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Twenty-Five Years of Progress in the Science of “Geological” Tsunamis Following the 1992 Nicaragua and Flores Events

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Abstract—We review a set of 47 tsunamis of geological origin (triggered by earthquakes, landslides or volcanoes) which have occurred over the past 25 years and provided significant new insight into theoretical, experimental, field, or societal aspects of tsunami science. Among the principal developments in our command of various aspects of tsunamis, we earmark the development of the *W*-phase inversion for the low-frequency moment tensor of the parent earthquake; the abandonment of the concept of a maximum earthquake magnitude for a given subduction zone, controlled by simple plate properties; the development and implementation of computer codes simulating the interaction of tsunamis with initially dry land at beaches, thus introducing a quantitative component to realistic tsunami warning procedures; and the recent in situ investigation of current velocities, in addition to the field of surface displacements, during the interaction of tsunamis with harbors. Continued research remains warranted, notably in the field of the real time identification of “tsunami earthquakes” whose tsunamis are larger than expected from their seismic magnitudes, especially conventional ones. The recent tragedy during the 2018 Krakatau flank collapse, along a scenario which had been quantitatively forecast, also emphasizes the need for a continued effort in the education of the populations at risk.

Key words: Tsunamis, 1992 Nicaragua tsunami, 1992 Flores tsunami, 2004 Sumatra tsunami, 2011 Tohoku tsunami.

1. *Introduction*

It has now been slightly over a quarter century since two very different earthquakes literally re-awakened the field of observational tsunami science, which had been to some extent stagnant since the catastrophic events of the 1950s and early 1960s (Kamchatka, 1952; Aleutian, 1957, Chile, 1960; Alaska, 1964), despite significant tsunamis in 1976 in Mindanao, Philippines, and in 1983 in the Sea of Japan. While substantial progress was made in the 1970s and 1980s on the theoretical and experimental front (e.g., Hammack 1973; Ward 1980; Bernard and Milburn 1985), scientists still lacked the motivation provided by exceptional and intriguing field observations.

The two tsunamis of 02 September 1992 in Nicaragua and 12 December 1992 in Flores Island, Indonesia provided our community with a wealth of challenges which spawned a large number of new investigations covering the observational, experimental and theoretical aspects of our science. They were followed over the next 25 years by many more events (in particular by the catastrophic tsunamis of 2004 in Sumatra, and 2011 in Japan), many of which resulted in significant new scientific developments, which are the subject of this special issue.

We restrict our study to those “geological” tsunamis generated by earthquakes, landslides and volcanic eruptions. Whether their origin rests with strain accumulated during the interseismic cycle (and released during earthquakes), gravitational unbalance resulting from geological processes (landslides), or volcanic activity, their energy can be traced eventually to convective heat loss in the Earth’s interior in the context of Plate Tectonics. By contrast, a separate paper (Rabinovich 2019) examines the case of “meteo-tsunamis” generated by coupling between atmospheric perturbations and the oceanic column. As such, the energy of meteo-tsunamis is drawn from the weather system, and eventually from the radiation received from the Sun.

In this paper, we present a detailed, chronological discussion of the unique properties of a selection of 47 among such geological tsunamis. Their sources

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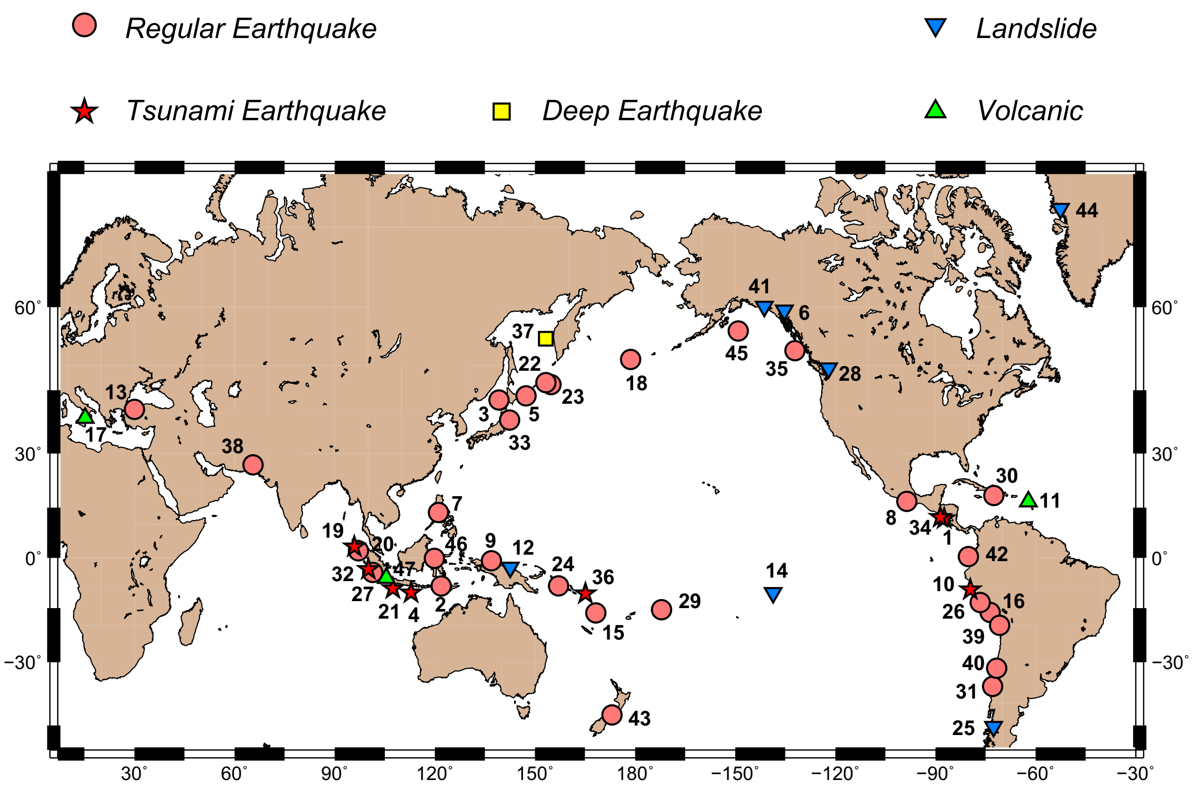

Figure 1

Map of the 47 events described in the text. Special symbols are used for tsunami earthquakes, for the deep Okhotsk earthquake (37), for tsunamis generated during volcanic events, and for those primarily due to major landslides. Event numbers are keyed to Table 1 and the text

are mapped on Fig. 1 and their fundamental parameters listed in Table 1. We emphasize that the list is not exhaustive, and represents a choice of events of significance in the development of tsunami science, out of the 320 events listed for that time window in NOAA's Global Tsunami database, 39 of which involving casualties, as reviewed in the companion paper by Gusiakov et al. (2019). Like all such choices, it may be subjective. Chronological plots of tsunami casualties and maximum run-up are given on Figs. 2 and 3. In this context, both Table 1 and Fig. 2 attempt to reflect tsunami casualties, not counting those directly attributable to the parent earthquake, which in some instances (e.g., İzmit, Event **13** or Pisco, Event **26**) were much heavier; we stress that in most cases, such a distinction remains a difficult exercise. Figure 4 shows energy-to-moment ratios (Newman and Okal 1998) for the 39 relevant earthquake sources.

2. *Significant Tsunamis, 1992–2018: A Timeline*

1. *Nicaragua, 02 September 1992*

This event was remarkable in many respects. First, it constituted the first *"tsunami earthquake"* to take place in the era of digital seismic instrumentation. We recall that the term "tsunami earthquake" was coined by Kanamori (1972) to characterize an event whose tsunami is significantly larger than expected from its magnitudes, especially conventional ones. Such events are particularly ominous as they can be felt, if at all, at a deceptively low level of shaking, while the ensuing tsunami can be catastrophic (170 fatalities in Nicaragua), thus negating the adage "The Shaking is the Warning", commonly used to sensitize populations at risk on tsunami-prone coastlines in the near field. While Kanamori (1972) was able to suggest that their large tsunamis resulted

Table 1

Significant tsunamis, 1992–2018

Number	Date D M (J) Y	Region	Seismic moment (10^{27} dyn × cm)	Seismic moment M_w	Death Toll	Maximum run-up (m)	References	Notes
1	02 SEP (246) 1992	Nicaragua	3.4	7.6	170	10	Abe et al. (1993)	Tsunami earthquake
2	12 DEC (347) 1992	Flores, Indonesia	5.1	7.7	1169	26	Tsuji et al. (1995)	Babi effect; Rangrioko landslide
3	12 JUL (193) 1993	Okushiri, Japan	4.7	7.7	198	31	Shuto and Matsutomi (1995)	“Tsuji Gulch”
4	02 JUN (153) 1994	East Java, Indonesia	5.3	7.8	238	16	Synolakis et al. (1995)	Tsunami earthquake
5	04 OCT (277) 1994	Shikotan, Kuriles	30	8.3	0	9	Yeh et al. (1995)	Slab tear event
6	03 NOV (307) 1994	Skagway, Alaska	–	–	1	9	Synolakis et al. (2002a)	Landslide tsunami; no earthquake detected
7	14 NOV (318) 1994	Mindoro, Philippines	0.51	7.1	81	7.3	Imamura et al. (1995b)	Strike-Slip event
8	09 OCT (282) 1995	Manzanillo, Mexico	11.5	8.0	1	11	Borrero et al. (1997)	Evidence of leading depression
9	17 FEB (048) 1996	Biak, Indonesia	24	8.2	110	7.7	Imamura et al. (1997)	Rare thrusting event at oblique boundary
10	21 FEB (052) 1996	Chimbote, Peru	2.2	7.5	12	5.1	Bourgeois et al. (1996)	Tsunami earthquake
11	26 DEC (361) 1997	Montserrat	–	–	0	3	Heinrich et al. (1998b)	Anticipated volcanic tsunami
12	17 JUL (198) 1998	Aitape, PNG	0.37	7.0	2200	15	Kawata et al. (1999)	Underwater landslide triggered by earthquake
13	17 AUG (229) 1999	İzmit, Turkey	2.9	7.6	155	3	Altınok et al. (2001)	Strike-slip earthquake
14	13 SEP (256) 1999	Fatu Hiva, Marquesas Is.	–	–	0	8	Okal et al. (2002a)	Subaerial landslide
15	26 NOV (330) 1999	Vanuatu	1.7	7.4	5	6.6	Caminade et al. (2000)	Successful evacuation at Baie Martelli
16	23 JUN (174) 2001	Camaná, Peru	47	8.4	86	8.8	Okal et al. (2002b)	First ionospheric detection
17	30 DEC (364) 2002	Stromboli, Italy	–	–	0	11	Tinti et al. (2005)	Volcanic Landslides
18	17 NOV (321) 2003	Aleutian Islands	5.3	7.7	0	0.26	Meining et al. (2005)	First alarm called off using DART
19	26 DEC (361) 2004	Sumatra-Andaman	1200	9.3	>200,000	51	[a]	Deadliest in history of mankind
20	28 MAR (087) 2005	Nias, Indonesia	100	8.6	8	4.2	Kerr (2005)	Deficient far-field tsunami from source in shallow waters
21	17 JUL (198) 2006	Central Java, Indonesia	4.6	7.5	802	21	Fritz et al. (2007)	Tsunami earthquake; similar to 1994 (4.)
22	15 NOV (319) 2006	Central Kuriles	35	8.3	0	22	Lobkovsky et al. (2009)	First (interplate thrust) of seismic doublet
23	13 JAN (013) 2007	Central Kuriles	18	8.1	0	16	Lobkovsky et al. (2009)	Second (normal, outer-rise) of seismic doublet
24	01 APR (091) 2007	Gizo, Solomon Is.	16	8.1	52	12.1	Fritz and Kalligeris (2008)	Rupture across triple junction
25	21 APR (111) 2007	Aysén, Chile	0.03	6.3	10	50	Barrientos et al. (2009)	Rockslide into fjord triggered by s.-slip earthquake
26	15 AUG (227) 2007	Pisco, Peru	11	8.0	3	10	Fritz et al. (2008)	Largely successful self-evacuation
27	12 SEP (255) 2007	Bengkulu, Indonesia	67	8.5	0	4	Borrero et al. (2009)	Only partial release of post-1833 strain
28	04 DEC (338) 2007	Chebalis Lake, B.C.	–	–	0	38	Wang et al. (2015)	Rock slide into closed lake
29	29 SEP (272) 2009	Samoa	17	8.1	192	22	Okal et al. (2010)	Composite seismic source
30	12 JAN (012) 2010	Haiti	0.44	7.0	7	3	Fritz et al. (2012)	Underwater landslides triggered by earthquake
31	27 FEB (058) 2010	Maule, Chile	187	8.8	156	29	Fritz et al. (2011b)	First transpacific tsunami in 46 years
32	25 OCT (298) 2010	Mentawai, Indonesia	6.8	7.8	431	17	Hill et al. (2012)	Tsunami earthquake

