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Tsunamigenic Earthquakes: Past and Present Milestones

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Abstract—We review a number of events which, taken individually, have significantly affected our understanding of the generation of tsunamis by earthquake sources and our efforts at mitigating their hazards, notably through the development of warning algorithms. Starting with the 1700 Cascadia earthquake, we examine how significant tsunamis have changed our views in fields as diverse as seismotectonics, the diversity of earthquake cycles, the development of warning algorithms, the response of communities at risk to warnings, and their education, the latter being either formal or rooted in ancestral heritage. We discuss in detail lessons from the 2004 Sumatra disasters and review the performance of warning centers and the response of affected populations during the nine significant tsunamis which have taken place since 2004.

1. Introduction

This paper examines a number of earthquakes whose tsunamis can be regarded as milestones in the development of our understanding and mitigation of the hazards posed by this form of disaster. The events selected for this discussion do not necessarily derive from a ranking in terms of size (expressed as seismic moment) or tsunami death toll, although the record holders in both categories, the 1960 Chilean and 2004 Sumatran earthquakes, are included. Rather, we compile events which, taken individually, have added an incremental element to our command of one or more aspects of tsunami science in disciplines as diverse as seismological source theory, numerical hydrodynamics, the development of ocean-bottom pressure sensors, and the societal aspects of the mitigation of tsunami hazards.

The milestone events are described in chronological order of their occurrence. In the case of historical tsunamis (e.g., 1700, 1868), this does not reflect the timing of the community's research and understanding of their characteristics. For example, the concept of source directivity, introduced by BEN-MENAHEM and ROSENMAN (1972) in the wake of the 1964 Alaskan tsunami, predated the identification of the 1700 Cascadia earthquake by SATAKE *et al.* (1996).

In addition, the last section of this paper critically analyzes the response of the warning centers and of the communities at risk during the nine significant tsunamis which have occurred since the 2004 Sumatra–Andaman disaster. It points out an alarming diversity of performance, including both false alarms and missed warnings, as well as both successful evacuations and tragic death tolls. This clearly indicates that a continued effort is required, in particular, regarding the education of populations at risk.

2. Cascadia, 26 January 1700—Danger in America's Backyard

Upon the advent of plate tectonics, it became clear that the Western US and Canadian margin, from Cape Mendocino, California to Vancouver Island, British Columbia, constitutes a subduction zone where the small Juan de Fuca plate, a remnant of the larger Farallon plate (ATWATER 1970), is consumed under North America. While typical attributes of subduction zones such as active arc volcanism and deeper than usual seismicity (albeit extending only to 73 km) are present in Cascadia, the area is notably deprived of large interplate thrust earthquakes expressing the subduction. Indeed, the CMT catalog, now extending over 34 years, lists no such event of

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moment >10^{25} dyn*cm. This relative quiescence had suggested that the subduction zone is unlocked, accommodating the convergence through aseismic creep (Ando and Balazs, 1979).

However, Savage *et al.* (1981) interpreted geodetic profiles in the Seattle area as suggesting that the plate boundary was actually locked. Heaton and Kanamori (1984) argued that Cascadia was, after all, not so different in its tectonic properties from other locations where giant earthquakes are known, such as Southwest Japan or Colombia, although decades later, the 2004 Sumatra earthquake was to prove that tectonic parameters alone are a poor predictor of the maximum earthquake along a subduction zone (Stein and Okal, 2007). Later, Atwater (1987) located buried vegetated soils in intertidal basins, which he interpreted as tsunami deposits.

Any large Cascadia events would have to feature extended recurrences times, so that the last one would predate the dawn of available historical records (essentially going back to Lewis and Clark's expedition in 1805), but would then be expected to recur in the future, casting a new and somewhat ominous light on the question of seismic risk in the Pacific Northwest of the United States (Heaton and Hartzell, 1987).

In this framework, Nelson *et al.* (1995) used ^{14}C dating of earthquake-killed vegetation to show that a major earthquake with a fault length of 900 km had taken place between the late 1600s and early 1800s. Finally, Satake *et al.* (1996) identified the "orphan" tsunami of 26 January 1700, whose records in Japan could not be associated with any known large Pacific earthquake, as having originated in Cascadia, and later provided a quantitative modeling of the far-field (tsunami) and local (subsidence) data to infer a most probable value of 5×10^{29} dyn*cm for the seismic moment of the proposed earthquake (Satake *et al.*, 2003). The precise year was also confirmed from tree-ring evidence (Jacoby *et al.*, 1997).

Later work by Obermeier and Dickenson (2000) on liquefaction evidence identified a previous event around 1100 A.D., but yielded deficient accelerations for the 1700 earthquake, which would require some level of source slowness in order to be reconciled with the Satake *et al.* (2003) moment value. Nelson *et al.* (2006) have further documented in the stratigraphic record a series of predecessors, whose exact sizes show identifiable fluctuations, as reported in many other provinces, since the pioneering work of Ando (1975).

The following are important lessons to be heeded from the 1700 earthquake, most of which will be common themes in the present study:

- The U.S. is at risk from a potentially catastrophic near-field tsunami for which warning times could be as short as 15 min.
- Mega-earthquakes ($M_0 \geq 10^{29}$ dyn*cm) can occur in areas where incomplete understanding of the tectonic framework has made them hitherto unexpected.
- Many mega-earthquakes feature source slowness, resulting in accelerations (in particular felt by humans) which can be deceptive as a warning of an impending tsunami.

3. *Lisbon, 01 November 1755—Europe's Deadliest Natural Disaster*

With a death toll approaching 100,000 (Chester, 2001), the All Saints Day earthquake and tsunami represent the largest natural disaster to affect Europe in modern times. The tsunami is also remarkable in that waves of up to 4–5 m amplitude were reported in the Caribbean, which constitutes one of only two known cases of damage in the far field across the Atlantic Basin.[1] Following numerous attempts by many authors (e.g., Thiébot and Gutscher, 2006) to interpret the earthquake and its tsunami in the context of the regional plate tectonics framework, Barkan *et al.* (2009) recently used numerical hydrodynamic simulations to forward model a large number of possible scenarios; they narrowed down the most probable source to being a thrust fault section of the Azores-Gibraltar segment of the Eurasia-Africa plate boundary, located at 36.5°N and 13°W in the Horseshoe abyssal plain, and striking ~345°N. They suggested a large moment, of about 10^{29} dyn*cm, but

[1] The other known transatlantic tsunami took place on 31 March 1761; its source may have been an aftershock of the 1755 earthquake (O'Loughlin and Lander, 2003).

any surficial expression of their proposed source of the 1755 earthquake remains to be documented in the local bathymetry.

Barkan *et al*. (2009) showed that only their model can explain the most remarkable variation of the tsunami reports along the Western shore of the Atlantic, namely damaging in the Caribbean and notable in Newfoundland, but conspicuously absent along the Eastern seaboard of the United States, despite the existence of many settlements there in 1755. In this respect, the distribution of tsunami amplitudes in the far field is a subtle combination of classical source directivity (Ben-Menahem and Rosenman, 1972) and focusing by irregular bathymetry (Woods and Okal, 1987; Satake, 1988).

The most important lesson from the Lisbon tsunami is the vulnerability of the Eastern coast of the Americas, from Newfoundland to the Caribbean, to transatlantic tsunamis. However, the variability in location and focal mechanism of the major earthquakes along the Azores-Gibraltar seismic belt (evidenced by the 1755, (1761?), 1941, 1969 and 1975 earthquakes), suggests that the next earthquake with potential transatlantic hazard may not duplicate the 1755 event. Even a minor change in fault orientation and/or in source location could significantly affect directivity and focusing, resulting in an altered distribution of tsunami amplitudes. In particular, there is no reason to believe that the somewhat miraculous protection of coastal North America in 1755 would be repeated under a future scenario.

4. *Southern Peru, 13 August 1868—A True Giant which Scoffs at Barriers*

This event was the last mega-earthquake to rupture the whole coast of southern Peru and to generate a basin-wide tsunami from that province. The tsunami ran up locally to as high as 18 m, and is perhaps best known for the anecdote of the *Watery*, a US Navy steamer which was visiting the port of Arica (then in Peru, now in Chile). The vessel was swept ashore and deposited against the cliff of El Morro, 3 km inland, only to be returned to the vicinity of the shoreline during the next tsunami, on 09 May 1877 (Billings, 1915). In the far field, the tsunami was particularly intense in New Zealand, with heights of 7–8 m, and reached all the way to Japan and the Philippines. There is some suggestion that it may have unseasonably calved large icebergs off the coast of Antarctica (Solov'ev and Go, 1984).

An intriguing aspect of this tsunami is that it caused complete destruction at Pisco, in central Peru, only 200 km southeast of Lima, suggesting that the 1868 earthquake could not be just a repeat of the previous large Southern Peru earthquake, on 23 November 1604, during which the tsunami had been more moderate. In attempting to model the effect of the 1868 tsunami in Pisco, Okal *et al*. (2006a) showed that it was necessary to extend the seismic rupture northwest some 300 km; this requires the fault to extend across the Nazca Ridge. In this context, the ridge cannot be regarded as a natural barrier acting to bound the rupture of large earthquakes, as it probably had done during the 1604 event (Dorbath *et al*., 1990). Thus, the a priori identification of the size of a future large earthquake along a given subduction province cannot be guided by our perception of natural barriers which may be jumped during exceptional events. Indeed, the tsunamigenic earthquake of 01 April 2007 in the Solomon Islands is another example in which the rupture propagated across a major tectonic feature—in this instance the triple junction between the Pacific, Australian and Woodlark plates (Taylor *et al*., 2008).

