six concentrate upon geologic field evidence for tsunami. Recently, just one monograph (Bryant, 2001) has presented an overview of the sedimentologic and geomorphologic impact of tsunami. In contrast, most present-day tsunami research is related to tsunami generating mechanisms; the origin, propagation and deformation of tsunami waves, or the physics of tsunami runup and inundation. Nevertheless, these topics contribute significantly to the understanding of tsunami and tsunami hazards and together with numerical models they play an important role in the establishment of tsunami warning systems or protective measures.

The aim of this study is to highlight the deficiency of reliable field evidences of Holocene and Pleistocene tsunami and the limited knowledge of geomorphic and sedimentologic traces of tsunami along the world's coastlines. In coastal studies we are lacking

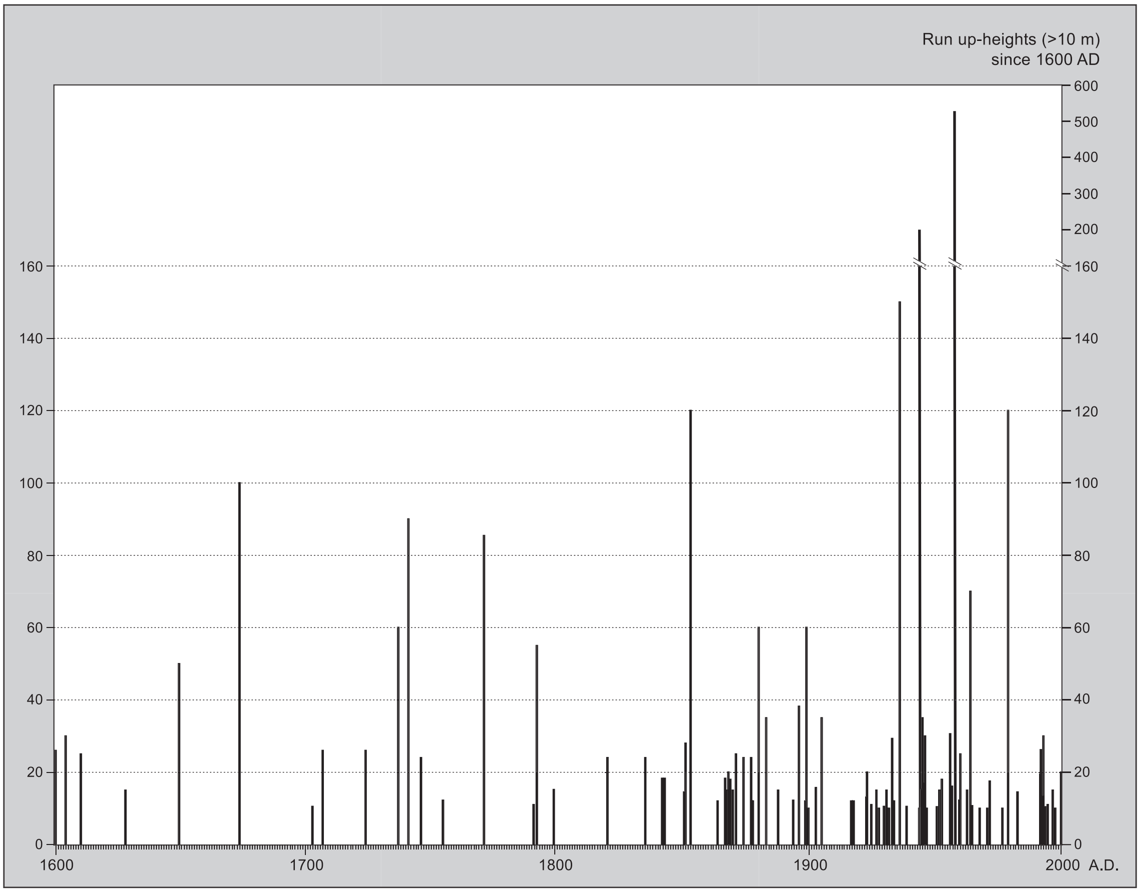

Fig. 2. Reliable high *runup* values (>10 m) of worldwide tsunami within the past 400 years (acc. to NGDC, 2001).

important information of these high-magnitude and high-frequency events at geological timescales. Additionally, without adequate understanding of sedimentologic and geomorphologic traces of tsunami impacts, a realistic model of the role of tsunami in coastal evolution is rather difficult to develop (Dawson et al., 1991).