Table 1 *continued*

Number	Date D M (J) Y	Region	Seismic moment (10^{27} dyn × cm)	Seismic moment M_w	Death Toll	Maximum run-up (m)	References	Notes
33	11 MAR (070) 2011	Tohoku, Japan	395	9.0	19,000	39	[a]	2nd deadliest in past 100 years; Fukushima disaster
34	27 AUG (240) 2012	El Salvador	1.3	7.3	0	6.3	Borrero et al. (2014)	Tsunami earthquake
35	28 OCT (302) 2012	Haida Gwaii, Canada	5.7	7.8	0	13	Fine et al. (2015)	Partitioned plate boundary
36	06 FEB (037) 2013	Santa Cruz, Solomon Is.	9	7.9	10	11	Fritz et al. (2013)	Tsunami earthquake
37	24 MAY (144) 2013	Sea of Okhotsk	39.5	8.3	0		Okal (2017)	Tsunami generated by deep earthquake
38	24 SEP (267) 2013	Gwadar, Pakistan	5.6	7.8	0	1	Heidarzadeh and Satake (2014)	Tsunami from onland earthquake
39	01 APR (091) 2014	Iquique, Chile	19	8.1	0	4.6	Catalán et al. (2015)	Major, successful evacuation
40	16 SEP (259) 2015	Illapel, Chile	32	8.3	8	13	Aránguiz et al. (2016)	In situ measurements of far-field currents
41	18 OCT (290) 2015	Taan Fjord, Alaska	–	–	0	193	Higman et al. (2018)	Rockslide into fjord
42	16 APR (107) 2016	Ecuador	5.9	7.8	0	0.1	Ye et al. (2016)	Large event with mediocre tsunami
43	13 NOV (318) 2016	Kaikōura, NewZealand	6.5	7.8	0	6.3	Power et al. (2017)	Unexpected event with complex rupture
44	17 JUN (168) 2017	Karrat Fjord, Greenland	–	–	4	50	Paris et al. (2019)	Rockslide into fjord
45	23 JAN (023) 2018	Gulf of Alaska	10	7.9	0	0.25	Lay et al. (2018)	Large strike-slip earthquake with benign tsunami
46	28 SEP (271) 2018	Palu, Indonesia	2.8	7.6	2200	11	Heidarzadeh et al. (2019)	Strike-slip event at bayhead
47	22 DEC (356) 2018	Anak Krakatau, Indonesia	–	–	437	30	Prasetya et al. (2019)	Volcanic flank collapse

[a] Being spoiled for choice, we give no reference for the 2004 Sumatra-Andaman and 2011 Tohoku events

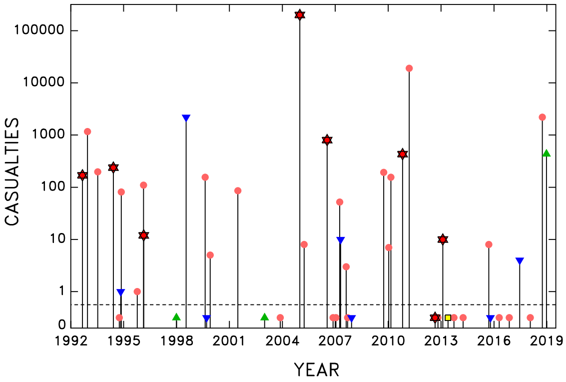

Figure 2
History of the 47 events (1992–2018). The vertical bars are scaled to the logarithm of the death toll, with events without known casualties plotted below the dashed line. Symbols are keyed to Fig. 1

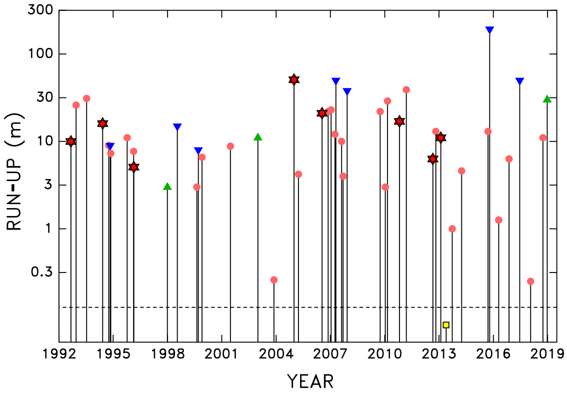

Figure 3
History of the 47 events (1992–2018). The vertical bars are scaled to the logarithm of the maximum observed run-up. The deep Okhotsk event (Number 37), for which no data is available, is plotted below the dashed line. Symbols are keyed to Fig. 1

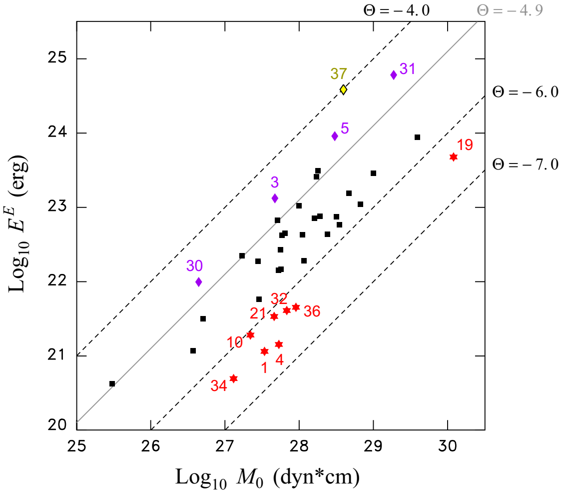

Figure 4
Energy-to-moment ratios for the 39 earthquake sources among the events studied (1992–2018). This plot is analogous to those published, e.g., by Newman and Okal (1998). The dashed lines identify constant values of Θ, with the grey solid line corresponding to the theoretical value (− 4.90) expected from scaling laws. Tsunami earthquakes (featuring $\Theta \leq -5.8$) are shown as red stars and keyed to their number in Table 1. Events defined as “snappy” (Okal and Saloor 2017) ($\Theta \geq -4.7$) are similarly shown as purple diamonds, with the deep Sea of Okhotsk earthquake shown in yellow

from an anomalously slow seismic rupture, the charter tsunami earthquakes in his study, the 1896 Sanriku and 1946 Aleutian shocks, obviously predated digital seismology. It was at the time extremely challenging if not outright impossible to quantify the high-frequency part of the seismic spectrum from analog records. Following the deployment of broadband digital instruments (Hutt et al. 2002), Boatwright and Choy (1986) made this possible by developing an algorithm to compute radiated seismic energy, and the 1992 Nicaragua tsunami earthquake (together with similar ones in 1994 in Java and Chimbote, Peru in 1996) motivated Newman and Okal (1998) to introduce the source slowness parameter $\Theta = \log_{10}(E^E/M_0)$ where E^E is the estimated radiated seismic energy and M_0 the seismic moment, as a robust identifier of tsunami earthquakes.

Second, the availability of high-quality broadband data allowed Kanamori (1993) to discover, on records of the Nicaraguan earthquake, an ultra-long period, fast-propagating seismic wavetrain, which he named the *W* phase, with the potential for a rapid estimate of the long-period seismic moment controlling the generation of tsunamis. Despite some initial interest (Okal 1993), the concept had to wait for the full development of digital networks to allow its now routine use for rapid, full-fledge moment tensor inversion (Kanamori and Rivera 2008).

Next, the 1992 Nicaragua tsunami saw the first of comprehensive International Post-Tsunami Surveys (Abe et al. 1993), which were to become systematic following later significant events (Synolakis and Okal 2005), even though similar efforts had occasionally taken place, notably after the 1976 Mindanao tsunami (Wallace et al. 1977). The substantial values of run-up documented by the 1992 survey (8–10 m) could not be modeled using then standard simulation algorithms, which stopped the simulation at a shallow, but arbitrary, water depth (typically 5–10 m), and considered the coastline as a fully reflecting boundary (Imamura et al. 1993), thus underestimating the surveyed values by as much as one order of magnitude. This motivated the development of codes extending the computation over initially dry land (Titov and Synolakis 1993), which later matured into codes such as, e.g., MOST (Titov and Synolakis 1998; Titov et al. 2016), TUNAMI–2 (Goto et al. 1997), or COMCOT (Liu et al. 1994).

Finally, the 1992 Nicaragua event provided the first opportunity for space-based detection of a tsunami on the high seas, using an 8-cm signal on ERS-1 and TOPEX/POSEIDON radar altimeters (Okal et al. 1999).