5. *Sanriku, Japan, 15 June 1896—The First Identified "Tsunami Earthquake"*

With a death toll of over 27,000, this event is the deadliest recorded tsunami in the history of Japan. It represents the first known "tsunami earthquake", whose tsunami was much larger than expected from the amplitude of its seismic waves. As summarized by Kanamori (1972), the earthquake was felt only mildly along the Sanriku coast, but the tsunami featured catastrophic proportions, with run-up reaching 30 m in the near field, up to 5 m in Hawaii, and damage reported in Santa Cruz, California. The anomalous character of the seismic source spectrum of the great 1896 "Meiji Sanriku" earthquake was asserted by Kanamori (1972) from a slower-than-normal decay of seismic intensities with distance, which argues for a lower-frequency seismic spectrum, and from the deficiency in high-frequency P waves with respect to a more regular local earthquake as recorded on a nearby short-period seismometer.

One hundred years after the event, Tanioka and Satake (1996) showed that local maregraph records of the tsunami could be modeled using a source rupturing in the sedimentary wedge overlying the interplate contact in the vicinity of the Sanriku trench, with a seismic moment of 1.2×10^{28} dyn*cm, about double the value obtained by Kanamori (1972) at a period of 20 s, and 60 times that inferred from 4-s S waves, thus upholding the concept of an anomalously slow rupture.

The geometry proposed by Tanioka and Satake (1996) is also in agreement with Fukao's (1979) model for the "tsunami earthquakes" of 20 October 1963 and 10 June 1975 in the Kurile Islands. However, those events occurred as aftershocks of larger earthquakes with regular rupture properties, whereas the 1896 Sanriku earthquake did not.

6. Kamchatka, 03 February 1923—The First Warning in the Far Field

This event represents, to our knowledge, the first case of a realistic, if unheeded, tsunami warning in the far field, based on the interpretation of seismic waves from the parent earthquake. The details of this remarkable episode are given by Jaggar (1930), even though he persistently describes the earthquake as located in the Aleutian Islands.

Thomas Jaggar was, at the time, Director of the Volcano Observatory located on the rim of Kilauea caldera, on the "Big" Island of Hawaii, where he had deployed Omori seismometers with the purpose of monitoring locally generated volcanic tremors. The Kamchatka earthquake occurred at 16:01 GMT, and its seismic waves were recorded in Hawaii (whose time zone was then GMT-10:30) around 05:40 local time. Upon reaching his laboratory on the morning of Saturday, 03 February, Jaggar noticed the recording of a very large earthquake. With only one station, he was unable to precisely locate the event, but he could estimate a distance, probably from the S–P delay, inferring that something "big and far" had just happened somewhere in the Pacific Basin. Just three months earlier, on 11 November 1922, Hawaii had been affected by the tsunami from the South Atacama Chilean earthquake, which had run up to 2.1 m in Hilo, and whose arrival time provided an average speed of tsunami waves on the high seas. Epicentral distance was all Jaggar needed to predict the arrival of a tsunami later that morning. He then notified the local authorities in Hilo, who unfortunately regarded his warning as nothing more than the fantasy of a gentleman scientist perched on "his" volcano, and simply ignored it. The tsunami arrived at 12:20 p.m. local time, inflicting more than 1.5 million 1923-dollars worth of damage on the islands, and killing one person.

The next tsunami alert in Hawaii came on 02 March 1933 following the Showa Sanriku earthquake. By a repeated stroke of luck, the event occurred at about the same time, leading to a remarkably similar timeline of measurements and warning by Jaggar. This time, however, the civil defense authorities in Hilo took it seriously, and evacuated people from critical areas. The tsunami was damaging but no lives were lost.

Unfortunately, as will be described in Sect. 7, the situation was different on 01 April 1946, during the Aleutian tsunami, which remains to this day the deadliest in the recorded history of Hawaii. The timing of the source (12:29 GMT), the anomalously slow character of the event (Kanamori, 1972; López and Okal, 2006) and Jaggar's retirement in 1940, combined to provoke a total surprise upon the arrival of the waves, which had a disastrous impact on Hilo (see Sect. 7).

Several lessons are to be learned from this story and remain pertinent to this day. First is the value of permanent, grass roots observation of seismic waves. Nowadays, this function has been delegated to computers, which can superbly locate earthquakes in real time and usually provide an adequate estimate of seismic moment. However, it takes the human mind to properly assess a new, unforeseen, observation. In addition, this episode illustrates the delicate interaction between the scientist and the civil defense decision-makers. The example of the 2006 Java tsunami (see Sect. 18) serves proof that progress is still needed in this respect.

Finally, it is worth noting that Jaggar issued an appropriate tsunami warning without much command of theoretical fluid dynamics [as transpires from a critical reading of JAGGAR (1930)], and above all without the correct location of the source. It is unclear whether he had formulated an estimate of the epicenter before issuing the warning, or was simply relying on "big and far". In the former case, his estimate would have been wrong, since 7 years later he still believed that the 1923 earthquake was off-shore from Unimak, 2,300 km from its true location. Yet, his warning was proved correct since the tsunami caused significant damage and death, even though the relevant error in epicentral distance would have amounted to an error of 2 h in arrival time, which, under today's standards, would most probably have resulted in the perception of a false alarm and consequently in an untimely "all clear". However, in the context of this 1923 episode, it may not be irrelevant to reflect on the possibly subtle value added to the usefulness of a far-field warning by elaborate real-time refinements of earthquake source parameters.

The 1923 Kamchatka tsunami is also remarkable in that it was followed on 13 April 1923 by a particularly destructive tsunami at Ust' Kamchatsk during an otherwise moderate aftershock (SOLOV'EV and FERCHEV, 1961). That event could constitute the first example of a "tsunami earthquake" reported in the aftermath of a larger shock, although the tsunami could also be due to underwater slumping off the mouth of the Kamchatka River.

7. *Aleutian Islands, 01 April 1946—First and Still Deadliest Tsunami Disaster in U.S. History*

With 159 deaths in Hawaii and 5 on Unimak, the 1946 Aleutian tsunami remains the deadliest to hit the U.S. and its possessions in the twentieth century, and is also the first major "tsunami earthquake" for which a quantitative analysis of its source characteristics is possible from historical seismograms (LÓPEZ and OKAL, 2006). The 1946 disaster resulted in the creation of the Tsunami Warning Center [later Pacific Tsunami Warning Center] at the Honolulu Geomagnetic Observatory in 1949.

The earthquake took place at 12:29 GMT, i.e., in the middle of the night at the epicenter. Its source slowness is reflected in the modest conventional magnitude ($M = 7.4$) assessed by GUTENBERG and RICHTER (1954), in the absence of hydroacoustic T waves (OKAL *et al*., 2003a), and in that its moderate aftershock (27 mn later) had been felt more strongly by the watchstanders at Scotch Cap lighthouse who would meet their deaths in the tsunami a few minutes later (SANFORD, 1946). The event generated a Pacific-wide tsunami which reached Hawaii in the early morning (06:54 local time or 17:24 GMT). It destroyed the coastal infrastructure in Hilo and did significant damage in the Marquesas, Easter Island, and as far South as Antarctica (FUCHS, 1982). In the near field, the tsunami eradicated the lighthouse at Scotch Cap, which had been built of reinforced concrete only 6 years earlier, with a local run-up reaching 42 m as measured later by OKAL *et al.* (2003b). Total losses from the tsunami in Hawaii were estimated at 25 million 1946-dollars (SHEPARD *et al*., 1950).

The disparity between the size of the seismic source (at least as measured from conventional waves) and the catastrophic nature of the tsunami led KANAMORI (1972) to introduce the concept of "tsunami earthquake", i.e., of an event whose tsunami is stronger than expected from the size of its seismic waves. Later work (FUKAO, 1979; NEWMAN and OKAL, 1998; POLET and KANAMORI, 2000) has shown that such earthquakes are characterized by a deficiency in rupture velocity along the fault plane, leading to destructive interference for all but the longest-period components of the seismic source, and resulting in an underestimation of its long-period or static level moment (responsible for tsunami excitation) when assessed from conventional seismic waves. Indeed, a very-long period investigation of the source of the 1946 earthquake has suggested a moment as large as 8.5×10^{28} dyn*cm and a slowness parameter $\Theta = -7.0$, making it one of the 10 largest events ever recorded, and the slowest one ever analyzed (LÓPEZ and OKAL, 2006).

Between 1999 and 2002, OKAL *et al.* (2002, 2003b) were able to reconstruct a database of run-up and inundation in both the near and far fields, based on the testimony of elderly witnesses. These datasets, comparable to those resulting from modern-day post-tsunami surveys, revealed two fundamental results. In the far field, run-up amplitudes exhibit a very strong directivity effect, which is the trademark of a dislocation source, and they can be successfully modeled using López and Okal's (2006) seismic source (Okal and Hébert, 2007). However, in the near field, both the exceptional amplitude of run-up and its concentration along a short segment of the coast of Unimak Island cannot be reconciled with generation by any dislocation compatible with seismic observations, even at the longest available periods; this requires an alternate source for the local tsunami, most probably a large landslide triggered by the seismic event, and for which Okal *et al*. (2003b) proposed a model with a volume of 200 km^3, allowing a satisfactory match to the surveyed run-up amplitudes. While anecdotal evidence exists, reported by elderly fishermen, to support the landslide hypothesis, a definitive identification is still lacking in the local bathymetry, and would require a modern mapping effort in this respect. Note, finally, that because of its much shorter wavelengths and extremely slow source process, any landslide source fails to propagate efficiently to the far field, where it has little effect on the distribution of run-up at distant receiving shores.

The reassessment of the seismic source of the 1946 event by López and Okal (2006) raises interesting questions in the local seismotectonic context. First, it requires a bilateral rupture of approximately 200 km along the Eastern Aleutian arc, which eliminates the so-called "Unimak gap" between the presumed Eastern extent of the 1957 Andreanof rupture, and the previously recognized fault area of the 1946 earthquake. To the East, the fault zone of the 1946 earthquake does not necessarily extend over the Shumagin gap. The latter remains a potential zone for a future large earthquake, although such an event may not necessarily duplicate the catastrophic earthquakes of 1788 in the Shumagin–Kodiak segment of the trench (Solov'ev, 1968), given the known variability in rupture length among large events of a given subduction zone (Ando, 1975).