2. Tsunami sediments along the coastlines of the world

Tsunami sediments in coastal environments are extremely difficult to detect. At first sight the observer may only suspect a tsunami origination if clearly wave-induced sediments are located in some distance inland or very coarse material has accumulated. Fine sediments are, because of their mostly hidden nature, not easy to recognize and in most cases are bound to a stratigrapical context (for further details see the review of tsunamigenic fine sediments by Dawson and Shi, 2000 and the post-survey of the Java tsunami 1994 carried out by Dawson et al., 1996). Whereas in general the analyses and age determination of fine sediments might be easier due to well-established methodologies in stratigraphy and dating routines, the unambiguous relation to a tsunami-induced origin is difficult as they may as well be deposited by wind or normal storm waves. In addition, the spatial distribution can only be determined via systematic cross-sections or drilling cores and fine sediments are in contrast to coarse debris almost nowhere characteristic for coastal geomorphologies. Therefore, often it is coincident that fine sediments are studied in order to demonstrate their tsunamigenic origin (Dawson, 1994, 1996, 1999; Dawson et al., 1991; Goff et al., 2001; Bondevik et al., 1997a,b).

One can establish though that fine sediments are widely overlooked by experts and in large-scale surveys are often subscribed, without further scientific proof of extreme storms. This leads to the astounding consequence that even in case of boulder depositions at certain sites paleotsunami have not been considered as a depositional mechanism. Moreover, most studies preferably try to detect tsunami sediments in regions of historical well-documented or potentially suggested submarine earthquakes to choosing an inductive approach with the analyses of field observations. The study of possible occurrences of Mediterranean tsunami by Dominey-Howes (1996) illustrates this latter point: The author chose five tsunami events with high magnitudes reported in antique and historical documents. The results of extensive field studies were rather disappointing as the sedimentary record did not reflect any traces of high-energy tsunami.

Therefore, an inductive approach, considering a tsunamigenic origin of unusual depositions or geomorphological features in coastal areas, seems to be more promising as most presently reliable known geological traces of tsunami events have been detected via inductive field research. Additionally, most studies describe tsunami imprints on a local scale and detailed regional characterisations with high-resolution mapping surveys of tsunami depositional traces have been solely carried out in Cyprus (Kelletat and Schellmann, 2001, 2002) and in the southern Caribbean (Scheffers, 2002a,b).

A worldwide distribution of geological tsunami imprints based on this inductive approach is represented in Fig. 3: Around the Atlantic Basin evidence of