2. *Flores, 12 December 1992*

This event took place on the Northern shore of Flores Island, Indonesia, where the Sunda plate subducts Southwards under the Australian plate. The tsunami was remarkable on two accounts. First, it gave rise to the intriguing “Babi effect”: at Babi Island, located a few km North of the main island, the maximum run-up (7.2 m) occurred in the lee of the incident tsunami, as the waves interfered constructively after rounding this circular island (Yeh et al. 1993). This effect was later reproduced in the laboratory (Briggs et al. 1995) and modeled theoretically (Yeh et al. 1994; Liu et al. 1995; Imamura et al. 1995a; Tinti and Vannini 1995). It negated the conventional wisdom suggesting that island structures could protect their residents on the lee side of an incoming tsunami wave.

In addition, the 1992 Flores tsunami featured an isolated extreme run-up of 26 m at Rangrioko in Northeastern Flores (Tsuji et al. 1995), which underwater surveys later documented was caused by a submarine landslide triggered by the earthquake (Plafker 1997). This phenomenon contributed to raising awareness for this particular kind of hazard.

3. *Okushiri, 12 July 1993*

This event took place in the Sea of Japan and resulted in the destruction of the port village of Aonae, with a run-up of 10 m. A detailed field survey (Shuto and Matsutomi 1995) documented a run-up reaching 31 m due to amplification by a river valley at the so-called “Tsuji Gulch”. Later simulation by Titov and Synolakis (1997) established the possibility of successfully modeling the highly non-linear interaction of tsunamis with originally dry land featuring extreme relief.

4. *East Java, 02 June 1994*

This was the second tsunami earthquake of the 1990s, running up as much as 16 m on beaches where the earthquake had not been felt, and resulting in 238 deaths (Synolakis et al. 1995).

5. *Shikotan, Kuriles, 04 October 1994*

This large earthquake (at the time the second largest in the CMT catalog) represented a tear in the slab below the Southern Kuriles. It resulted in significant local destruction, but the tsunami inflicted no casualties despite run-up of 5–9 m, as surveyed by Yeh et al. (1995). It nevertheless emphasized the need to include events other than interplate thrusts in the assessment of tsunami hazard at subduction zones, as already evidenced by such disasters as the 1933 Sanriku tsunami (Okal et al. 2016).

6. *Skagway, Alaska, 03 November 1994*

This local tsunami in the port of Skagway destroyed a wharf in a shipping terminal and killed one worker, in the absence of any detectable earthquake (Kulikov et al. 1996). Thomson et al. (2001) suggested that the failure of the wharf was responsible for the tsunami; however, the identification of an underwater slide down the fjord led Synolakis et al. (2002a) to a successful simulation of the failure of the wharf under a system of waves generated by that natural landslide.

7. *Mindoro, Philippines, 14 November 1994*

This was a very significant tsunami, which ran up as high as 7.3 m, killed 81 persons, and displaced a 4000-ton barge 1.6 km in a local estuary (Imamura et al. 1995b). Yet, the parent earthquake had a strike-slip mechanism, generally perceived as posing little if any tsunami risk. However, Tanioka and Satake (1996) showed that the lateral offset produced by a strike-slip fault at the edge of the island can generate a tsunami in the same fashion as a wavemaker paddle in the laboratory. The reverse situation (a marine strike-slip fault hitting the head of a bay) is thought to be responsible for the catastrophic 2018 tsunami at Palu, Indonesia (see **46.** below), even though ancillary landslides certainly played an additional role in its generation (Satake, pers. comm., 2019).

8. *Manzanillo, Mexico, 09 October 1995*

This was a typical tsunami generated by a major interplate thrust earthquake at the Mexican subduction zone. As part of the field survey, Borrero et al. (1997) obtained photographs from witnesses documenting a leading recession at Tencatita Bay. Although this phenomenon had been predicted theoretically by Tadepalli and Synolakis (1994, 1996), this observation verified that, in the most widely expected geometry of a shallow angle interplate thrust fault, the local beach will benefit from a natural warning to the population at risk, in the form of an initial down-draw; this may help explain the relatively low death toll, reported between 1 and 10.

9. *Biak, Indonesia, 17 February 1996*

This tsunami took place at a subduction zone featuring very oblique convergence, resulting in plate motion partitioning, and in a scarcity of megathrust earthquakes at the subduction interface, a situation to be repeated during the 2012 Haida Gwaii earthquake (see **35.** below). A remarkable aspect of the field survey is the estimation, for the first time, and based on an application of Bernoulli’s theorem, of current velocities (Matsutomi and Iizuka 1998; Matsutomi et al. 2001).

10. *Chimbote, Peru, 21 February 1996*

Just 4 days after the Biak event, a new significant tsunami took place in Northern Peru, following the third “tsunami earthquake” of the decade. Investigations into the anomalous slowness of the earthquake (Ihmlé et al. 1998) led to successful tsunami simulation using for the first time a reduced rigidity μ for the seismic source material (Heinrich et al. 1998a).

11. *Montserrat, Lesser Antilles, 26 December 1997*

This tsunami resulted from the penetration of the ocean by a pyroclastic flow during the eruption of Montserrat. It ran up 1 m at Deshaies on the nearby island of Guadeloupe, in a geometry comparable to that of the 2018 Krakatau disaster (see **47.** below), but on a much reduced scale. Remarkably, this scenario had been accurately anticipated[1] by Heinrich et al. (1998b). It was essentially repeated at the same location on 13 July 2003 (Pelinovsky et al. 2004).

12. *Aitape, Papua New Guinea, 17 July 1998*

With about 2100 casualties, this tsunami was one of the deadliest of the past century. Yet, it followed a moderate earthquake whose moment ($M_0 = 3.7 \times 10^{26}$ dyn × cm) could not justify run-up reaching 15 m on a narrow stretch of coastline centered on Sissano Lagoon (Kawata et al. 1999). The combination of extreme amplitudes, limited lateral extent of the devastation, minimal amplitudes in the far field, and an apparent delay in the arrival of the wave, led Synolakis et al. (2002b) to propose as the origin of the tsunami a submarine landslide triggered 13 minutes after the seismic shock. The landslide was later identified during a survey involving seismic reflection and submarine ROV operations (Sweet and Silver 2003), and documented through its *T* phases throughout the Pacific Basin (Okal 2003).

The high death toll of the Papua New Guinea tsunami raised awareness among scientists and Civil Defense officials worldwide for hazards from potential landslides, notably in areas where offshore seismicity would have otherwise minimized tsunami risk, such as the Los Angeles Basin (Borrero et al. 2003).

13. *Kocaeli (İzmit), Turkey, 17 August 1999*

This tsunami added significant damage in the Eastern part of the Sea of Marmara to a catastrophic earthquake with a total death toll of 17,000. Its source was a combination of a strike-slip mechanism at the head of İzmit Bay (in retrospect comparable to the 2018 Palu geometry (see **46.** below)), vertical motion at pull-apart basins, and possible landslides in the Sea of Marmara, with inundation aggravated by local

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[1] We refrain from using the word *“predicted”*, which would imply a precise date for the forecast. Note that the received date for the original manuscript (05 November 1997) is indeed anterior to the event.

subsidence, notably at Gölçuk (Altınok et al. 2001; Tinti et al. 2006).

This event is particularly significant, as it falls in the pattern of inexorable, if somewhat slow and certainly irregular, westward stress transfer along the Northern Anatolian Fault, initiated in Erzincan in 1939 (Stein et al. 1997). As such, it casts the ominous augury of the next event, expected to occur off İstanbul, a megalopolis with a population of 15 million.

14. *Fatu Hiva, Marquesas, 13 September 1999*

In the absence of any detectable seismic tremor, this tsunami was caused by the spontaneous collapse, into the sea, of a 4 million m^3 rock slide, part of the flank of an eroding 1.3 m.y. old volcano, following a 4-month drought throughout the Pacific, which acted to desiccate clays resulting from alteration of volcanic dykes (Okal et al. 2002a). It destroyed coastal infrastructure, including the wall of the school yard of the village of Omoa, and flooded the school where miraculously, 85 children escaped unharmed.

In a rare example of proactive development, the village school was relocated out of harm's way a few years later, about 1 km up the valley.

15. *Vanuatu, 26 November 1999*

The tsunami followed a moderate earthquake (Pelletier et al. 2000), and is noteworthy because of the successful evacuation of the village of Baie Martelli on the Southern coast of Pentecost Island (Caminade et al. 2000). The villagers had been sensitized to tsunami danger through a video based on the 1998 Fatu Hiva disaster, stressing the need to immediately self-evacuate low-lying areas upon feeling strong earthquake tremors, especially if accompanied by a recess of the sea. When the earthquake struck in the middle of the night, and a down-draw was reported, the village chief ordered an immediate full evacuation. The tsunami completely destroyed the village, but, out of the 300 residents, only three lost their lives: two elderly invalids who could not be evacuated and a drunken man, who refused to.

The lesson, if need be, from this event is simply: "Education works!"

16. *Camaná, Peru, 23 June 2001*

The earthquake was, at the time, the largest recorded worldwide in 36 years, and it generated a tsunami damaging 400 km of coastline, and killing 86 people (Okal et al. 2002b). A most remarkable aspect of the field survey was the concentration of the casualties on the river delta at Camaná, where farmers from the hinterland, poorly sensitized to tsunami hazards, were at work, while residents of fishing communities with a strong ancestral tradition had largely self-evacuated upon noticing the initial down-draw (Dengler et al. 2003). A much greater disaster was avoided by the occurrence of the tsunami on a beach deserted during the Winter season, which would have been packed with tourists during the Summer.

The Camaná event is also remarkable in that it provided the first detection of a tsunami through the oscillation of the ionosphere due to the continuation of its eigenfunction into the atmosphere (Artru et al. 2005), an idea originally suggested by Peltier and Hines (1976).

17. *Stromboli, Italy, 30 December 2002*

This volcanic tsunami was triggered by landslides, one submarine, the other aerial falling into the sea, at La Sciara on the flank of Stromboli (Tinti et al. 2005). It caused major damage in the nearby villages of Piscità and Ficogrande, but again a major disaster was avoided thanks to its occurrence during a season of low tourist activity.

A remarkable aspect of this event was the recording of the actual tsunami waves on horizontal seismometers located 20 km away on the island of Panarea (La Rocca et al. 2004), to our knowledge the first modern such instance, following Angenheister's (1920) observation in the far field after the Kuriles event of 07 September 1918.

18. *Aleutian Islands, 17 November 2003*

While this tsunami caused no damage or casualties, and had a maximum reported run-up of only 26 cm at Shemya, it is noteworthy because it constituted the first use of DART sensor records as part of a real-time accurate forecast of tsunami amplitudes inside a distant harbor, in this case 20 cm at Hilo, Hawaii

(Titov et al. 2005a). The alert in the Hawaiian Islands was canceled, thus preventing an unnecessary evacuation, and saving an estimated 68 million USD (Meining et al. 2005).