The same variability would suggest that not all large earthquakes along the Unimak segment—past and future—share the characteristics of size and slowness of the 1946 event. This may help explain the apparent discrepancy between the large size of the 1946 earthquake and the lack of evidence from geodetic data for a locked contact along its rupture zone in what could be the very early stages of a long interseismic cycle (Mann and Freymueller, 2003).

8. *Kamchatka, 04 November 1952—The Cloaked Killer*

With a moment estimated at 3.5 × 10^{29} dyn*cm (Kanamori, 1976), the 1952 Kamchatka earthquake was, at the time, the largest seismic event recorded instrumentally, and remains to this day the fourth largest. With significant progress (Benioff, 1935) in long-period instrumentation in the 1930s, Benioff (1958) was, indeed, able to propose the first detection of the Earth's fundamental free oscillation, ${}_0S_2$, on a Pasadena strainmeter record of the event, a claim later validated (not without certain qualifications) by Kanamori (1976). A strong tsunami was generated, causing close to one million 1952-dollars in damage in Hawaii, but fortunately no deaths.

Because of the absence of casualties in the far field, this event was often perceived as involving a deceptive tsunami, as no reports were available from the near field. The 1952 Kamchatka tsunami was, in fact, a closely guarded state secret in the then-USSR, especially since we now know that it had eradicated the sensitive naval base at Severo-Kuril'sk. After the fall of the Soviet Union in 1991, information started to slowly trickle out in the form either of dissemination abroad of existing reports (e.g., Savarenskiy *et al*., 1958), or of studies resulting from new research into this matter (Kaistrenko and Sedaeva, 2001). Among the latter, Smyshlyaev (2003) reported 7,802 civilian deaths in the Northern Kurils, and estimated that the total death toll in the city of Severo-Kuril'sk, including military casualties, must have reached 10,000 and perhaps as high as 17,000, making the event by far the deadliest tsunami in the twentieth century.

9. *Chile, 22 May 1960—Still in a Class by Itself*

With a moment estimated anywhere from 2 to 5 times 10^{30} dyn*cm, the 1960 Chilean earthquake remains the largest seismic event recorded instrumentally and studied quantitatively (Cifuentes and Silver, 1989). It is also the last one whose tsunami exported destruction and death across the entire Pacific Basin, all the way to Japan, where it claimed 142 lives.

In Hawaii, the tsunami totally destroyed the waterfront district of the city of Hilo, inflicting 20 million 1960-dollars worth of damage, and causing 61 deaths. A most unfortunate aspect of this episode is that the combination of reports from the epicentral area and an assessment by scientists at the Honolulu Geomagnetic Observatory and the Hawaii Volcano Observatory, had led to a warning at 18:47 local time (9.5 h after origin time), resulting in a call for evacuation at 20:30 for an expected arrival time around midnight local time. As detailed by Eaton *et al.* (1961), after the first wave reached Hilo around 00:13 (local time; 23 May) with a benign run-up on the order of 1.5 m, the alarm was not maintained, and the much larger third wave ran up 12 m and penetrated 1 km in land at 01:05 on 23 May, devastating the waterfront area.

The lesson to be learned from the Hilo disaster in 1960 is that the maximum wave during a distant tsunami is rarely the first one. The very long periods of the phenomenon (typically 40 mn or longer) can give a sense of security to residents—and to civil defense authorities who will be tempted to sound an all clear—even though the worst is yet to come. This situation was to be dramatically repeated in Crescent City, California, four years later during the Good Friday Alaskan tsunami.

The exceptional size of the 1960 Chilean earthquake led to a paradox, first outlined by Kanamori (1977a), as the combination of the slip released during the event (at least 20 m), and the perceived recurrence rate of catastrophic earthquakes along the Central Chilean subduction zone (125 years) leads to a rate of seismic release (16 cm/year) greater than inverted from global kinematic models of plate motions (11 cm/year) or, in other words, to a seismic efficiency along the plate boundary >100%. This inconsistency was eventually resolved from paleotsunami studies (Cisternas *et al.*, 2005) which showed that most predecessors of the 1960 earthquake were actually of smaller size, and could not be considered as equivalent instances in the seismic cycle, illustrating once again the Ando (1975) model of randomness in the sequences of earthquake ruptures at subduction zones.

10. Alaska, 28 March 1964—The Concept of Directivity

This earthquake (which occurred on Good Friday, 27 March at its epicenter) is the largest ever to hit the United States. Its moment, assessed at 8.2×10^{29} dyn*cm by Kanamori (1970) using 250-s surface waves, may feature a longer component to its source (Nettles *et al.*, 2005), and is essentially in a tie with the 2004 Sumatra earthquake for second-largest seismic moment ever measured. It generated a tsunami which killed 124 people (as opposed to only 15 from the earthquake). The event resulted in the creation of the Alaska/West Coast Tsunami Warning Center in 1967.

In the near field, the detailed effects of the tsunami were enhanced by a number of local landslides (Haeussler *et al.*, 2007). In the far field, the tsunami did considerable damage and caused 12 deaths in Crescent City, California. Even though a warning had been issued and an evacuation ordered, the residents acquired a sense of safety after the first two waves, and several returned to their houses to start the process of clean-up. The third wave, running up to 7 m in the middle of the night (1:40 a.m. local time), caused more destruction and killed the majority of the victims. By contrast, no victims were to be claimed in Hawaii, where the tsunami did cause some flooding.

The earthquake also gave rise to significant seiches in estuaries along the Gulf of Mexico (Donn, 1964), which McGarr (1965) modeled theoretically as locally excited by Love and Rayleigh waves of exceptional amplitudes but of conventional periods. Such oscillations are, however, unrelated to the tsunami, since similar effects have been observed in the far field for continental earthquakes (Kvale, 1955; Barberopoulou *et al.*, 2006).

The onslaught of the tsunami in the far field (towards the North American coastline from British Columbia to California) featured a geographic distribution different from that of the 1946 event, which was aimed at the Central Pacific. In a landmark contribution, Ben-Menahem and Rosenman (1972) showed that this could be explained by directivity resulting from the spatial extent of the source. Using the formalism introduced by Ben-Menahem (1961) to explain the directivity pattern of seismic surface waves, and the 600-km fault line suggested by Kanamori (1970), but allowing for the slow phase velocities of tsunamis (at most 220 m/s) relative to the rupture velocities along fault lines [typically 3 km/s, and at least 1 km/s for even the slowest ruptures (Polet and Kanamori, 2000)], Ben-Menahem and Rosenman (1972) explained that tsunamis are of maximum amplitude in the direction perpendicular to the fault strike (the only one for which the interference between the various source segments along the fault can be constructive). This, of course, was different in 1946 and 1964, due to the curvature of the Alaska–Aleutian arc. Okal and Talandier (1991) later showed that the width of the directivity lobe decreases with increasing earthquake size.

This concept of source directivity, first introduced in the wake of the 1964 Good Friday tsunami, is crucial to understanding the long range propagation of tsunamis. For example, it readily explains the extreme amplitudes of the 2004 Sumatra tsunami in Somalia, as opposed to Southern Africa (and of course Australia), and suggests that a future large Mentawai tsunami would not share the directivity pattern of 2004, with the results that different far-field shores would find themselves at maximum risk (Okal and Synolakis, 2008).

11. Petatlan, Mexico, 14 March 1979; Gulf of Alaska, 30 November 1987 and 06 March 1988

On the Long Road to DART Sensors

The 1979 Petatlan event was a relatively moderate subduction earthquake ($M_0 = 1.7 \times 10^{27}$ dyn*cm) which generated a minor tsunami with a run-up of 1.3 m in Acapulco. What makes it remarkable is that it produced the first ever recording of a tsunami in deep water, on a pressure sensor deployed on the ocean floor 981 km away from the epicenter, at the entrance to the Gulf of California, during a seafloor magnetotelluric experiment (Filloux, 1982). This observation led to the development of ocean-bottom pressure recorders specifically engineered as tsunami detectors (Bernard and Milburn, 1985), which, coupled with real-time communications, later resulted in the Deep-Ocean Assessment and Reporting of Tsunamis (DART) network.

The first detections by long-term DART prototypes were obtained off the Alaska peninsula from tsunamis generated by the Gulf of Alaska intraplate earthquakes of 1987 and 1988 (González *et al.*, 1991). Despite the low seismic moment of these events (8×10^{26} and 4×10^{27} dyn*cm, respectively), their tsunamis were recorded in deep water with equivalent surface amplitudes of 1–3 cm, on the same order of magnitude as suggested by preliminary numerical simulations using the SWAN code (Mader, 1998). These successful detections and interpretations of tsunami signals motivated the later development of the full DART real-time algorithm (González *et al.*, 1998).

In retrospect, an additional interesting aspect of the detection of the tsunamis generated by the 1987–1988 Alaska Bight earthquakes is that these had strike-slip mechanisms. Conventional wisdom suggests that this geometry produces no vertical displacement of the ocean floor and hence should not generate tsunamis. However, when investigated under Ward's (1980, 1981) application of normal mode theory, strike-slip geometries are found to be relatively efficient tsunami generators. Okal (2008) has explained this paradox by noting that a strike-slip fault contributes to static vertical ground motion through zones of deformation located at the tips of the fault. Other strike-slip events having generated detectable tsunamis include the Macquarie earthquake of 23 December 2004 (Okal and MacAyeal, 2006).

12. Nicaragua, 02 September 1992

First Digital Age "Tsunami Earthquake" and the Initiation of Systematic Surveys

This event represents the first "tsunami earthquake" for which digital data allows a modern investigation of its seismic source. The earthquake was characterized by an exceptional discrepancy between its body-wave magnitude, $m_b = 5.3$, and its conventional surface-wave magnitude, $M_s = 7.2$, with a Harvard CMT of $M_0 = 3.4 \times 10^{27}$ dyn*cm. As a result of this deficiency in high-frequency body waves, the earthquake was not felt in many sections of the Nicaraguan coast, thus depriving the population of any natural tsunami warning. The tsunami arrived 40 min later, running up to 9.9 m, causing considerable damage, and killing more than 160 persons.