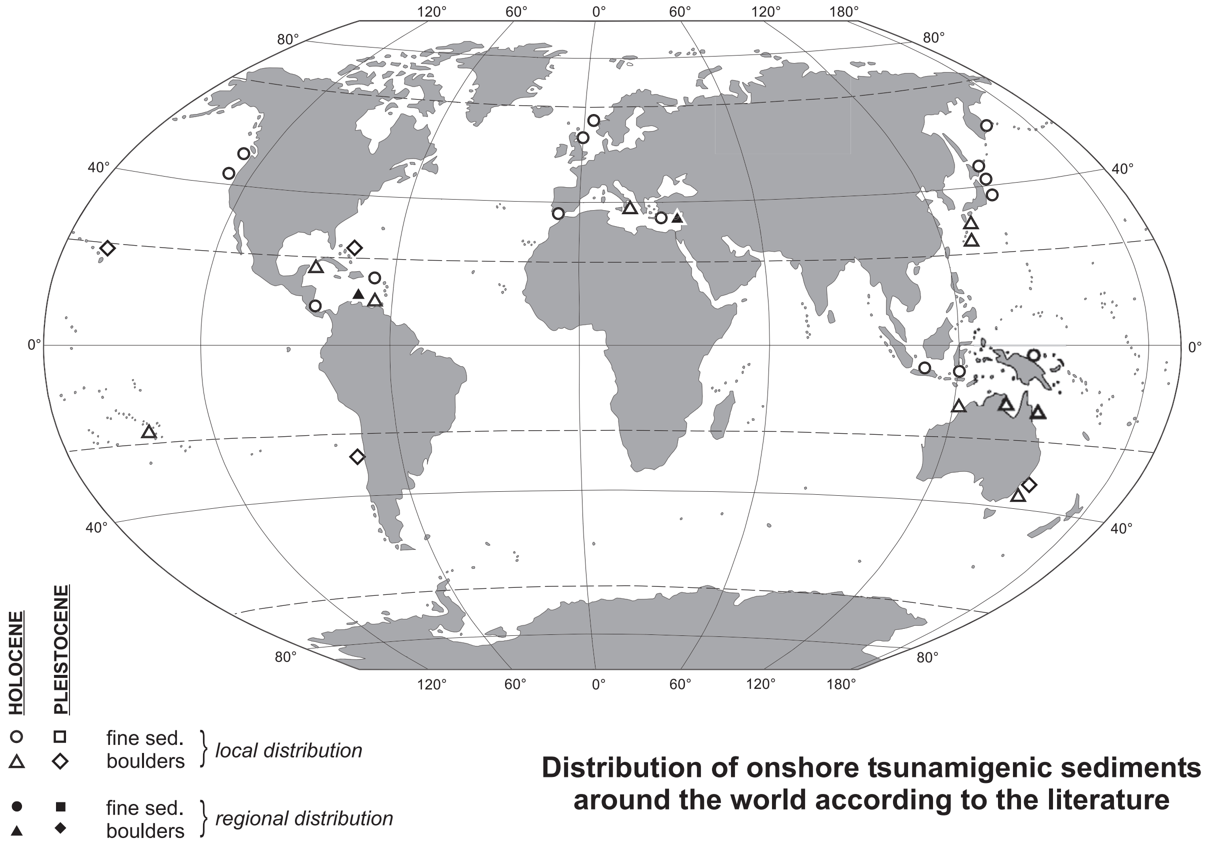

Fig. 3. Localities and regions with reliable tsunami evidence documented in sedimentary records and/or geomorphological imprints.

tsunami in sedimentary records can be found in the Caribbean (Grand Cayman, Bahamas, Puerto Rico, Nicaragua, Curaçao, Bonaire and Aruba, as well as in Venezuela), in Scotland and western Norway and along the southern coast of Portugal. In the Mediterranean tsunami, deposited sediments are located at sites in southern Italy, the Aegean Sea and Cyprus. Sedimentary evidence for tsunami in the Indian Ocean is restricted so far to northwestern Australia (Nott, 2000; Bryant, 2001). The Pacific Ocean experiences the highest tsunami frequency due to the surrounding active plate boundaries. Here, besides field evidence in Indonesia, New Guinea, northern and southeastern Australia and New Zealand, tsunami occur in particular in areas in the South Seas (Tuamotu), the Hawaiian Islands, the northwestern coast of the USA and British Columbia, Kamchatka, and especially Japan and the Kuriles Islands.

Analyses of fine sediments in these settings make up 45% of the literature (e.g. Dawson et al., 1988; Long et al., 1989, 1995, 1996; Darienzo and Peterson, 1990; Minoura and Nakaya, 1991; Andrade, 1992; Atwater, 1992; Bourgeois, 1993; Yeh et al., 1993; Clague et al., 1994; Minoura et al., 1994; Sato et al., 1995; Shi et al., 1995; Bondevik, 1996; Hindson et al., 1996; Clague, 1997; Moya, 1999; Clague et al.,

Table 1

Some quantitative data of sediments transported by large tsunami events compiled from different sources

Fine sediments

Region	Sediments	Thickness (m)	Height asl (m)	Distance to coastline (km)
Point Sampson (W-Australia)	sand, gravel	30	60	0.5
Shoalhaven Delta (SE-Australia)	sand	1	30	10
Honshu (Japan)	sand	–	–	4
Ryukyu (Japan)	sand	–	–	2.5
Jervis Bay (SE-Australia)	sand, gravel	20	130	1
Cape Leveque (W-Australia)	sand, gravel	several meters	30	30 ?
Papua-New Guinea	sand	2	2	6.75
Algarve (Portugal)	sand	0.5	2	1
Vancouver Island to Oregon	sand	0.3	5	0.5

Coarse sediments

Region	Sediment	Weight (t)	Height asl (m)	Distance to coastline (m)	Transport figure[a]
Port Stephens (Bahamas)	boulders	2000	11	500	11,000,000
Ryukyu (Japan)	coral boulders	250	30	300	2,250,000
Japan	concrete boulder	>1000	7	150	1050.000
Jervis Bay (SE-Australia)	boulders	50	33	80	132,000
New South Wales (Australia)	boulders	90	12	100	108,000
Bonaire (N.A.)	boulders	135	5	160	108,000
Grand Cayman	boulders	50	12	150	90,000
Curaçao (N.A.)	boulders	281	2.5	100	70,250
Tuamotu Atoll	coral boulders	1400	1	50	70,000
Queensland (Australia)	boulders	286	6	40	68,640
Cyprus	boulders	30	10	100	30,000
Trafalgar (Spain)	boulders	90	1	150	13,500
Mallorca (Spain)	boulders	23	8	35	6440
Apulia (Italy)	boulders	80	1.8	40	5760
Hilo (Hawaii)	concrete boulder	20	1	180	3600
Ningaloo (W-Australia)	boulders	4	4	100	1600
Ishigaki (Japan)	coral boulder	–	–	85	–
Krakatao	boulders	600	–	–	–

[a] = weight × height × distance to coastline.