19. *Sumatra-Andaman, 26 December 2004*

With more than 200,000 casualties, this tsunami, the first in recorded history to have exported death and destruction across the Indian Ocean Basin, was probably the most lethal one in the history of mankind, considering the exponential growth of coastal populations in the past few centuries. The tsunami was the first in the era of modern technology to be detected worldwide (Rabinovich and Thomson 2007) and to be simulated on a full spherical model of the Earth’s oceans (Titov et al. 2005b). It transformed the word “tsunami”, used at the time only by a small community of specialists, into a worldwide household term.

It cannot be our purpose here to list every scientific result obtained in its wake, but rather we pinpoint fundamental observations which had a seminal effect on tsunami science, technology or societal response in the following years.

- From the operational standpoint, the failure to provide adequate warning to distant populations was traced to inexistent means of communication and unpreparedness in the coutries at risk, rather than to a systematic deficiency in scientific analysis (Marris 2005); at the time, the existing warning centers, in particular PTWC and ATWC, had no responsibility for the Indian Ocean, and hence no way to transmit a warning following their detection of the earthquake. The 15 years elapsed since the Sumatra disaster have seen a considerable investment into the worldwide development of a number of tsunami warning centers, notably in the Indian Ocean and in particular in Australia, Indonesia, and Oman. Only the trial of time will evaluate their performance for far-field warning.
- Perhaps the most important scientific result in the wake of the 2004 tsunami was the development of a new CMT inversion algorithm based on the *W* phase (Kanamori and Rivera 2008), following its observation at a record amplitude during the 2004 earthquake (Lockwood and Kanamori 2006). The algorithm has now been implemented worldwide at warning centers (Hayes et al. 2009), and has become the new de facto standard in long-period moment-tensor inversion.
- Another crucial development has been the abandonment of the paradigm linking plate age and convergence rate to a proposed maximum earthquake magnitude at subduction zones, originally proposed by Ruff and Kanamori (1980). Under this model, the Sumatra trench should not have hosted events bigger than $M_w \approx 8.2$, below the threshold for transoceanic tsunami hazard. Noting that a similar problem plagued the Cascadia subduction zone, where evidence for the 1700 megathrust event (Satake et al. 1996) came posterior to Ruff and Kanamori’s (1980) study, Stein and Okal (2007) conducted a critical analysis of an updated dataset of tectonic and earthquake parameters, finding a significantly degraded correlation to support the paradigm; they also noted that Ruff’s (1989) later suggestion to involve trench sediment thickness fared no better. In this context, a precautionary attitude is to consider that any sufficiently long subduction zone may be the site of a mega-event in the future, a conclusion shared by McCaffrey (2007).
- A large number of observations established the slowness of the seismic rupture of the 2004 event. They ranged from the growth of seismic moment with period (Stein and Okal 2005), seismic source tomography (e.g., Ishii et al. 2005), and the duration of high-frequency *P* waves (Ni et al. 2005) and hydroacoustic *T* waves (Guilbert et al. 2005), in addition to a clearly deficient Θ parameter (Stein and Okal 2007). In this context, and following Choy and Boatwright (2007), we classify the event as a “tsunami earthquake” on Figs. 1, 2, 3 and 4.

  In view of the slow precursor to the 1960 Chilean earthquake identified by Kanamori and Cipar (1974), and of the reassessment of the low-frequency moment of the 1964 Alaskan event (Nettles et al. 2005), this slowness in the source of the 2004 earthquake raises the legitimate question of whether all “super-mega” earthquakes ($M_0 > 10^{30}$ dyn $\times$ cm) feature a similar behavior, which would have significant implications for tsunami hazard in their aftermath (Okal 2013); the extreme scarcity of such events (a grand total of 3 have been analyzed) leaves the jury out at this time.

- The 2004 Sumatra earthquake was so large that its tsunami was recorded by a number of instruments which were not designed for it, generally as the result of coupling between very different media, such as the sea, the solid Earth and the atmosphere. This coupling would be expected to be very small, but in the presence of a monumental event, can yield tangible observations which were not only documented, but also often quantitatively forward- or inverse-modeled, occasionally all the way to an appropriate estimate of the moment of the earthquake. This was the case, for example of hydrophones of the IMS (Hanson and Bowman 2005; Okal et al. 2007), radar altimeters (Smith et al. 2005) leading to an explanation of the intriguing case of "tsunami shadows" (Godin et al. 2009), of the detection of the tsunami in the ionosphere from perturbation to GPS signals (Liu et al. 2006; Occhipinti et al. 2006), and systematically by horizontal seismometers on oceanic islands (Yuan et al. 2005) in a pattern that Okal (2007) showed could be interpreted as mirroring an Ocean-Bottom Seismometer record. Most such techniques were later applied regularly to smaller tsunamis.

  Finally, the tsunami was recorded by seismometers temporarily deployed on large icebergs floating off the coast of Antarctica, providing what remains to this day the only in situ recording of the horizontal motion of the ocean surface during the passage of a tsunami (Okal and MacAyeal 2006).
- Surveying in the near field benefited from technological advances such as the scientific decoding of video recordings to reconstruct a quantitative estimate of tsunami flow velocities (Fritz et al. 2006), which in particular documented their increase with time within a wavetrain, leaving essentially no chance for the population to escape.
- An unexpected observation compiled at several locations during the numerous field surveys covering the entire Indian Ocean Basin, was the occasional development of strong currents in distant harbors several hours after the arrival of the initial wave, and often after the all clear had been given by local authorities, e.g., in Toamasina, Madagascar (Okal et al. 2006a), Le Port, Réunion (Okal et al. 2006b) and Salallah, Oman (Okal et al. 2006c). This effect, which can lead to hazardous situations when major vessels break their moorings in ports, is explained as the setting up of harbor resonance by higher-frequency components of the tsunami traveling outside the shallow-water approximation. Since 2004, similar effects have been observed during other events. In this context, harbor communities must be educated to this form of hazard, and evacuation procedures, especially the issuance of all clear, adapted accordingly.

20. *Nias, Indonesia, 28 March 2005*

This "second" Sumatra event, remarkably anticipated a few days earlier by McCloskey et al. (2005) in the context of Coulomb stress transfer, was indeed gigantic ($M_0 = 1.05 \times 10^{29}$ dyn × cm), and took 600 lives in Nias and 100 in Simeulue. However, its tsunami was modest, running up to only 4.2 m, apparently without fatalities in the near field. It was also negligible in the far field, despite 10 casualties in traffic accidents due to panic generated by night-time evacuation (Okal et al. 2006a; Borrero et al. 2011). This intriguing situation is explained by a significant fraction of the deformation in the source area taking place either under large islands ("the earthquake moved a large amount of rock and not much water"), or at shallow depths, the tsunami then faltering under Green's (1838) law when reaching deep basins (Synolakis and Arcas, quoted by Kerr 2005).

In addition, the population of Simeulue was sensitized to tsunami hazard through the *Smong* tradition, possibly derived from the catastrophic "tsunami earthquake" of 1907 (Martin et al. 2019), and self-evacuated during both the 2004 and 2005 tsunamis (McAdoo et al. 2006).

21. *Central Java, 17 July 2006*

This "tsunami earthquake" was essentially a repeat of the 1994 event (see **4.** above), 580 km to the East. As such, it reopens the question of any possibly regional character to tsunami earthquakes. In an early study, Okal and Newman (2001) had found meager evidence for it in the Peruvian system. The 2006 event in Java shows a stronger case, supported also by the 2012 El Salvador and 2013 Santa Cruz events (see **34.** and **36.** below).

22. *Central Kuriles, 15 November 2006*
23. *Central Kuriles, 13 January 2007*

We discuss those two events together, since they occurred as a seismic doublet, in Winter, in a remote, unpopulated part of the island chain, and it took 9 months before a field survey could be arranged (MacInnes et al. 2009), which thus could not assign *a priori* the field evidence (up to 22 m of run-up) to one or the other. Tsunami records in the far field (at a minimum distance of 600 km) were obtained at tidal gauges across the Pacific and on DART sensors (Rabinovich et al. 2008), showing a smaller tsunami in 2007 at all locations.

The first event was a classical interplate thrust, followed 2 months later by a slightly smaller normal faulting event on the outer rise, probably triggered by stress transfer (Ammon 2008). As expected under such a scenario, source tomography studies (e.g., Lay et al. 2009) revealed that the smaller 2007 event featured larger slip distributed over a smaller surface than the 2006 mainshock. Using these source models, Rabinovich et al. (2008) carried out simulations which confirmed far-field observations, but suggested that the 2007 event could have featured larger amplitudes in deep water along the Central Kuriles than the 2006 one (on the order of 7 m as opposed to 5). Based on these results, and on full run-up calculations at a number of surveyed sites, MacInnes (2010) assigned some of her maximum run-up amplitudes to the 2007 event.

These two tsunamis emphasized the fundamental difference between near-field amplitudes, directly related to maximum slip on the fault, and far-field ones, controlled by the full integral of its distribution, i.e., by the seismic moment.

Perhaps because of the lack of local information, the warning centers for the Pacific Basin underestimated the 2006 event and canceled initial warnings, even though the tsunami was to cause one injury and damage in Hawaii, and especially in Crescent City, California, to the extent of 9.8 million USD (Dengler et al. 2009). The 2006 tsunami served as a particularly acute reminder of the vulnerability of that community to a wide range of tsunami sources in the Pacific, and resulted in the implementation of a more detailed, quantified set of warning criteria at the US Tsunami Warning Centers (Whitmore et al. 2008).

24. *Gizo, Solomon Islands, 01 April 2007*

This earthquake was remarkable in that it ruptured along the Solomon Islands trench, across the triple junction separating the Australian plate from the Woodlark mini-plate (Taylor et al. 2008), an important observation which shows that plate boundaries cannot be considered as barriers limiting the size of potentially tsunamigenic earthquakes in subduction zones. A similar scenario was proposed for the 1932 Manzanillo, Mexico earthquake by Okal and Borrero (2011).

The death toll (52) was contained despite widespread flooding and destruction, thanks to systematic self-evacuation in this region characterized by a high level of seismic and volcanic activity (Fritz and Kalligeris 2008). Very similar conclusions were reached after the tsunami of 03 January 2010, only 200 km to the ESE, which involved no casualties (Newman et al. 2011a).