This tragedy renewed interest in the so-called "tsunami earthquakes", defined by KANAMORI (1972) as events whose tsunamis are stronger than would be expected from their conventional seismic magnitudes. The availability of high-quality data from digital networks allowed detailed studies of the seismic source, which documented extremely slow rupture velocities leading to destructive interference in the high-frequency part of the source spectrum (KANAMORI and KIKUCHI, 1993; VELASCO *et al.*, 1994), and later interpreted as expressing an irregular rupture over a jagged plate interface resulting from sediment starvation (TANIOKA *et al.*, 1997; POLET and KANAMORI, 2000).

In the wake of this event (and of similar "tsunami earthquakes" in 1994 in Java, and in 1996 at Chimbote, Peru), NEWMAN and OKAL (1998) introduced a slowness parameter, $\Theta = -\log_{10} E^E/M_0$, comparing the estimated energy E^E carried by high-frequency seismic body waves, to the seismic moment M_0 measured on long-period surface waves. This parameter, inspired by BOATWRIGHT and CHOY's (1986) quantification of seismic energy, is expected to be an invariant for earthquakes whose sources follow seismic scaling laws; on the other hand, typical "tsunami earthquakes" feature deficiencies in Θ of 1–2 logarithmic units. The slowness parameter can be computed in real-time using robust algorithms which have been implemented at the warning centers (WEINSTEIN and OKAL, 2005). The 1992 Nicaragua earthquake was also remarkable for its deficient T phases, which similarly led OKAL *et al.* (2003a) to define a discriminant quantifying the ratio of their energy flux to seismic moment.

The substantial low-frequency component of the 1992 Nicaragua earthquake was noted on its seismograms in the form of an ultra-long period oscillation taking place between P and Rayleigh waves by KANAMORI (1993), who identified it as energy multiply reflected in the upper mantle, and hence baptized it "W" phase, by analogy with whistling radioelectric modes in the atmosphere. Despite early investigations (OKAL, 1993), it would not be until the 2004 Sumatra earthquake that the potential of the W phase would be realized for providing an early estimate of the size of seismic sources at the longest seismic periods (KANAMORI and RIVERA, 2008).

The 1992 Nicaragua tsunami also inaugurated the era of systematic surveying in the wake of major tsunamis (SYNOLAKIS and OKAL, 2005), in order to build comprehensive, homogeneous databases of horizontal and vertical inundation, which can be later used for numerical modeling. The Nicaragua survey documented substantial values of run-up (8–10 m) along a 290-km stretch of coastline (ABE *et al.*, 1993), which turned out to be impossible to model using the then-standard simulation algorithms, which consisted of stopping the calculation at a shallow, but arbitrary, water depth (typically 5–10 m), and of considering the coastline as a fully reflecting boundary (IMAMURA *et al.*, 1993). In such computations, the tsunami waves were as much as one order of magnitude smaller than the surveyed values. This discrepancy pointed out the crucial effect of the interaction of the tsunami with the shore, and motivated the development of a prototype computational algorithm, modeling the penetration by the wave over initially dry land, which was able to successfully reproduce the surveyed values (TITOV and SYNOLAKIS, 1993), and which later matured into the MOST code (TITOV and SYNOLAKIS, 1998).

13. Mexico, 09 October 1995—Validating the Leading Depression Wave

This earthquake remains moderate by the standards of mega-earthquakes ($M_0 = 1.15 \times 10^{28}$ dyn*cm), but it generated the largest tsunami along the Mexican coast since the 1932 series, along essentially the same stretch of shore. Run-up was surveyed in the 5-m range along a 200-km stretch of coastline, with a splash on a cliff locally reaching a height of 10.9 m (Borrero *et al*., 1997).

The field survey was remarkable in that it documented for the first time (with evidence recorded in the form of a photograph) the systematic initial withdrawal of the sea at a local beach upon arrival of the tsunami. Such a "leading depression" wave had been predicted theoretically by Tadepalli and Synolakis (1994, 1996), and challenged the paradigm of a soliton model, in the expected geometry of an interplate thrust fault. Beyond providing a welcome experimental validation to the theory, this observation predicts that in the most widely expected geometry of an inter-plate thrust fault, the local beach will benefit from a natural warning to the population at risk in the form of an initial down-draw, which should be inherently benign to individuals on the shore.

Note, however, that the characteristic of tsunami waves in this framework, fortunate from the standpoint of warning and mitigation, suffers from several significant limitations: (1) it obviously does not apply in the far-field where the polarities of the wave are expected to be inverted; (2) an initial down-draw may be dangerous at sea, e.g., boats in harbors may be slammed against the bottom, and water intake activities, crucial, for example, to the safety of nuclear plants, may face starvation; and (3) not all tsunamigenic earthquakes are interplate thrusts, even in subduction provinces. In the case of outer rise normal faults, the polarity of the tsunami would obviously be reversed, as was the case, for example, during the 1933 Showa Sanriku earthquake.

14. Papua New Guinea, 17 July 1998—Landslides on Front Stage

This moderate earthquake ($M_0 = 3.7 \times 10^{26}$ dyn*cm) took place along the subduction zone separating the Australian plate and the Caroline fragment of the Pacific plate. It generated a locally catastrophic tsunami which eradicated several villages in the vicinity of Sissano Lagoon, with a death toll of 2,300. Field work in the area (Synolakis *et al*., 2002) revealed a number of singular properties: (1) the run-up on the shore (at this location a perfectly linear coastline) reached 15 m, an excessive value given the slip on the fault, suggested to be around 1 m by seismic scaling laws; (2) the large run-up values were concentrated on a stretch of coastline not exceeding 25 km, and fell quickly to benign values outside that segment; (3) the tsunami was locally lethal but recorded only at decimetric amplitudes in Japan. All these observations suggested a break-down of the scaling laws governing the excitation of tsunamis by seismic sources, as expressed later theoretically by Okal and Synolakis (2004), and thus required a different mechanism for the generation of the tsunami.

The case was cracked by witness reports of a delay in the arrival of the wave, which ruled out generation of the tsunami by the main seismic shock. Examination of hydroacoustic records at a number of hydrophone and seismic stations in the Pacific Basin identified an event occurring 13 min after the mainshock with an epicenter located inside an underwater amphitheater (Okal, 2003), which was interpreted as a 4-km^3 landslide triggered (with a slight delay) by the main shock. Although they could obviously not be dated to this precision, fresh landslide debris were identified during oceanographic cruises (Sweet and Silver, 2003), using both seismic reflection and direct visualization from a remotely operated vehicle. Finally, numerical hydrodynamic modeling of the tsunami using the landslide source provided a good fit to the surveyed run-up (Heinrich *et al*., 2000; Synolakis *et al*., 2002).

This identification of a landslide as the source of a locally catastrophic tsunami, triggered by a moderate earthquake, acted to sensitize the tsunami community to the hazard posed by these specific sources. They present a particular challenge since the Papua New Guinea case showed that landslides can be triggered by relatively small earthquakes, which are not limited to large subduction zones, but could occur in a wide spectrum of tectonic environments. In particular, in Southern California, a number of offshore faults have a history of hosting earthquakes with $M = 6$–7, accounting for as much as 20% of the shear between the North American and Pacific plates (DeMets and Dixon, 1999). In addition to having, themselves, the potential for a locally damaging tsunami, the largest events among them could be responsible for triggering the large landslides documented in the bathymetry (Edwards *et al*., 1993; Legg and Kamerling, 2003; Locat *et al*., 2004), whose recurrence could generate tsunamis running up to as much as 15 m on nearby coasts (Borrero *et al*., 2001).

15. Vanuatu, 26 November 1999—Education Works!

This relatively moderate earthquake ($M_0 = 1.7 \times 10^{27}$ dyn*cm) shook the central islands of Vanuatu and was accompanied by a number of sub-aerial and underwater landslides; it generated a local tsunami, which was damaging on the islands of Pentecost and Ambryn (Pelletier *et al*., 2000).

What makes the event noteworthy is the history of the village of Baie Martelli on the southern coast of Pentecost (Caminade *et al*., 2000). Following the 1998 Papua New Guinea disaster, a video program had been shown in the local language on battery-operated television sets, explaining the natural origin of tsunamis, and stressing the need to immediately self-evacuate low-lying areas upon feeling strong earthquake tremors, especially if accompanied by a recess of the sea. Just a few months later, the earthquake struck in the middle of the night, and a villager reported a down-draw. The village chief then ordered an immediate full evacuation. The tsunami completely destroyed the village, but fortunately, of the 300 residents, only three lost their lives: two elderly invalids who could not be evacuated and a drunken man, who refused to leave.

The lesson from this event is simple: Education works!

16. Aleutian Islands, 17 November 2003

First Operational Use of DART Sensor in Real Time

This event represents the first successful operational use of DART buoys in real time. The seismic epicenter (51.14°N, 177.86°E) was only 450 km west of that of 07 May 1986 (51.33°N, 175.43°W), an event which had triggered a false alarm at the Pacific Tsunami Warning Center, resulting in the evacuation of the Waikiki beaches and district in Honolulu, at an estimated cost to the local economy of 40 million 1986-dollars (Bernard *et al*., 2006). The 2003 event was, however of smaller seismic moment ($M_0 = 5.3 \times 10^{27}$ dyn*cm as opposed to 1.04×10^{28} dyn*cm).

At the time of the 2003 event, the algorithm later described by Titov *et al*. (2005) was operational at PMEL. After the earthquake occurred at 06:43 GMT, a tsunami advisory was issued by PTWC and a regional warning for the Aleutian Islands by ATWC, at 07:09. The tsunami was received at the recently deployed DART buoy Number D-171 at 07:50 with an equivalent amplitude of 2 cm. Based on pre-computed far-field tsunami amplitudes for a database of sources in the Aleutians, expected wave heights were then estimated for the Hawaiian Islands, including a benign value of only 11 cm at Hilo. On this basis, the tsunami warning was cancelled at 08:12 (McCreery, 2005). The tsunami reached Hilo at 12:00 GMT with a maximum amplitude of 17 cm, only slightly higher than the simulation performed 4 h earlier.