2000; Dawson and Smith, 2000). About 55% of the articles focus on coarse sediments, and here predominantly boulder deposits (e.g. Davies and Hughes, 1983; Miyoshi et al., 1983; Moore and Moore, 1984, 1988; Bourrouilh-Le Jan and Talandier, 1985; Ota et al., 1985; Harmelin-Vivien and Laboute, 1986; Talandier and Bourrouilh-Le Jan, 1988; Paskoff, 1991; Bryant et al., 1992, 1996; Jones and Hunter, 1992; Jones, 1993; Nakata and Kawana, 1993, 1995; Shi et al.,1993, 1995; Moore et al., 1994; Nishimura and Miyaji, 1995; Schubert, 1994; Bryant et al., 1996; Hearty, 1997; Nott, 1997, 2000; Mastronuzzi and Sanso, 2000; Felton et al., 2000; Kelletat and Schellmann, 2001, 2002; Scheffers, 2002a,b.

Strong tsunami events are capable of transporting sand and other fine materials more than 1 km inland and, according to Bryant and Nott (2001), even 30 km at sites along the Australian west coast. Single boulders or boulder assemblages might have been deposited several meters above sea level and 100–400 m inland. One of the most controversial evidences is located on the island of Lanai (Hawaii), where coral gravel was deposited by tsunami at a height of more than 300 m during the Last Interglacial (Moore and Moore, 1984). However, the tsunamigenic origin of the deposits is discussed controversially (Felton et al., 2000). Table 1 presents some of the quantitative data cited in the literature for sediment transported by large tsunami events. The energetic dimensions of tsunami are illustrated best by boulder deposits. The transportation and accumulation of boulders requires large drag-and-lift forces particularly if the material is broken off from rocky platforms, terraces or cliff fronts. Boulders moved by Holocene tsunami may have a weight of more than 200 t (Caribbean: see Scheffers, 2002a,b; or Queensland/Australia: see Nott, 1997), or more than 1800 t reported on the Tuamotu-Islands in the southern Pacific (Bourrouilh-Le Jan and Talandier, 1985) and some exceeding 2000 t described for the Younger Pleistocene on the Bahamas (Hearty, 1997). Moreover, boulder deposits permit an approximate estimation of the minimum amount of sediment transported by the tsunami. On the Netherlands Antilles the amount of material transported onshore by Holocene tsunami exceeds more than 1 million t (Scheffers, 2002a). Tsunami might deposit ridge formations often in parallel, but at a distance to the coastline (Scheffers, 2002a). A rough estimation of the transport energy for boulder movement is given by the “transport figure” in Table 1, which is simply the result of multiplying the weight, distance and height above sea level of a boulder. As tsunami ridges resemble normal storm ridges in shape and morphology we assume that some of the tsunami ridges have been ambiguously interpreted as storm deposits at a higher Holocene sea level.

Key questions in every paleotsunami study are the identification of the associated sea level in order to calculate the transport against gravity and the absolute age determination of the event. In any case of extreme high potential tsunami deposits source and mechanism should be investigated accurately.

3. Geomorphologic imprints of tsunami

Whereas research focusing on geologic evidences of tsunami has shown a broad variety of tsunami depositional traces, we still know little about geomorphologic tsunami imprints along the coastlines of the world. Field evidence of geomorphic alterations due to tsunami is restricted to four regions, which are described in about 15 articles (Algarve: Andrade, 1992; SE- and NW-Australia: Bryant, 2001; Bryant and Young, 1996; Bryant et al., 1996, 1997; Young and Bryant, 1992, 1993; Cyprus: Kelletat and Schellmann, 2001; Southern Caribbean: Scheffers, 2002a,b). Very few investigations attempt to describe and estimate the role of tsunami impacts on the Pleistocene and Holocene coastal development. According to Bryant (2001), the effects of tsunami on coastal forming processes are in general rather limited, but occasionally they may have played a major role. Bryant et al. (1996) suggested that extreme Holocene tsunami events have been the dominant factor for the coastal development in southeastern Australia and were primarily responsible for the formation of barrier islands, cliffs, canyons and sculptured bedrock forms. To carve bedrock forms like, e.g. flutes or vortexes, extreme flow velocities are necessary—a fact which suggests that tsunami are responsible, as opposed to large storm waves. The largest paleotsunami waves in Australia swept sediment across the continental shelf and obtained flow depths of 15–20 m at the coastline with velocities in excess of 10 m