25. *Aysén, Chile, 21 April 2007*

This tsunami resulted from a massive rock slide into Aysén Fjord (Barrientos et al. 2009), triggered by an earthquake on the nearby Liquiñe-Ofqui fault system (LOFS), which marked the culmination of an intense seismic swarm lasting 3 months (Legrand et al. 2011). The remoteness of the area helped contain the death toll, but splashes on Mentirosa Island reached ~ 50 m, in a scenario reminiscent of the 1958 Lituya Bay tsunami (Miller 1960), albeit on a smaller scale. The exact role of the LOFS in the local plate tectonic framework should be further investigated in the context of local tsunami hazard, especially since Kanamori et al. (2019) have recently suggested that it may have contributed a significant component to the great 1960 Chilean earthquake.

26. *Pisco, Peru, 15 August 2007*

Following heavy structural damage and casualties inflicted by the earthquake on this Central Peruvian city, the tsunami locally reached run-up heights of 10 m, but "sergeants" acting in a sense as lifeguards on beaches conducted an evacuation that helped contain the death toll from the tsunami to three casualties in the town of Lagunilla, which inexplicably was not part of the program (Fritz et al. 2008).

It is noteworthy that this event had been anticipated, albeit on a greater scale, by Okal et al. (2006d).

27. *Bengkulu, Indonesia, 12 September 2007*

This very large event produced a relatively contained tsunami, with run-up not exceeding 4 m (Borrero et al. 2009), and despite significant tsunami damage, no deaths were reported, thanks to successful self-evacuation.

The event is noteworthy, since it took place in a region highlighted for tectonic strain accumulated since the 1833 mega-earthquake, as well as under stress transfer in the wake of the 2004 Sumatra and 2005 Nias earthquakes (Nalbant et al. 2005; Pollitz et al. 2006). However, the 2007 Bengkulu earthquake failed to release all the slip accumulated since 1833, and thus the area remains a candidate for a significant tsunami in the near future (Okal et al. 2009).

28. *Chebalis Lake, B.C., 04 December 2007*

This event resulted from the fall of a 3-million m^3 rockslide into Lake Chebalis in Southwestern British Columbia. Fortunately, the local campsites were closed for the Winter, and no lives were lost, but a wave splashed 38 m onto the opposite bank of the 1-km wide lake. The event was successfully modeled by Wang et al. (2015).

29. *Samoa, 29 September 2009*

This large event at the Northern corner of the Tonga arc actually had a composite source, starting as a normal faulting shock, followed $\sim$100 s later by a more regular interplate thrust one (Li et al. 2009; Lay et al. 2010). It raised a powerful tsunami, running up to 22 m on Tafahi, Tonga, and bringing death and destruction to American Samoa, Samoa, and Tonga, with a total of 192 casualties, mostly in [independent] Samoa.

Despite the complex mechanism, tsunami modeling based on the inversion of DART data assuming a regular shallow angle thrust provided acceptable fits to surveyed amplitudes, thus demonstrating the robustness of the approach (Okal et al. 2010). The field survey revealed a generally successful evacuation on American Samoa, reflecting a well-prepared community, as opposed to [independent] Samoa, where in particular the absence of signage may have contributed to a higher death toll (Fritz et al. 2011a).

30. *Haiti, 13 January 2010*

This is another example of a catastrophic strike-slip earthquake generating a minor tsunami, constrained to a few locations in Gonâve Bay and along the Southern coast (Fritz et al. 2012), with a run-up not exceeding 3 m, and a death toll of 7 (as opposed to perhaps 300,000 from the earthquake). At both locations, the tsunamis were due to underwater landslides triggered by the earthquake; note in particular that in this case, the Enriquillo strike-slip fault does not intersect the shoreline, preventing a "Mindoro"-type generation, which could have been much more damaging.

31. *Chile, 27 February 2010*

This megathrust event generated the first tsunami in 46 years with transpacific runup in excess of 1 m, in the Kuril Islands and at certain sites in California. In the near field, it caused considerable damage, with run-up reaching 29 m at Constitución, and 156 fatalities, many of them trapped on a campground on Orrego Island in the mouth of the Maule River (Fritz et al. 2011b). The real-time handling of the warning by Chilean authorities was generally regarded at best as deficient, at worst as inept, and in particular no warning was issued for Juan Fernández Island, where the loss of 18 lives could have been prevented, when the tsunami attacked the island 49 minutes after the earthquake. This led to a successful major restructuring of the Chilean Tsunami Warning Center (see **39.** below).

The 2010 Maule tsunami was also the first one to be detected as a perturbation of the geomagnetic field of the Earth (Manoj et al. 2011), following Tyler's (2005) model of induction currents caused by the displacement of conducting seawater in the Earth's field.

32. *Mentawai, Indonesia, 25 October 2010*

This “tsunami earthquake” occurred up-dip of the 2007 Bengkulu event (see **27.** above), in the typical configuration of an “Aftershock Tsunami Earthquake” (Okal and Saloor 2017). The high death toll (431) resulted from the combination of deceptively low shaking and of the occurrence, only a year before, of the intermediate-depth, intraplate Padang earthquake (Hill et al. 2012). The 2009 event had created a negligible tsunami (maximum run-up 27 cm), but had been strongly felt in the Mentawai Islands, instilling in the residents the false sense that a dangerous tsunami would require even greater shaking.

Incidentally, the anomalously slow nature of the earthquake had been documented 17 minutes after origin time (and thus before the tsunami could reach the Mentawai Islands), on the basis of the comparison of duration and energy of teleseismic *P* waves (Newman et al. 2011b), but there existed no way to transmit this information to Indonesia, let alone to the people at risk, many of whom were in communities lacking electrical power, where the local warning from the Indonesian Tsunami Warning Center was apparently not received.

33. *Tohoku, Japan, 11 March 2011*

The catastrophic 2011 Tohoku tsunami ranks only second the 2004 Sumatra one in terms of death toll in the past 100 years. Its run-up reached 6 m in the far field, and it wrought damage as far as the Chilean coast, and even in Antarctica, where it caused calving of a large iceberg (Brunt et al. 2011). A selection of the main points of scientific and societal interest includes:

- *Violation of Scaling Laws*
  Detailed seismic tomography of the earthquake source, later confirmed by GPS studies and modeling of DART records, identified a patch of extremely large seismic slip on the fault, reaching ~ 50 m over a length of no more than 100 km (Lay et al. 2011), thus clearly violating seismic scaling laws widely used in the assessment of tsunami risk.
- *Great Success in the Far Field*
  Despite large run-up amplitudes leading to some structural damage, adequate warnings were given—and generally well heeded—in the far field, resulting to our knowledge in only two fatalities (one in Crescent City, California, and one close to Jayapura, Indonesia), which were preventable since both occurred in violation of mandatory evacuation orders. This positive outcome may have been helped by the daytime occurrence of the tsunami in Japan, which allowed immediate worldwide TV coverage of the catastrophic magnitude of the event (as opposed for example, to the night-time occurrence of the Chilean tsunami the previous year).
- *Fukushima Nuclear Accident*
  The 2011 tsunami is of course known worldwide for the nuclear meltdown at the Fukushima Dai-Ichi nuclear plant, caused by cooling water starvation following the flooding of the emergency diesel power generators by the tsunami. As of 2019, and probably for decades to come, an exclusion zone of $\sim 300\,\mathrm{km}^2$ is maintained, affecting about 50,000 residents.
  Careful analyses of the origin of the disaster by Nöggerath et al. (2011) and Synolakis and Kânoğlu (2015) have evidenced a cascade of design, scientific, engineering, and managerial blunders in the construction and operation of the plant, which suggests that the disaster was preventable, the best proof being that the Oganawa nuclear power plant, located only 127 km to the North, in a stretch of coastline which suffered considerably higher run-up, was safely shut down, and after a lengthy upgrade, is now scheduled to be re-started in the next few months.
- *Reasonable Success in Evacuation*
  As offensive as this statement may sound in the wake of a 19,000 death toll, the evacuation process in the near field can be regarded as generally successful. It has been estimated that approximately 200,000 people were present in the areas totally eradicated by the tsunami, and thus that about 90% of them saved their lives by proper evacuation (Dengler, pers. comm., 2011; Fritz, pers. comm., 2011); this figure might even have been higher, but for horrific instances of orderly evacuation to shelters located at underestimated heights. It nevertheless constitutes a tribute to the awareness, education, and responsibility of the

people of Japan, once again stresses the value of education in the mitigation of natural disasters, and stands in blunt contrast to the ineptitude underlying the whole Fukushima tragedy.

34. *El Salvador, 27 August 2012*

This tsunami went largely unnoticed as it resulted in very little damage and no fatalities, mostly because it occurred in an unpopulated segment of the Pacific coast of Central America. Yet, it ran up to 6.3 m, and most significantly, was identified as a tsunami earthquake through its deficient energy-to-moment ($\Theta = -6.0$) and energy-to-duration ratios (Borrero et al. 2014).

This is important, since it brings some support to the concept that the Central American coast, site of the 1992 Nicaragua event only 150 km away (see **1.** above), could feature a regional preference for tsunami earthquakes. A rather obscure event on 26 February 1902 towards the Guatemalan border may also have shared some comparable properties (Cruz and Wyss 1983).

35. *Haida Gwaii, British Columbia, 28 October 2012*

This earthquake featured a rare shallow thrust fault mechanism at the Pacific-North America plate boundary, characterized in the area by extreme oblique convergence, and thus slip partitioning along the Queen Charlotte Fracture Zone (Lay et al. 2013). It featured locally substantial run-up values (up to 13 m), but took place in a seasonally unpopulated area (Leonard and Bednarski 2014). We dismiss the lone casualty, from a traffic accident in Hawaii caused by a drunken driver ramming into cars parked during the evacuation, as it is not a direct victim of the tsunami.

Like the 1996 Biak earthquake (see **9.** above), this event underscores the possibility of significant tsunami hazard from rare thrust components to oblique subduction along partitioned boundaries featuring mostly strike-slip events.

36. *Santa Cruz Islands, 06 February 2013*

This event, which qualifies as a “tsunami earthquake”, triggered a tsunami running up to 11 m on Nendö Island, where it killed 10 people (Fritz et al. 2013). It is noteworthy that it shares its epicenter with another tsunami earthquake, on 21 July 1934, which led Okal and Saloor (2017) to identify systematic variations of coupling correlating with the slowness parameter Θ along the Solomon-Vanuatu arc; however the 1934 event happened as an aftershock of a regular earthquake, 100 km to the South, while the 2013 event was primary.

37. *Sea of Okhotsk, 24 May 2013*

This event, the largest deep earthquake ever recorded ($M_0 = 3.95 \times 10^{28}$ dyn $\times$ cm), did generate a tsunami recorded at millimetric amplitudes by two DART sensors off the Kuril Islands (Okal 2017). While it did not cause any damage, this unique detection raises the possibility of tsunamis observable at coastlines being generated by deep earthquakes, should even larger ones occur in the future.