Because the tsunami was, in the end, benign in Hawaii, and no evacuation had been mandated, its successful quantitative prediction did not attract much publicity among the general public. Nevertheless, based on the experience in 1986, and allowing for inflation, it is estimated that the cancellation of what would have become a false alarm saved 67 million 2003-dollars. In this respect, it can be stated that the whole DART program, as it existed in 2003, paid for itself during this one event. The coordinated performance of PMEL and PTWC on that occasion must be regarded as an astounding success. It remains to be hoped that it will be as seamless, and will lead to saving lives through a successful evacuation, when the next dangerous transpacific tsunami strikes in the future.

17. Sumatra–Andaman, 26 December 2004—Deadliest in Recorded History

With a death toll generally estimated between 250,000 and 300,000, the 2004 Sumatra earthquake unleashed the deadliest tsunami in recorded history and probably in the whole history of mankind. Among its many aspects, which have been described in detail in countless publications, we will retain the following, which have arguably changed the outlook of the community on both the scientific and operational aspects of tsunami mitigation.

17.1. The Earthquake Occurred Where It Was Not Expected

Prior to the 2004 earthquake, our perception of the largest earthquake possible on any subduction zone was governed by a seminal model proposed by Ruff and Kanamori (1980). These authors had argued that a combination of age of subducted lithosphere and rate of convergence at the boundary adequately predicts the maximum earthquake observed in the seismic or historical record at individual subduction zones. The rationale behind their model was that an increased lithospheric age would make the subducting plate colder, and hence heavier, thereby helping subduction and decreasing the coupling at the interface, while on the other hand, an increase in convergence rate would enhance coupling. Based on a compilation of events recorded at 21 subduction zones, they claimed an impressive 80% correlation between observed maximum magnitudes and those predicted by their model.

According to Ruff and Kanamori's (1980) model, the northern Sumatra subduction zone should have featured a maximum magnitude of 8.2, corresponding to a moment of 2.5×10^{28} dyn*cm. The 2004 earthquake was about 40 times larger. Furthermore, Stein and Okal (2007) showed that, over 25 years, progress in estimates of convergence rates, lithospheric ages and moments of historical earthquakes, actually decreased the correlation between maximum earthquakes observed and predicted by Ruff and Kanamori's model to about 35%, a value which becomes statistically insignificant (essentially, there are more subduction zones violating the paradigm than there are following it).

In this respect, the 2004 Sumatra event is a lesson in humility: we must accept that we cannot rule out mega-earthquakes at a subduction zone simply on the basis of its most easily observable physical properties. Alternatively, Ruff (1989) had suggested that sedimentary cover could play a role in sealing the plate contact and enhancing plate coupling, thus favoring large earthquakes. This idea, recently revived by Scholl *et al.* (2007), has merit, but suffers from significant exceptions, e.g., Southern Peru and Northern Chile (Stein and Okal, 2007). Thus, the precautionary conclusion is that the maximum earthquake size on any given subduction zone may be constrained only by the maximum length over which a coherent fault rupture may develop. As discussed above (Sect. 4), the determination of that maximum length may itself be far from trivial.

17.2. However, Predecessors Existed

The largest events known prior to 2004 along the Northern Sumatra–Andaman boundary were the Car Nicobar earthquake of 31 December 1881, and the Andaman event of 26 June 1941. Ortíz and Bilham (2003) reassessed the seismic moment of the former as $M_0 = 9 \times 10^{27}$ dyn*cm based on Indian maregraph records. The latter was assigned a very high magnitude, $M = 8.7$, by Gutenberg and Richter (1954), certainly an excessive figure given Brune and Engen's (1969) later study of its 100-s Love waves, for which they proposed $M_{100} = 8.0$, which Kanamori (1977b) later expressed as a much smaller $M_w = 7.6$. A reassessment of this event based on inversion of mantle waves at four stations in the $100 - 200$ s period range, using the PDFM method (Okal and Reymond, 2003) yields $M_0 \approx 3 \times 10^{28}$ dyn*cm. Thus, the only quantified large events in that province were clearly much smaller than the 2004 earthquake.

By contrast, and further South, Zachariasen *et al.* (1999) had documented the exceptional size ($M_0 = 6 \times 10^{29}$ dyn*cm) of the 1833 Central Sumatra event, based on the inversion of coral uplift data in the Mentawai Islands. However, their results were limited to the central section of Sumatra, and in the absence of a similar study to the North of Mentawai, the potential for a mega-earthquake in the Northern Sumatra–Andaman province was not realized before 2004. In retrospect, the newly quantified 1833 event was one more example of a violation of Ruff and Kanamori's (1980) paradigm.

In the aftermath of the 2004 disaster, paleoseismic data from the Andaman Islands and the Eastern coast of India suggested the identification of predecessors with a recurrence time on the order of 1,000 years (Rajendran *et al.*, 2007). More recently, Jankaew *et al.* (2008) and Monecke *et al.* (2008) used tsunami deposits from excavations in marshy swales in Southern Thailand and Northern Sumatra to date the last two predecessors of the 2004 event at about 600 and 1,100 years B.P.

This discussion illustrates, if need be, the incomplete character of our command of the seismic record concerning mega-earthquakes in provinces featuring recurrence times greater than a few centuries, but also the significant promise of paleotsunami studies in this respect. There remains the practical fact that the incentive to initiate such valuable research projects will often come only after a destructive tsunami. While Cascadia (see Sect. 2 above) constitutes a remarkable exception to the trend, sedimentologists will know where to start digging only in the aftermath of a major disaster.

17.3. The Failure to Warn was a Failure of Communication More than of Science

While a considerable death toll was reported in Sumatra, which was hit as little as 20 min after the initiation of rupture (H_0), the numbers were catastrophic in Thailand (reached at H_0 + 01:30; 5,000 deaths), Sri Lanka (H_0 + 02:00; 31,000 deaths), India (H_0 + 02: 30; 16,000 deaths) and Somalia (H_0 + 07:30; 300 deaths). Even Tanzania (H_0 + 09:30; at least 20 deaths) and South Africa (H_0 + 11:30; 2 deaths) suffered casualties. Such travel times should have allowed the issuance of warnings and, in turn, the protection of the populations at risk through evacuation. In this context, it is worth retracing why no warning was issued.

The initial estimates of the moment M_0 of the earthquake were deficient, and expectedly so. The first estimates, obtained at (H_0 + 00:15), were in the range of 1.2×10^{28} dyn*cm, revised around (H_0 + 01:00) to about 7×10^{28} dyn*cm. The value listed in the global CMT catalogue (3.95×10^{29} dyn*cm) required a customized processing at longer periods (300 s) than the routine algorithm then allowed, and was available at (H_0 + 04:20). The final seismic estimates of the moment ($\sim 10^{30}$ dyn*cm) required the analysis of the Earth's free oscillations and were obtained one month after the event (Stein and Okal, 2005); a composite, authoritative and customized multiple source inversion at very long periods was finalized in the Spring of 2005 (Tsai *et al.*, 2005). Such delays in the assessment of the long-period characteristics of the earthquake source are expected for mega-earthquakes when only conventional methods are used in real time to retrieve its seismic moment, since source finiteness has long been known to result in primarily destructive interference for all types of standard seismic waves (Ben-Menahem, 1961; Geller, 1976).

The use of alternate strategies to infer the low-frequency or static value of M_0, such as duration of high-frequency P waves (Ni *et al.*, 2005), W phases (Kanamori and Rivera, 2008), or even possibly geodetic data (Blewitt *et al.*, 2009), may significantly improve warning times. However, one must keep in mind that mega-earthquakes are expected from scaling laws to feature extremely long sources (in practice 600 s for the 2004 Sumatra event). It is clear that when the duration of the earthquake becomes comparable to, or even conceivably greater than, the travel time of the tsunami to the nearest beach, accurate predictions in the near field are inherently impossible. Once again, near-field mitigation must rely on direct evacuation by personally motivated, and therefore educated, individuals.

But the point remains that the estimate available 1 h after H_0, $M_0 = 7 \times 10^{28}$ dyn*cm (incidentally, the largest moment ever computed at the warning centers), was already sufficient to have triggered a basin-wide tsunami alarm, had it involved the Pacific Basin, for which an algorithm was in place at the Pacific Tsunami Warning Center (PTWC). Such an alarm would certainly have helped mitigate the human disaster in Sri Lanka and beyond, and possibly even in Thailand.

It is worth repeating that there existed at the time no tsunami warning system in the Indian Ocean, and that PTWC was not, in 2004, charged with the issuance of warnings for that ocean. The center had no client to whom to send a warning, especially since it was Christmas Day in Honolulu, and Sunday, Boxing Day, in the Indian Ocean. In short, this was the wrong time for what amounted to leafing through the yellow pages in search of an adequate contact. There can be no room for improvisation in an emergency situation. This absence of established communication protocol at the time of the event remains the major reason for the failure to provide a useful warning in the far field.

17.4. Some People Escaped, but Tsunami Exposure is a Worldwide Threat

Notwithstanding the horrible death toll, it is worth mentioning here several cases of successful evacuation during the Sumatra tsunami. First, there were no reported casualties among the Sentinelese people of the Andaman Islands, who live essentially in the Stone Age. Apparently alone among the residents of the epicentral areas, they spontaneously evacuated to higher ground upon feeling the earthquake. Perhaps because their culture had not been displaced by outside influences resulting from the explosion of information technology, they were able to keep the ancestral memory of tsunamis for at least 20 generations, in practice long enough to span what we now know to be the exceptionally long recurrence time of mega-earthquakes along the Northern Sumatra Subduction zone (Jankaew *et al*., 2008).

The story of Tilly Smith, the 10-year old British school girl vacationing in Phuket, Thailand, who identified the impending tsunami and triggered an evacuation which probably saved 100 lives, based on a geography class she had been taught at school only two weeks before, has been publicized all over the world press. A significant ingredient in her story is the presence of a Japanese person in the hotel staff who relayed the warning, and who was himself culturally educated about tsunamis.