s^{-1}. Tsunami may deposit sediments well above extreme cyclone storm wave limits. In New South Wales, along the cliffs of Jervis Bay, waves reached elevations of more than 80 m asl with evidence of flow depths in excess of 10 m (Bryant and Nott, 2001).

Andrade (1992) examined barrier islands located in front of the Algarve in southern Portugal and demonstrated that their shape and other associated forms, in particular *overwash*-features, can be attributed to the Lisboa Tsunami of 1755.

As the impact of a tsunami event is limited to a duration of seconds, we can compare its morphogenic effects with the constant forming processes in a limestone coastal environment, e.g. bioerosion (Kelletat and Schellmann, 2001, 2002). The relation of both forming processes can be estimated with 1:1 billion, as the time span for the development of a 1-m notch is approx. 1000 years, whereas the destruction by a tsunami needs less than 30 s. Small-scale geomorphological forms and fine structures on rocky limestone shorelines can provide valuable information for relative age determinations of tsunami events. These methods played an integrative role in the documentation of paleotsunami on Aruba, Curaçao and Bonaire (Netherlands Antilles) by Scheffers (2002a,b), one of the most comprehensive studies concerning geomorphological and sedimentological effects of Holocene tsunami. A detailed discussion of tsunamigenic depositional and erosional signatures is compiled by Bryant (2001). The author in particular refers to small-scale erosional indicators of high velocity flows such as impact marks, drill holes, comma marks, sinuous grooves, troughs or cavettos and flutes, which so far have been attributed exclusively to the outburst of huge subglacial meltwater streams. Larger bedrock sculptures of greater than 1 m are vortex, whirlpools, canyons, drumlin-like and keel-like features. Most of them require flow velocities greater than 10 m s^{-1} given that a tsunami may last only a couple of minutes. Sedimentary evidence of large tsunami impacts may include mega-ripples, with a relative height of more than 7 m and a crest-to-crest distance of approx. 1000 m as reported by Bryant (2001) from western Australia, or so-called *chevrons*, characterized by lance-like shaped and parallel convoluted accumulations often mapped as parabolic dunes. Bryant (2001) also describes chevron deposits at Jervis Bay in New South Wales, where the features reach a height of up to + 130 m asl. In NW-Australia, chevron ridges have been identified even 30 km inland from the modern coastline. However, tsunami-induced chevron ridges may be much more widespread in Australia as what a study by the authors of this article shows (Scheffers and Kelletat, 2001, in press).

4. Conclusions: future steps in tsunami field research along the coastlines of the world

Future research should concentrate on four main topics in order to understand the high magnitude–low frequency tsunami events in coastal evolution:

Development of standardized field methods for the identification of tsunami sediments, in particular boulder deposits. In every paleotsunami study and for each location, the associated sea level has to be investigated in order to estimate the correct runup values.

Detailed mapping surveys of depositional and erosional tsunami signatures as well as geomorphological alterations subsequent to recent large tsunami impacts including the entire coastal zone and the foreshore area. It is not sufficient to survey inundation and runup as is commonly practiced in most field studies. It seems striking that no detailed geomorphological field surveys have been carried out for the well-documented large tsunami events on the Hawaiian Islands in 1946, 1960 and 1964.

Geomorphological tsunami traces should be surveyed and mapped at reference localities, where objective data sets (e.g. bathymetry) as well as images may provide valuable information. Potential areas include, e.g., the Hawaii-Islands, certain sites in the Mediterranean, Japan or Indonesia.

Research activities should focus on areas where frequent Pleistocene and Holocene paleotsunami have been identified. Reliable age determinations may help to estimate the frequency of tsunami more accurately. With this, the intensity of forming processes over a certain geological time period can be better understood. Areas in Alaska, Oregon, northern California, the Caribbean, Peru, Chile and Australia with identified teletsunami impacts may provide favourable conditions for such studies.

In the future an intensified participation of geologists and geomorphologists in tsunami-related research is required.

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