38. *Gwadar, Pakistan, 24 September 2013*

This rather unusual scenario involved a tsunami in the Indian Ocean triggered by an earthquake occurring onland, about 200 km from the nearest shoreline. While of moderate size, the tsunami reached 1 m on the coast of Oman, and the process was accompanied by the emergence of a mud island off Gwadar, Pakistan. Heidarzadeh and Satake (2014) analyzed tidal gauge records of the event and concluded that the tsunami could not be caused by the emergence of the mud volcano, but rather by a probable underwater slump located about 70 km off the coast, at a total distance of $\sim$ 400 km from the epicenter of the earthquake. This event serves as a reminder, if need be, of the capability of inland earthquakes to generate tsunamis through the triggering of underwater landslides; the 400-km distance is indeed large, but far from a record, since the 1910 Rukwa earthquake near Lake Tanganyika, in present day Tanzania, severed telegraphic cables in the Mozambique channel, at a distance of 900 km (Ambraseys 1991).

39. *Iquique, Chile, 01 April 2014*

This large event took place in what was defined as the Northern Chilean seismic gap (Chlieh et al. 2011), where the last major earthquake and tsunami took place in 1877. However, despite its large magnitude, it did not release the full accumulated strain, and thus seismic and hence tsunamigenic potential remains to this day (Hayes et al. 2014).

A remarkable aspect of the 2014 Chilean tsunami is that it apparently did not cause any casualties. This reflects the orderly, professional evacuation of about 1 million people from coastal areas in less than an hour, in stark contrast to the case of the Maule tsunami just 4 years earlier, and following a complete revamping of the country’s Tsunami Warning Center system.

40. *Illapel, Chile, 16 September 2015*

This new Chilean tsunami took place about 1000 km South of the 2014 epicenter. It produced much higher run-up reaching 13 m, and resulted in 8 fatalities (Aránguiz et al. 2016). As in the case of the 2014 event (see **39.** above), a successful warning and evacuation took place, again involving about 1 million residents.

A remarkable experiment conducted during this tsunami was the in situ measurement of currents in the harbor of Ventura, California. Taking advantage of the $\sim$14-h travel time of the tsunami from Chile to California, Kalligeris et al. (2016) were able to deploy floaters equipped with GPS receivers, and documented current velocities of up to 1.5 m/s in turbulent flow. Because hazards to navigation in harbors depend crucially on current velocities, the collection of such data opens new opportunities for research critical to their further mitigation.

41. *Taan Fjord, Icy Bay, Alaska, 18 October 2015*

This remarkable event, fully described by Higman et al. (2018), shares many similarities with the classic 1958 Lituya Bay tsunami, 260 km to the SE, which splashed to a record height of 525 m (Miller 1960): it was generated by a massive landslide into a narrow fjord serving as estuary to an ice stream, and essentially faltered (because of extremely short wavelengths) upon reaching the open ocean. However, no detectable earthquake could be identified as its trigger, while the 1958 event followed a large shock ($M_s = 7.9$). The field survey documented run-up reaching 193 m on the opposite side of the fjord. Seismic waves from the landslide were detected worldwide and inverted to suggest a slide mass of 10^{11} kg.

42. *Ecuador, 16 April 2016*

This major earthquake occurred in a section of the South American subduction system characterized by diversity and complexity in the mechanism of strain release. The tsunami was only of marginal amplitude, reaching at most 10 cm on local tide gauges, and resulting in no fatalities. By contrast, the Colombia-Ecuador region was the site a mega-event in 1906, whose tsunami was recorded Pacific-wide and killed about 5000 people in the near field. It was followed by smaller shocks in 1942, 1958 and 1979, which released strain only over distinct fragments of the presumed 1906 rupture area. Only the 1979 event generated a substantial tsunami with about 600 victims. No mention can be found of a tsunami following the 1942 earthquake.

From the standpoint of its seismic source, and as detailed by Ye et al. (2016), the 2016 event may be a replica of the one in 1942, and the deceptive amplitude of their tsunamis explained by a relatively deep rupture, failing to reach the uppermost part of the subduction contact (Heidarzadeh et al. 2017). This brings the question of the nature of coupling at that shallow interface, which, if presently locked, could be ripening for a future event in the form of a tsunami earthquake. However, no such events are known in the historical record, which incidentally is very short in Southern Colombia and Northern Ecuador, with no events listed by Solov’ev and Go (1984) prior to 1906, despite Spanish presence going back to 1531.

43. *Kaikōura, New Zealand, 13 November 2016*

This earthquake nucleated on land, but propagated along a complex series of offset faults, both on land and at sea, in the general transition zone between the Alpine Fault system and the Hikurangi Trough (Power et al. 2017). The tsunami was destructive both in the southern part of the rupture area, with a maximum run-up of 6.3 m, and farther South in the Banks Peninsula, as a result of the extreme indentation of the latter’s numerous bays. No comparable historical seismicity was known in the area, and thus the tsunami was unexpected. No casualties were attributed to the tsunami.

Modeling by Heidarzadeh and Satake (2017) has suggested a combined generation by elements of the complex dislocation and possible submarine landslides.

44. *Karrat Fjord, Greenland, 17 June 2017*

This tsunami was generated by the fall of an aerial landslide involving about 50 million m^3 into a fjord on the West coast of Greenland. At its source, the tsunami ran up to a height of 50 m across the fjord (Fritz et al. 2018). It attacked the village of Nuugaatsiaq, located 32 km away, running up 10 m and killing 4 persons. While no tidal gauges were available, a seismic station was being operated at Nuugaatsiaq, and its horizontal records were deconvolved by Paris et al. (2019) to reconstruct an equivalent tsunami amplitude time series in the channel facing the village. This documented a resonant oscillation of the channel comparable to observations in the Panama Canal by McNamara et al. (2011).

45. *Gulf of Alaska, 23 January 2018*

With a moment of only 1.0×10^{28} dyn × cm, this intraplate earthquake was still the largest one recorded in 2018. It was characterized by an extremely complex rupture, involving several subsources located on offset segments of a primarily strike-slip fault structure (Lay et al. 2018), in the general vicinity of the slightly smaller events of 30 November 1987 and 06 March 1988. Like these two events, incidentally the first ones recorded by a prototype DART sensor (González et al. 1991), the 2018 earthquake generated only a mediocre tsunami, barely reaching 25 cm at Kodiak, and in the far field at Crescent City and in the Marquesas Islands.

46. *Palu, Indonesia, 28 September 2018*

With more than 2200 casualties, this tsunami stands as the most lethal one since the great 2011 Tohoku event. At the time of writing, its mechanism remains unclear. The geometry of the event advocates a “Mindoro-type” bayhead effect (see **7.** above), where the strike-slip fault hits the coast of Sulawezi (Heidarzadeh et al. 2019); however visual evidence of underwater slides, in the form of surface eddies, suggests their contribution to the genesis of the tsunami (Harig et al. 2019).

47. *Anak Krakatau, Indonesia, 22 December 2018*

This catastrophic tsunami, killing upwards of 400 persons on the coasts of Java and Sumatra, resulted from the flank collapse of Anak Krakatau, as part of an eruption cycle which had started 6 months earlier. It is remarkable that the scenario had been forecast, at a quantitatively astonishing level of accuracy, by Giachetti et al. (2012). The flank collapse was well recorded seismically, and interpreted as a 0.3-km^3 slide, originating above sea level and propagating about 3 km under water (G. Ekström, pers. comm., 2019). In the absence of records from DART sensors (which did not trigger into higher sampling mode), horizontal seismograms at island stations can be deconvolved (Okal et al. 2019) to confirm amplitudes in the range of 0.1–1.5 mm on the high seas, due to the faltering, according to Green’s (1838) law, of a tsunami generated in extremely shallow waters.

Preliminary results from surveys suggest flow depths on the order of 2–5 m along the coast of Java, and run-up values of 30 m in the source area (Prasetya et al. 2019).

The 2018 tsunami differs fundamentally from the monstrous, worldwide one in 1883, which Press and Harkrider (1966) showed was due to an acoustic-gravity wave following an atmospheric explosion which they estimated at between 100 and 150 Megatons. In 2019, infrasound signals at the 10 Pa level were recorded at the Cocos Island infrasound array (1160 km away) from an explosion following the landslide by 7 minutes, but had already fallen below noise level at Diego Garcia, 3440 km away (Okal et al. 2019).

3. *Discussion and Conclusion*

In conclusion of this review, the main developments in the past 25 years can be summarized as follows:

- We have acquired the capacity to obtain in quasi-real time (i.e., possibly before the tsunami reaches regional beaches) quantitative information on the earthquake source spectrum, both at low frequencies through *W*–phase inversions (Kanamori and Rivera 2008) and at high-frequency through the energy radiated by *P* waves, which can be compared either to seismic moment, or to source duration (Newman et al. 2011b).

- We have developed algorithms to successfully model run-up as the non-linear interaction of tsunamis with originally dry land at the beaches, both in the near and far fields. As a result, countless scenarios have been prepared to assist Civil Defense authorities in the advanced mitigation of tsunami hazards (e.g., Barberopoulou et al. 2011), the resulting inundation maps providing a considerable improvement for the issuance of tsunami evacuation orders under operational conditions.
- In the wake of the recent tsunami activity, and most particularly of the 2004 Sumatra event, the past 15 years have seen an explosion in the amount of high-quality data available under operational conditions to Tsunami Warning Centers, including broad-band seismic data and coastal and ocean-bottom sensors. We have developed real-time algorithms, such as SIFT (Gica et al. 2008), to successfully forecast tsunami amplitudes in the far field, introducing a quantitative component to the issuance of warnings for distant communities.
- Possibly as a result of this progress, we have seen, since the 2004 Sumatra disaster, a spectacular reduction in the number of casualties in the far field (i.e., 1000 km or more from the epicenter), which amounts to a grand total of 2 in the past 14 years (not counting traffic fatalities during evacuation, which are not direct effects of the tsunami), both of which occurred in violation of mandatory evacuation. This also reflects a better education of the lay public worldwide to tsunami hazards, obviously the result of the catastrophic tsunamis of 2004 and 2011.
- Elaborate techniques during post-tsunami surveys are starting to greatly improve our understanding of currents, i.e., particle flow velocities at beaches and harbors, which are the primary factors controlling momentum transfer, and therefore structural damage during inundation.
- The examples of Montserrat and Krakatau show that accurate quantitative forecasts can be made even for complex sources such as flank collapses during episodes of volcanic activity.