Finally, one of the most remarkable stories is that of our colleague Professor Chris Chapman, a specialist in theoretical seismology, who was at the time staying as a tourist at a beachfront hotel in Ahangulla, Sri Lanka (Chapman, 2005). Intrigued by the first (and small) positive wave, he correctly deduced that it had to have been generated by an earthquake, and together with his wife, warned the hotel manager of impending danger. When the much larger recess of the sea took place 20 min later, the hotel staff, again warned by the Chapmans, ordered vertical evacuation of the beach area before the onslaught of the second wave, another 20 min later. Despite a few close calls, no lives were lost among guests or staff of the hotel.

These three stories, among many others, exemplify once again the value of education, and illustrate that it can take diverse forms: ancestral, schooling, and professional.

Another lesson learned from the 2004 tsunami is that, in a world where vacationers travel vast distances away from their homeland, geological hazards such as tsunamis are not the exclusive concern of countries located in zones at risk: Sweden, for example, lost 428 people (mostly tourists) to the 2004 disaster, or about one in 21,000 of its citizens, a figure strikingly similar to the world-wide statistic (250,000 victims for a 5.5-billion population of the planet). This remark stresses that tsunami education knows no frontiers and must be a world-wide effort, especially in developed countries where long-reach travel is common for business or vacation.

17.5. A Tsunami is a Global Physical Phenomenon Involving the Whole Earth as a System

The 2004 Sumatra tsunami was so big that it was recorded by many instruments which had not been designed for that purpose. Such apparently anecdotal situations were often the result of a subtle coupling between the ocean, in which the tsunami is developed, and other media such as the atmosphere and the solid Earth. As such, they point to interesting physical concepts which may bear some promise in terms of the potential use of unsuspected technologies in the context of tsunami warning. In other instances, the tsunami was recorded outside of its classical technical domain, underlying some known but hitherto undetected properties. We itemize the following observations:

17.5.1 Satellite Altimetry

The 2004 Sumatra tsunami was recorded by a number of satellite altimeters, most notably Jason-1 (Gower, 2005). While Okal *et al*. (1999) had reported a similar recording of the 1992 Nicaragua tsunami by the ERS-1 satellite, its amplitude, a mere 8 cm on the high seas, was at the limit of the noise level. The amplitude of the 2004 Jason-1 signal, 70 cm zero-to-peak, and its sharpness provide irrefutable evidence of the concept. This measurement is crucial because it matches the numerical simulations in the far field (e.g., Titov *et al*., 2005) and thus validates them for the first time against a direct observation of the deformation of the surface of the ocean, rather than through the convoluted, if legitimate, detection by sea–floor pressure sensors (González *et al*., 1998), until then the only available measurement of a tsunami on the high seas.

Unfortunately, satellite altimetry bears little promise of useful contribution to future tsunami warning systems, as it requires intensive and time-consuming data processing, and above all, the presence of a satellite at the right place at the right time. In this respect, the availability of altimeter satellites over the Bay of Bengal in the hours following the Sumatra event was nothing short of a lucky coincidence.

17.5.2 IMS Hydrophones

The Sumatra tsunami was recorded by hydrophones of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test Ban Treaty Organization (CTBTO), notably at Diego Garcia (Hanson and Bowman, 2005). These instruments are pressure detectors floating in the SOFAR channel and tethered through the ocean bottom to a nearby shore station (Okal, 2001). Since they were designed to detect underwater explosions, they include a hard-wired high-pass filter with a corner frequency of 10 Hz, and it is remarkable that they recorded conventional tsunami waves traveling under the shallow-water approximation (SWA) with periods of $\sim$1,800 s. More importantly, they provided the first record in the far field of the full tsunami branch, dispersed outside the SWA, down to periods of $\sim$70 s. Okal *et al*. (2007) showed that the corresponding spectral amplitudes around 10 mHz could be modeled quantitatively using the formalism describing a tsunami as a special branch of spheroidal free oscillations of the Earth (Ward, 1980). The conventional frequencies, while observed, could not be modeled quantitatively, as the response of the instrumental filter had lessened their signal to less than one digital unit (Okal *et al*. 2007).

This first modeling of the high-frequency components of the tsunami is important because surveys on the Western shore of the Indian Ocean Basin have revealed that in several ports (Le Port, Réunion; Toamasina, Madagascar; Salallah, Oman; and tentatively Dar-es-Salaam, Tanzania), strong currents developed (with large ships breaking their moorings and damaging or threatening infrastructure), several hours after the passage of the conventional tsunami (Okal *et al*., 2006b, c, d, 2009). Preliminary modeling for Toamasina has shown that the phenomenon results from the harbor being set in resonance at a period of 105 s, precisely upon arrival of the relevant component of the tsunami, delayed by its dispersion outside the SWA (Pančošková *et al*., 2006). The successful modeling of 10-mHz energy on the Diego Garcia hydrophone record shows that one can predict quantitatively the timing and amplitude of the resonant component threatening a distant port, paving the way for realistic simulation models in advance of future tsunamis.

17.5.3 Ionospheric Detection

Shortly before the Sumatra tsunami, Artru *et al*. (2005) had shown, notably in the case of the 2001 Peru tsunami, that there exists an ionospheric signal accompanying tsunami propagation in the far field. The idea behind this phenomenon, suggested nearly 40 years ago by Hines (1972) and detailed by Peltier and Hines (1976), is that the tsunami wave is prolonged into the atmosphere at the ocean surface, which is not a "free" boundary with a vacuum, but merely one between two fluids, the upper one simply having a considerably lesser density. Because of the rapid rarefaction of the atmosphere with height, the amplitude of the particle motion of the tsunami's continuation in the atmosphere can actually grow with altitude, to the extent that a 10-cm tsunami on the ocean could induce kilometric oscillations of the bottom of the ionosphere, at 150 km altitude. The latter can be detected and mapped using perturbations in GPS signals traversing the ionosphere, and recorded at dense arrays, such as the Japanese GEONET (Artru *et al.*, 2005).

Ionospheric detection was repeated during the 2004 Sumatra tsunami (Liu *et al.*, 2006) and Occhipinti *et al.* (2006) successfully modeled the variation in Total Electron Content observed around 300 km of altitude, by using a numerical simulation of the tsunami at the surface of the ocean as an initial condition for the generation of gravity waves in the atmosphere.

Such observations could bear some promise in terms of application to warning, through the use of techniques such as Over-The-Horizon (OTH) radar, which allow a fully land-based probing of the ionosphere. Furthermore, the approach of Lognonné *et al.* (1998), which considers a single wave spanning the ocean and its adjoining media (atmosphere and solid Earth), should allow an efficient direct quantification of the relationship between earthquake source, tsunami amplitude and ionospheric oscillations.

17.5.4 Tsunami Shadows

Prior to the 1990s, there existed a number of anecdotal reports of people "sighting" tsunami waves from elevated positions, e.g., lighthouses or flying aircraft (Dudley and Lee, 1998; p. 5), upon their arrival near a shore. Walker (1996) gave them credence by publishing frames from a video made by an amateur standing on a beach in Northern Oahu during the 1994 Kuriles tsunami. Later, Godin (2004) suggested that the phenomenon could be explained through a combination of hydrodynamics and atmospheric physics. Specifically, a shoaling tsunami wave may increase the slope of the ocean surface to the extent that the boundary conditions for atmospheric circulation are modified and can result, in the presence of an appropriate wind, in the development of a turbulent regime in the lowermost layers of the atmosphere. In turn, the turbulence would affect the reflective properties of light rays at the sea surface, making it appear darker and creating the "tsunami shadow".

Following the 2004 tsunami, Godin *et al.* (2009) studied the amplitude of the signal reflected by the Jason-1 altimeter (see above), and were indeed able to confirm the detection of a "tsunami shadow" in two separate frequency bands.

Godin *et al.*'s (2009) space-based observation bears little promise for tsunami warning because of the difficulties inherent in sparse spacecraft coverage, as discussed above regarding detection by satellite altimetry. However, land-based techniques such as OTH radar might be used in the future to probe distant ocean surfaces for tsunami shadows.

17.5.5 Infrasound

Le Pichon *et al.* (2005) reported the observation, on the infrasound array of the IMS/CTBTO at Diego Garcia, of a deep infrasound signal (0.05–0.1 Hz) whose origin they traced to the Southern coast of Myanmar at the time of arrival of the tsunami at that shoreline. It is intriguing that this powerful signal emanated from a location where the amplitude of the tsunami was moderate (maximum run-up: 3 m), and its damage relatively contained (61 reported casualties) (Swe *et al.*, 2006). While no modeling of the generation of the infrasound signal has been proposed to date, these effects may be related to the interaction of the tsunami with the extended continental shelf present offshore of Myanmar.

17.5.6 Tsunami Recorded by Onland Seismometers

Following the Sumatra earthquake, Yuan *et al.* (2005) made the remarkable observation that the arrival of the tsunami was clearly recorded on horizontal seismograms at island (or coastal continental) stations of the Indian Ocean, filtered in the 0.1–10 mHz band, with amplitudes on the order of a few mm of ground displacement. These results were confirmed by Hanson and Bowman (2005). Okal (2007a) conducted a systematic search of such signals, and showed that they could be recorded worldwide, as long as the receiver was within $\sim$35 km (i.e., 1/10 of a typical tsunami wave length) of an abyssal plain. He further showed that the recording could be interpreted quantitatively by making the radical assumption that the seismometer sat on the ocean floor and recorded not only the small horizontal component of the prolongation of the tsunami eigenfunction into the solid Earth, but also its associated components of tilt and gravity potential (GILBERT, 1980). He further showed that such signals could be detected at a smaller amplitude on vertical seismometers, and also identified during smaller tsunamis.

Such observations open the way, at least in principle, for the use of existing seismic stations as in situ detectors of tsunamis propagating in ocean basins, complementing, in essence, the network of bottom pressure sensors. As described in OKAL (2007a), such recordings are directly representative of the properties of the tsunami on the high seas, as opposed to a maregraphic record which is affected by harbor response. In addition, the deployment and maintenance of seismic stations come at much lower costs than that of DART stations; they require, however, an island environment, and thus can only serve in a complementary role.