However, there remain significant challenges which need to be addressed in the forthcoming years:

- Paramount among them is the question of “tsunami earthquakes”, which have not been recognized effectively by warning centers in the past 15 years (e.g., Java, 2006; Mentawai, 2010; El Salvador, 2012). While an approach such as Newman et al.’s (2011b) is promising in this respect, a major challenge will be to instill its fundamental ingredient (the disparity between the duration and amplitude of shaking) in the minds of the populations at risk. In this context, it is remarkable that some survivors of the Mentawai disaster have reported to the Post-Tsunami Survey Team that the shaking had been “weak and long” (Hill et al. 2012). An emphasis on the ominous character of such a harbinger must be part of the tsunami education of coastal communities.
- Finally, it is a bitter thought that the latest lethal tsunami took place during a catastrophic episode of a volcanic crisis which had taken months to build up, during which adequate seismic and geodetic monitoring could have been used to maintain awareness in the populations at risk. In hindsight, common sense would suggest that a closed building on an unprotected beach may not have been the best venue to hold a rock concert on the coast of Java, while Anak Krakatau was glowing red in the night sky, only 40 km away. Here again, a considerable effort of education is necessary in the communities at risk.

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REFERENCES

Abe, K., Abe, K., Tsuji, Y., Imamura, F., Katao, H., Iio, Y., et al. (1993). Field survey of the Nicaragua earthquake and tsunami of September 2, 1992. *Bulletin of the Earthquake Research Institute of Tokyo University*, *68*, 23–70.

Altınok, Y., Tinti, S., Alpar, V., Yalçıner, A. C., Ersoy, Ş., Bortolucci, E., et al. (2001). The Tsunami of August 17, 1999 in İzmit Bay. *Turkey, Natural Hazards*, *24*, 133–146.

Ambraseys, N. N. (1991). The Rukwa earthquake of 13 December 1910 in East Africa. *Terra Nova*, *3*, 202–211.

Ammon, C. J. (2008). A great earthquake doublet and seismic stress transfer cycle in the central Kuril Islands. *Nature*, *451*, 561–565.

Angenheister, G. (1920). Vier Erdbeben and Flutwellen im pazifischen Ozean, beobachtet am Samoa Observatorium, 1917–1919, *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematische-physikalische Klasse*, 201–204.

Aránguiz, R., González, G., González, J., Catalán, P. A., Cienfuegos, R., Yagi, Y., et al. (2016). The 16 September 2015 Chile tsunami from the post-tsunami survey and numerical modeling perspectives. *Pure and Applied Geophysics*, *173*, 333–348.

Artru, J., Dučić, V., Kanamori, H., Lognonné, P., & Murakami, M. (2005). Ionospheric detection of gravity waves induced by tsunamis. *Geophysical Journal International*, *160*, 840–848.

Barberopoulou, A., Borrero, J. C., Uslu, B., Legg, M. R., & Synolakis, C. E. (2011). A second generation of tsunami inundation maps for the State of California. *Pure and Applied Geophysics*, *168*, 2133–2146.

Barrientos, S. E., Vigny, C., Ward, S. N., & Bataille, K. D. (2009). Earthquake-induced rockfall and tsunami in Southern Chile. *Eos, Transactions of the American Geophysical Union*, *90*(53), NH43B–1315 [abstract].

Bernard, E. N., & Milburn, H. B. (1985). Long-wave observations near the Galápagos Islands. *Journal of Geophysical Research*, *90*, 3361–3366.

Boatwright, J., & Choy, G. L. (1986). Teleseismic estimates of the energy radiated by shallow earthquakes. *Journal of Geophysical Research*, *91*, 2095–2112.

Borrero, J. C., Ortíz, M., Titov, V. V., & Synolakis, C. E. (1997). Field survey of Mexican tsunami produces new data, unusual photos, Eos. *Transactions of the American Geophysical Union*, *78*, 85 and 87–88.

Borrero, J. C., Yalçıner, A. C., Kânoğlu, U., Titov, V. V., McCarthy, D., & Synolakis, C. E. (2003). Producing tsunami inundation maps in California. In A. C. Yalçıner, E. N. Pelinovsky, E. A. Okal, & C. E. Synolakis (Eds.), *Submarine landslides and tsunamis* (pp. 315–329). Dordrecht: Kluwer Academic Publishers.

Borrero, J. C., Weiss, R., Okal, E. A., Hidayat, R., Suranto, A. D., & Titov, V. V. (2009). The tsunami of 12 September 2007, Bengkulu Province, Sumatra, Indonesia: Post-tsunami survey and numerical modeling. *Geophysical Journal International*, *178*, 180–194.

Borrero, J. C., McAdoo, B. G., Jaffe, B., Dengler, L., Gelfenbaum, G., Higman, B., et al. (2011). Field survey of the March 28, 2005 Nias-Simeulue earthquake and tsunami. *Pure and Applied Geophysics*, *168*, 1075–1088.

Borrero, J. C., Kalligeris, N., Lynett, P. J., Fritz, H. M., Newman, A. V., & Convers, J. A. (2014). Observations and modeling of the August 27, 2012 earthquake affecting El Salvador and Nicaragua. *Pure and Applied Geophysics*, *171*, 3421–3435.

Briggs, M. J., Synolakis, C. E., Harkins, G. S., & Green, D. R. (1995). Laboratory experiments of tsunami run-up on a circular island. *Pure and Applied Geophysics*, *144*, 569–594.

Brunt, K. M., Okal, E. A., & MacAyeal, D. R. (2011). Antarctic ice-shelf calving triggered by Honshu earthquake and tsunami, March 2011. *Journal of Glaciology*, *57*, 785–788.

Caminade, J.-P., Charlie, D., Kânoğlu, U., Koshimura, S., Matsutomi, H., Moore, A., et al. (2000). Vanuatu earthquake and tsunami cause much damage, few casualties, Eos. *Transactions of the American Geophysical Union*, *81*, 641 and 646–6470.

Catalán, P. A., Aránguiz, R., González, G., Tomita, T., Cienfuegos, R., González, J., et al. (2015). The 1 April 2014 Pisagua tsunami: Observations and modeling. *Geophysical Research Letters*, *42*, 2918–2925.

Chlieh, M., Perfettini, H., Tavera, H., Avouac, J.-P., Remy, D., Nocquet, J.-M., et al. (2011). Interseismic coupling and seismic potential along the Central Andes subduction zone. *Journal of Geophysical Research*, *116*, B12405, 21 pp.

Choy, G. L., & Boatwright, J. (2007). The energy radiated by the 26 December 2004 Sumatra-Andaman earthquake estimated from 10-minute *P*-wave windows. *Bulletin of the Seismological Society of America*, *97*, S18–S24.

Cruz, G., & Wyss, M. (1983). Large earthquakes, mean sea level, and tsunamis along the Pacific coast of Mexico and Central America. *Bulletin of the Seismological Society of America*, *73*, 553–570.

Dengler, L., Borrero, J., Gelfenbaum, G., Jaffe, B., Okal, E. A., Ortíz, M., et al. (2003). Tsunami. In A. Rodriguez-Marek & C. Edwards (Eds.), *Southern Peru earthquake of 23 June 2001, reconnaissance report* (Vol. 19, pp. 115–144). Oakland: Earthquake Spectra. Supp. A.

Dengler, L., Uslu, B., Barberopoulou, A., Yim, S. C., & Kelly, A. (2009). The November 15, 2006 Kuril Islands-generated tsunami in Crescent City. *California, Pure and Applied Geophysics*, *166*, 37–53.

Fine, I. V., Cherniawsky, J. Y., Thomson, R. E., Rabinovich, A. B., & Krassovski, M. V. (2015). Observations and numerical modeling of the 2012 Haida Gwaii tsunami off the coast of British Columbia. *Pure and Applied Geophysics*, *172*, 699–718.

Fritz, H. M., & Kalligeris, N. (2008). Ancestral heritage saves tribes during 1 April 2007 Solomon Islands tsunami. *Geophysical Research Letters*, *35*(1), L01607, 5 pp.

Fritz, H. M., Borrero, J. C., Synolakis, C. E., & Yoo, J. (2006). 2004 Indian Ocean tsunami flow velocity measurements from survivor videos. *Geophysical Research Letters*, *33*(24), L24605, 5 pp.

Fritz, H. M., Kongko, W., Moore, A., McAdoo, B., Goff, J., Harbits, C., et al. (2007). Extreme run-up from the 17 July 2006 Java tsunami. *Geophysical Research Letters*, *34*(12), L12602.

Fritz, H. M., Kalligeris, N., Borrero, J. C., Broncano, P., & Ortega, E. (2008). The 15 August 2007 Peru tsunami run-up observations and modeling. *Geophysical Research Letters*, *35*(10), L10604, 5 pp.

Fritz, H. M., Borrero, J. C., Synolakis, C. E., Okal, E. A., Weiss, R., Titov, V. V., et al. (2011a). Insights on the 2009 South Pacific tsunami in Samoa and Tonga from field surveys and numerical simulations. *Earth Science Reviews*, *107*, 66–75.

Fritz, H. M., Petroff, C. M., Catalán, P. A., Cienfuegos, R., Winckler, P., Kalligeris, N., et al. (2011b). Field survey of the 27 February 2010 Chile tsunami. *Pure and Applied Geophysics*, *168*, 1989–2010.

Fritz, H. M., Vilmond-Hillaire, J., Molière, E., Wei, Y., & Mohammed, F. (2012). Twin tsunamis triggered by the 12 January 2010 Haiti earthquake. *Pure and Applied Geophysics*, *170*, 1463–1474.

Fritz, H. M., Papantoniou, A., Biuokoto, L., & Gilly, A. (2013). The Solomon Islands tsunami of 6 February 2013 field survey in the Santa Cruz Islands. *Eos, Transactions of the American Geophysical Union*, *96*(53), NH41A-1696. [abstract].

Fritz, H. M., Giachetti, T., Anderson, S. A., & Gauthier, D. (2018). Field survey of the 17 June 2017 landslide-generated tsunami in Karrat Fjord, Greenland. *Geophysical Research Abstracts*, *20*, EGU-2018-18345 [abstract].

Giachetti, T., Paris, R., Kelfoun, K., & Ontowirjo, B. (2012). Tsunami hazard related to a flank collapse of Anak Krakatau Volcano, Sunda Strait, Indonesia. *Geological Society of London, Special Publications*, *361*, 79–90.

Gica, E., Spillane, M., Titov, V. V., Chamberlin, C., & Newman, J. C. (2008). Development of the forecast propagation database for NOAA’s Short-term Inundation Forecast for Tsunamis (SIFT). *NOAA Tech. Memo. OAR PMEL*, *139*, 89. pp.

Godin, O. A., Irisov, V. G., Leben, R. R., Hamlington, B. D., & Wick, G. A. (2009). Variations in sea surface roughness induced by the 2004 Sumatra-Andaman tsunami. *Natural Hazards Earth Science Systems*, *9*, 1135–1147.