Finally, we note that a similar observation had been made at Apia by ANGENHEISTER (1920), following the 1918 Kuriles tsunami. While we recently confirmed the existence of the signal on a copy of the original record, its quantification remains elusive, due to instrumental non-linearity in the relevant seismogram.

17.5.7 Tsunami Recorded by Seismometers on Icebergs

As part of a project investigating the origin of high-frequency tremor in tabular icebergs, OKAL and MACAYEAL (2006) operated portable seismometers during the austral Summer 2004–2005 on two icebergs parked in the Ross Sea, and on a fragment of the Ross Ice Shelf expected to calve in the next few years (Station "Nascent"). These three stations recorded the arrival of the Sumatra tsunami 16 h after the earthquake. OKAL and MACAYEAL (2006) showed that the amplitude of the signal (14 cm peak-to-peak at Nascent) was in agreement with the iceberg just floating like a raft on the ocean surface and thus directly recording the deformation η of the surface upon the passage of the tsunami. What makes this observation remarkable is that the recording was three-dimensional, i.e., that the seismometer caught the horizontal displacement of the iceberg (and hence of the water) as well (133 cm peak-to-peak on the north–south component at Nascent), with the aspect ratio (9.5) of the particle motion in good agreement with the theoretical value predicted in the Shallow-Water Approximation $\left[u_x/u_z = (1/\omega)\sqrt{g/h}\right]$. To our knowledge, this constitutes the first detection of the horizontal motion of a tsunami on the high seas. Since this number is much larger than 1, this observation opens up, at least in principle, the possibility of detecting a tsunami on the high seas in real time by recording (e.g., by GPS) the horizontal drifting of a floating observatory, which could take the form of a DART-type buoy, or simply of a ship in transit whose trajectory could be slightly affected by the passage of the tsunami.

18. Tsunamis Since Sumatra—Have We Become Wiser?

In the aftermath of the 2004 Indian Ocean disaster, "tsunami" has become a household word, and this in itself constitutes a positive development, since it raises worldwide awareness of this form of natural hazard. However, at least nine large tsunamis have followed since 2004, with alarmingly disparate results in terms of the behavior (and eventual death toll) of the populations at risk, of the performance of the warning algorithms, which included both extremes (false alarm and failure to warn), and of the implementation of actual alerts following the issuance of warnings, at least one of which remained unheeded.

We present here a brief report card on these events, aimed at analyzing what constituted a satisfactory, life-saving response or, on the other hand, a clear functional or behavioral failure with a tragic ending. This sort of "wisdom index" is not meant to be quantitative and, in particular, does not simply express the death toll inflicted by the tsunami. Rather, it assesses, in an admittedly subjective way, the performance of both the populations at risk and the decision-makers responsible for issuing and carrying out an alert in mitigation of the tsunami hazard. The events studied are listed in order of decreasing success.

- We award a "Gold" mark to the Bengkulu earthquake of 12 September 2007 (BORRERO *et al.*, 2009). This event featured what was then the third largest solution in the CMT catalog (6.7×10^{28} dyn*cm), and generated a significant local tsunami which caused damage over a 300-km stretch of coastline. Yet, no deaths or injuries were attributed directly to the tsunami. The field survey revealed that the population had correctly self-evacuated upon feeling the earthquake. This happy outcome (probably helped by the timing of the event, 18:10 local time) is an illustration of a successful scenario, proving once again the value of awareness and education among coastal populations. Incidentally, the 2007 event was not the mega-earthquake largely expected to occur in the not-too-distant future in the prolongation of the 2004 and 2005 ruptures (and neither was the tragic Padang intermediate-depth event of 30 September 2009, which did not generate a tsunami). Hence, the Mentawai segment is still ripe for a mega-earthquake which will occur in the future, albeit at an unpredictable date. When it does, it is imperative that the population respond as well as in 2007. Only continued awareness fueled by regular education will achieve this goal.

- We give a bright "Green" mark to the Solomon Islands earthquake of 01 April 2007. This major event ($M_0 = 1.6 \times 10^{28}$ dyn*cm) is remarkable in that its rupture jumped the triple junction between the Pacific, Australia, and Woodlark plates (Taylor *et al.*, 2008), re-emphasizing the difficulty of predicting maximum rupture lengths of future large events. It triggered a strong local tsunami which affected more than 300 coastal communities in the Western Solomon Islands. As detailed by Fritz and Kalligeris (2008), only 52 people were killed by the tsunami, despite the destruction of more than 6,000 houses, thanks to spontaneous self-evacuation of the low-lying areas in the minutes following the shaking. This fortunate reflex led to fatality ratios among the population at risk as low as in the case of Baie Martelli, Vanuatu (1999; see Sect. 15). It was motivated by the fresh memory of the 2004 Sumatra disaster, and by ancestral heritage, with the last regional tsunami (17 August 1959) still present in the memory of the village elders. Remarkably, the smaller event of 03 January 2010 ($M_0 = 5.3 \times 10^{26}$ dyn*cm) generated a tsunami which similarly caused no casualties, despite running up to 5 m on Rendova Island (Fritz and Kalligeris, 2010), once again thanks to self-evacuation by the local population. These tsunamis illustrate the significance of awareness and education in mitigating local tsunami risks.

- We give an "Olive" card to the Nias event of 28 March 2005. This tint, intermediate between green and yellow, reflects positive aspects in the near field, where no victims were attributed to the tsunami, but also the panic generated, in the far field, by a warning which turned out to be a false alarm.

We recall that this earthquake was indeed gigantic ($M_0 = 1.05 \times 10^{29}$ dyn*cm), and took 600 lives in Nias and 100 in Simueleu. Its tsunami was weaker than expected, since a significant fraction of the deformation in the source area involved those large islands ("the earthquake moved a large amount of rock and not much water"). Nevertheless, the local impact of the tsunami was important, but no deaths were definitively attributed to it, largely because of awareness rooted in ancestral tradition, and of the fact that most inhabitants had been relocated away from the beaches in the wake of the 2004 disaster (McAdoo *et al.*, 2006).

In the far field, the tsunami was recorded instrumentally, but was too small to be reported by witnesses. This effect was explained by its generation in shallow seas (Okal and Synolakis, 2008), and constituted a perfect illustration of Green's (1837) law. However, because of the large seismic moment of the Nias earthquake, a tsunami warning had been issued for the entire Indian Ocean Basin, and resulted in a false alarm. In itself, this should not be considered *prima facie* as a failure of the warning process, given the value of precaution and the specific circumstances; after all, the Nias earthquake would have been the largest one in 40 years, but for the 2004 Sumatra event. More ominous was the reaction of distant populations, sensitized to tsunami hazards by the Sumatra disaster only 3 months earlier, who responded to the warning in a chaotic fashion. Six people were killed in traffic accidents that night in Toamasina, Madagascar, during an episode of panic cruising through its streets (Okal *et al.*, 2006c).

- We give a "Yellow" card to the Kuril Islands tsunami of 15 November 2006. This very large earthquake ($M_0 = 3.5 \times 10^{28}$ dyn*cm; seventh largest in the Global CMT catalogue) expectedly generated a substantial tsunami, which went largely unreported because of the remoteness of the local shores. It took nine months for a surveying party to reach the uninhabited Central Kuril Islands and to document run-up reaching 21 m on Matua Island (MacInnes *et al.*, 2009). As there were no casualties, and no infrastructure to be destroyed, the tsunami was largely ignored by the scientific community. Yet, it attacked Crescent City, California 8.5 h after origin time, and caused significant damage to floating docks and to several boats, another 2.5 h later (Dengler *et al.*, 2009). Initial estimates of the damage in Crescent City ranged around $700,000, but a full assessment later documented structural damage to the pilings of the floating docks; their reconstruction may cost up to $9 million (Dengler *et al.*, 2009). Flooding was also reported at several locations in Hawaii.

The performance of the warning centers during the 2006 Kuril tsunami was mediocre: In Hawaii, PTWC cancelled the tsunami warning 2.5 h before the arrival of the wave, the latter causing some local damage, with one swimmer having a very close call. Similarly, WCATWC repeatedly issued statements of "no warning" or "no watch" for California, several hours before the onslaught on Crescent City harbor. Yet, numerical simulation of the tsunami (Dengler *et al.*, 2008) reproduces the marigram eventually recorded at Crescent City and, in particular, the evolution with time of the amplitude of the wave. The failure to warn may have been influenced by the late character of the seismic source. In a way reminiscent of the 2001 Peru earthquake (Weinstein and Okal, 2005), the initial rupture corresponds to a smaller source, and the full extent of moment release occurs only 50 s into the rupture. We describe such sources as "late" or "delayed", as opposed to "slow", since their spectra are not anomalous, and in contrast to truly slow events (e.g., "tsunami earthquakes"), they do not exhibit deficient energy-to-moment ratios when the full extent of their source is analyzed (Okal, 2007b). It is clear that the recognition of delayed events in real time is a challenge since algorithms analyzing only a fraction of the P waveforms will fail to catch their true size.

In addition, this event points to the lack of awareness in the community at risk (Crescent City) of the singularities in the response of the harbor and, in particular, of the delays in the arrival of the most destructive wavetrains, which may reflect maximum amplitudes or maximum current velocities.

- The tsunami of 15 August 2007 in Peru also gets a "Yellow" card, despite a moderate death toll (only three fatalities attributed to the tsunami). With a moment of 1.1×10^{28} dyn*cm, this earthquake was among the weaker tsunamigenic events in central Peru, being smaller than the 1974 earthquake, and certainly no match for the catastrophic events of 1687 and 1746 (Dorbath *et al.*, 1990; Okal *et al.*, 2006a). The earthquake caused widespread destruction in the city of Pisco, resulting in more than 500 fatalities. It generated a significant tsunami, which ran up to a maximum of 10 m South of the Paracas Peninsula, with sustained values in the 5–7 m range along a 40-km segment of coastline (Fritz *et al.*, 2008). Despite such high values, most shoreline villages were successfully evacuated based on a network of Coast Guard sergeants triggering the evacuation upon feeling the earthquake and directing people to pre-arranged shelters, none of which were reached by the tsunami. This episode illustrates the success of an evacuation featuring awareness of the population and a well designed and rehearsed plan originating at the community level, an important point since most local communications had been knocked down by the earthquake.

On the other hand, no evacuation was conducted at the village of Lagunilla, which had no Coast Guard outpost, and where three people lost their lives to the tsunami. This gap in an otherwise well designed and well executed evacuation plan is both regrettable and unexplained.

- The recent Maule, Chile tsunami of 27 February 2010 also earns a "Yellow" card, on account of the alarming diversity of response in both the near and far fields. With a moment of 1.8×10^{29} dyn*cm, this earthquake was the second largest in 46 years, surpassed only by the 2004 Sumatra event, and the first one since 1960 to generate run-up amplitudes of 80 cm in Japan across the whole extent of the Pacific Ocean. Yet, the death toll, probably definitive at the time of writing, is contained to a total of about 500, of which <300 are attributable to the tsunami. No casualties are known outside Chile.

In the near field, a higher death toll was avoided through a reflex of self-evacuation by the local population, thanks to proper education of the coastal community, and despite the night-time occurrence of the disaster. Tragically, the majority of the tsunami victims in coastal Chile were campers trapped with little if any means of escape on Orrego Island in the estuary of the Maule River in Constitución, many of them vacationers from the hinterland with little awareness of tsunami danger (Petroff, 2010).

By contrast to a largely successful, individually triggered evacuation, the response at the National government level was nothing short of abysmal. The official warning unit of the Chilean Navy failed to issue a tsunami alert, and the President herself dismissed the possibility of the generation of a tsunami in the minutes following the earthquake. In a country with a long history of local tsunamis, common sense should have dictated (as it did to the coastal populations) that a clearly major earthquake of particularly long duration, inflicting significant damage to countless buildings and a total black-out in the capital city of Santiago, had the potential for a dangerous tsunami.

This failure to warn was particularly tragic in the case of the Juan Fernández Islands, located 700 km offshore of central Chile, for which a useful warning could have been issued before the tsunami reached them a little less than 1 h after origin time; its onslaught was catastrophic with run-up reaching 15 m (Fritz, 2010) and about 30 deaths.

In the far field, warning centers had the luxury of time, allowing the computation of simulated forecasts which correctly predicted that the lobe of tsunami energy would be focused south of Hawaii, where inundation would be minimal and run-up heights less than metric; the coastal areas of Hawaii were nonetheless evacuated. Further south, an evacuation was ordered for the coastal areas of the 68 populated islands of French Polynesia. As a result, and despite run-up reaching 4 m in the Marquesas Islands, no victims were reported, and only one fishing boat was lost, his owner having refused to take it out to sea (Reymond *et al*., 2010).

Response in California, where the tsunami did at least $10 million damage, was rather chaotic, with some beaches being evacuated and others not. Perhaps more importantly, it demonstrated a lack of sophistication, with the coastal community not prepared to wait long enough for individual harbor responses, characterized by strong and potentially treacherous currents, to develop during the arrival of higher frequency components traveling outside the Shallow-Water Approximation [C. Synolakis, pers. comm., 2010]. In this respect, it is worth sensitizing the population to the fact that tsunami arrival times broadcast by the warning centers represent the expected initiation of the phenomenon, which can last many hours thereafter.

In conclusion, the 2010 Maule tsunami points out to the need to further educate decision-makers, both in the near and far field.

- The Samoan event of 29 September 2009 earns an "Orange" star. Its tsunami was very destructive locally (Okal *et al*. 2010), causing more than $200 million of damage, principally on the islands of Tutuila (American Samoa; where it ran up to 17 m at Poloa), Upolu (Samoa) and Niuatoputapu (Tonga). In particular, the downtown area in Pago Pago was heavily damaged as a result of the amplification of the waves in its narrow bay, as were the cities of Leone (Utuila), and Lepa (Upolu). Under the circumstances, the total death toll, 189, would appear reasonably contained, as a result of the population having generally self-evacuated the shoreline upon either feeling the earthquake, or more often, noticing a recess of the ocean.

In this respect, one can generally credit the local inhabitants on Tutuila with awareness of tsunami danger, which may have been enhanced by a comprehensive signage project, under which standard, blue "tsunami hazard zone" signs had been erected along the shore, although to be precise, those do not suggest *whither* to evacuate. A strong element of community bonding, notably on the part of local elected officials, resulted in a grassroots warning and evacuation, which probably helped keep the death toll on Tutuila at 34. While, of course, regrettable, this figure means hundreds, perhaps thousands, of lives saved thanks to the evacuation, which stemmed from a certain level of education of the population.

Unfortunately, the situation was to be different on Upolu, where 143 people lost their lives, even though the tsunami spared the more populated northern shore, devastating mostly the southeastern corner of the island (Okal *et al.*, 2010). While many inhabitants knew to evacuate after the earthquake, and scores successfully did so, a significant number became victims of entrapment in vehicles, either stuck in traffic jams, or proceeding parallel to the shore. The general lack of preparedness was also reflected by the absence of signage of hazard zones, the alleged emphasis on the capital city, Apia located on the northern shore, during tsunami drills, and the erroneous perception of automobiles as being a great help—if not an outright panacea—in mitigating tsunamis, notably in the immediate aftermath of the "road switch" to left-hand driving, which took place 22 days prior to the tsunami.

The orange card given to this event reflects the contrast between what amounts to a reasonably successful evacuation on Tutuila, and significant deficiencies in preparedness and execution on Upolu. It stresses once again the value of education and stepped up awareness of the populations at risk for the eventual reduction in loss of life from near-field tsunamis.

- The tragic event of 17 July 2006 in Java earns a "Red" star. This "tsunami earthquake" was strongly reminiscent of the 1994 East Java tsunami, whose lessons should have remained vivid just 12 years later and only 600 km away along the coast of Java. While the slow character of the event resulted in minimal felt intensities along the coast, the long-period moment (4.6×10^{27} dyn*cm) was assessed at a sufficient level for the Japan Meteorological Agency to issue a warning 27 min after the earthquake. This delay was relatively long, but the warning might still have been useful, had it been heeded. By contrast, PTWC issued a statement of no warning 17 min after the event. Possibly because of these conflicting statements, and probably on account of the wrongful perception of a benign event based on felt reports, no official evacuation was mandated. Forty minutes after the earthquake, the tsunami inflicted severe damage, and a death toll of about 700, on a 200-km section of coastline centered on Pangandaran, with run-up reaching 21 m (Fritz *et al.*, 2007). This represents an unfortunate instance of insufficient and contradictory warnings, mismanagement of the existing one, and lack of preparedness on an island which had lived through an essentially similar disaster 12 years earlier. It also reaffirms the particular challenge posed by "tsunami earthquakes", which must be detected in real time. The pair of Java events (1994, 2006) strongly suggests that there is a regional character to their occurrence, an idea already hinted at by Okal and Newman (2001), but which clearly warrants more research.

19. Conclusion

The review of 27 tsunamis generated by earthquakes over the past 310 years outlines a number of common conclusions. From the seismological standpoint, we must accept that we still lack a reliable understanding of the conditions controlling the occurrence of mega-earthquakes with the potential for transoceanic tsunamis. In the wake of the 2004 Sumatra event, we have had to abandon the paradigm of a "maximum earthquake" predictable from simple tectonic parameters (RUFF and KANAMORI, 1980), and a growing number of studies have reaffirmed the ANDO (1975) concept of an element of randomness in the exact size (determined for example through the analysis of paleotsunami deposits) of large events which might otherwise qualify as repeating instances in the earthquake cycle (CISTERNAS *et al*., 2005; KELSEY *et al*., 2005; OKAL *et al*., 2006a). Similarly, we lack a full understanding of the environments prone to hosting the treacherous "tsunami earthquakes" which still pose a formidable challenge to the warning community.

Our ability to produce in real time, and occasionally before tsunamis reach distant shores, reliable simulations of their detailed inundation characteristics expresses our good command of the fundamental aspects of the generation of tsunamis by earthquakes. Yet, some events clearly violate this pattern, with wave amplitudes either too large or too small. The former could arise from the triggering of underwater landslides as in the case of Papua New Guinea (Sect. 14), and the latter from shallow bathymetry and/or the presence of islands at the source, as in the case of the 2005 Nias event. Such situations emphasize the challenges faced when attempting to automate the process of tsunami warning in real time.

The study of the most recent, post-Sumatra, tsunamis reveals a disturbing diversity, both in the performance of the warning centers, and in the response of the communities at risk. It is somewhat discomforting to retrace the 2006 Java debacle (and to a lesser extent, the damage suffered in the far field at Crescent City following the 2006 Kuril event), while at the same time realizing that a successful evacuation had taken place 73 years earlier in Hilo, following T. Jaggar's warning of the 1933 Sanriku tsunami. A common conclusion of the close examination of both successes and failures during recent tsunamis remains the value of education, either in a traditional, ancestral form deeply rooted in the local culture, or in formal programs such as schooling and drills. This is particularly critical in the near field where there can be no substitute for self-evacuation, which inherently requires awareness and preparedness of the populations involved.

In summary, this review documents how individual tsunamis have resulted in critical progress in our understanding of the intricate mechanism by which large earthquakes can (but occasionally, do not) trigger dangerous tsunamis, and in our efforts in mitigating their effects. Such incremental steps remind us of the great French poet Victor Hugo, who once wrote "Science is the asymptote of Truth" (HUGO, 1864). While the converse might have been more proper mathematically, we can expect that future catastrophic tsunamis will keep bringing us closer to a sense of perfection in knowledge, and through an appropriate application to societal needs, to the mitigation of their disastrous effects. Yet, an asymptote is never reached, and there will always come the intriguing tsunami with an unforeseen property, which will seed further research and, we hope, generate improved mitigation; the latter will always require an enhanced educational effort.

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