González, F. I., Mader, C. L., Eble, M. C., & Bernard, E. N. (1991). The 1987–88 Alaskan Bight tsunamis: Deep ocean data and model comparisons. *Natural Hazards*, *4*, 119–139.

Goto, C., Ogawa, Y., Shuto, N., & Imamura, F. (1997). Numerical method of tsunami simulation with the leap-frog schemes. *IOC Manuals and Guides*, *35*, 126. pp., UNESCO, Paris.

Green, G. (1838). On the motion of waves in a variable canal of small depth and width. *Transactions of the Cambridge Philosophical Society*, *6*, 457–462.

Guilbert, J., Vergoz, J., Schisselé, E., Roueff, A., & Cansi, Y. (2005). Use of hydroacoustic and seismic arrays to observe rupture propagation and source extent of the $M_w = 9.0$ Sumatra earthquake. *Geophysical Research Letters*, *32*(15), L15310, 5 pp.

Gusiakov, V. K., Dunbar, P., & Arcos, N. (2019). Twenty-five years (1992–2016) of global tsunamis: Statistical and analytical overview. *Pure and Applied Geophysics*. https://doi.org/10.1007/s00024-019-02113-7.

Hammack, J. L. (1973). A note on tsunamis: Their generation and propagation in an ocean of uniform depth. *Journal of Fluid Mechanics*, *60*, 769–799.

Hanson, J. A., & Bowman, J. R. (2005). Dispersive and reflected tsunami signals from the 2004 Indian Ocean tsunami observed on hydrophone and seismic stations. *Geophysical Research Letters*, *32*(17), L17606. 5 pp.

Harig, S., Androsov, A., & Rakowsky, N. (2019). Simulating landslide generated tsunamis in Palu Bay, Sulawesi, Indonesia. *Geophysical Research Abstracts*, *21*, EGU2019–7094 [abstract].

Hayes, G. P., Rivera, L., & Kanamori, H. (2009). Source inversion of the *W* phase: Real-time implementation and extension to low magnitudes. *Seismological Research Letters*, *80*, 817–822.

Hayes, G., Herman, M. W., Barnhart, W. D., Furlong, K. P., Riquelme, S., Benz, H. M., et al. (2014). Continuing megathrust earthquake potential in Chile after the 2014 Iquique earthquake. *Nature*, *512*, 295–298.

Heidarzadeh, M., & Satake, K. (2014). Possible sources of the tsunami observed in the northwestern Indian Ocean following the 2013 September 24 $M_w = 7.7$ Pakistan inland earthquake. *Geophysical Journal International*, *199*, 752–766.

Heidarzadeh, M., & Satake, K. (2017). Possible dual earthquake-landslide source of the 13 November 2016 Kaikoura, New Zealand tsunami. *Pure and Applied Geophysics*, *174*, 3737–3749.

Heidarzadeh, M., Murotani, S., Satake, K., Takagawa, T., & Saito, T. (2017). Fault size and depth extent of the Ecuador earthquake ($M_w = 7.8$) of 16 April 2016 from teleseismic and tsunami data. *Geophysical Research Letters*, *44*, 2211–2219.

Heidarzadeh, M., Muhari, A., & Wijanarto, A. B. (2019). Insights on the source of the 28 September 2018 Sulawesi tsunami, Indonesia based on spectral analyses and numerical simulations. *Pure and Applied Geophysics*, *176*, 25–43.

Heinrich, P., Schindelé, F., Guibourg, S., & Ihmlé, P. (1998). Modeling of the 1996 Peruvian tsunami. *Geophysical Research Letters*, *25*, 2687–2690.

Heinrich, P., Mangeney, A., Guibourg, S., Roche, R., Boudon, G., & Cheminée, J.-L. (1998). Simulation of water waves generated by a potential debris avalanche in Montserrat, Lesser Antilles. *Geophysical Research Letters*, *25*, 3697–3700.

Higman, H., Shugar, D. H., Stark, C. P., Ekström, G., Koppes, M. N., Lynett, P., et al. (2018). The 2015 landslide and tsunami in Taan Fiord, Alaska. *Science Reports*, *8*(1), 12993, 12 pp.

Hill, E. M., Borrero, J. C., Huang, Z., Qiu, Q., Banerjee, P., Natawidjaja, D. H., et al. (2012). The 2010 $M_w = 7.8$ Mentawai earthquake: Very shallow source of a rare tsunami earthquake determined from tsunami field survey and near-field GPS data. *Journal of Geophysical Research, Solid Earth*, *117*(6), B06402, 21 pp.

Hutt, C. R., Bolton, H. F., & Holcomb, L. G. (2002). U.S. contribution to digital global seismograph network. In W. H. K. Lee, H. Kanamori, P. Jennings, & C. Kisslinger (Eds.), *International Handbook of Earthquake and Engineering Seismology* (pp. 319–332). New York: Academic Press.

Ihmlé, P., Gomez, J.-M., Heinrich, P., & Guibourg, S. (1998). The 1996 Peru tsunamigenic earthquake: Broadband source process. *Geophysical Research Letters*, *25*, 2691–2694.

Imamura, F., Shuto, N., Ide, S., Yoshida, Y., & Abe, K. (1993). Estimate of the tsunami source of the 1992 Nicaraguan earthquake from tsunami data. *Geophysical Research Letters*, *20*, 1515–1518.

Imamura, F., Gica, E., Takahashi, T., & Shuto, N. (1995). Numerical simulations of the 1992 Flores tsunami: Interpretation of tsunami phenomena in Northeastern Flores and damage at Babi Island. *Pure and Applied Geophysics*, *144*, 555–568.

Imamura, F., Synolakis, C. E., Gica, E., Titov, V. V., Listanco, E., & Lee, H. J. (1995). Field survey of the 1994 Mindoro Island, Philippines tsunami. *Pure and Applied Geophysics*, *144*, 875–890.

Imamura, F., Subandono, D., Watson, G., Moore, A., Takahashi, T., Matsutomi, H., et al. (1997). Irian Jaya earthquake and tsunami cause serious damage. *Eos, Transactions of the American Geophysical Union*, *78*, 197 and 201.

Ishii, M., Shearer, P. M., Houston, H., & Vidale, J. E. (2005). Extent, duration and speed of the 2004 Sumatra-Andaman earthquake, imaged by the Hi-Net array. *Nature*, *435*, 933–936.

Kalligeris, N., Skanavis, V., Tavakkol, S., Ayça, A., El Safty, H., Lynett, P. J., et al. (2016). Lagrangian flow measurements and observations of the 2015 Chilean tsunami in Ventura, CA. *Geophysical Research Letters*, *43*, 5217–5224.

Kanamori, H. (1972). Mechanism of tsunami earthquakes. *Physics of the Earth and Planetary Interiors*, *6*, 346–359.

Kanamori, H. (1993). *W* phase. *Geophysical Research Letters*, *20*, 1691–1694.

Kanamori, H., & Cipar, J. J. (1974). Focal process of the great Chilean earthquake, May 22, 1960. *Physics of the Earth and Planetary Interiors*, *9*, 128–136.

Kanamori, H., & Rivera, L. (2008). Source inversion of *W* phase: Speeding up tsunami warning. *Geophysical Journal International*, *175*, 222–238.

Kanamori, H., Rivera, L., & Lamotte, S. (2019). Evidence for a large strike-slip component during the 1960 Chilean earthquake. *Geophysical Journal International*, *218*, 1–32.

Kawata, Y., Benson, B. C., Borrero, J. C., Borrero, J. L., Davies, H. L., de Lange, W. P., et al. (1999). Tsunami in Papua New Guinea was as intense as first thought. *Eos, Transactions of the American Geophysical Union*, *80*, 101–105.

Kerr, R. (2005). Model shows islands muted tsunami. *Science*, *308*, 341.

Kulikov, E. A., Rabinovich, A. B., Thomson, R. E., & Bornhold, B. D. (1996). The landslide tsunami of November 3, 1994, Skagway Harbor, Alaska. *Journal of Geophysical Research*, *101*, 6609–6615.

La Rocca, M., Galluzzo, D., Saccorotti, G., Tinti, S., Cimini, G. B., & Del Pezzo, E. (2004). Seismic signals associated with landslides and with a tsunami at Stromboli Volcano, Italy. *Bulletin of the Seismological Society of America*, *94*, 1850–1867.

Lay, T., Kanamori, H., Ammon, C. J., Hutko, A. R., Furlong, K., & Rivera, L. (2009). The 2006–2007 Kuril Islands great earthquake sequence. *Journal of Geophysical Research, Solid Earth*, *114*(B11), B11308, 31 pp.

Lay, T., Ammon, C. J., Kanamori, H., Rivera, L., Koper, K. D., & Hutko, A. R. (2010). The 2009 Samoa–Tonga great earthquake triggered doublet. *Nature*, *466*, 964–968.

Lay, T., Ammon, C. J., Kanamori, H., Xue, L., & Kim, M. J. (2011). Possible large near-trench slip during the 2011 $M_w = 9.0$ off the Pacific coast of Tohoku earthquake. *Earth, Planets and Space*, *63*, 687–692.

Lay, T., Ye, L., Kanamori, H., Yamazaki, Y., Cheug, K. F., Kwong, K., et al. (2013). The October 28, 2012 $M_w = 7.8$ Haida Gwaii underthrusting earthquake and tsunami: Slip partitioning along the Queen Charlotte Fault transpressional plate boundary. *Earth and Planetary Science Letters*, *375*, 57–70.

Lay, T., Ye, L., Bai, Y., Cheung, K. F., & Kanamori, H. (2018). The 2018 $M_w = 7.9$ Gulf of Alaska earthquake: Multiple fault rupture in the Pacific plate. *Geophysical Research Letters*, *45*, 9542–9551.

Legrand, D., Barrientos, S. E., Bataille, K., Cembrano, J., & Pavez, A. (2011). The fluid-driven tectonic swarm of Aysén Fjord, Chile (2007) associated with two earthquakes ($M_w = 6.1$ and $M_w = 6.2$) within the Liquiñe-Ofqui Fault Zone. *Continental Shelf Research*, *31*, 154–161.

Leonard, L. J., & Bednarski, J. M. (2014). Field survey following the 28 October 2012 Haida Gwaii tsunami. *Pure and Applied Geophysics*, *171*, 3467–3482.

Li, X., Shao, G., & Ji, C. (2009). Rupture process of the 2009 $M_w = 8.1$ Samoa earthquake constrained by joint inverting teleseismic body, surface waves and local strong motion. *Eos, Transactions of the American Geophysical Union*, *91*(53), U21D-03 [abstract].

Liu, J. Y., Tsai, Y. B., Chen, S. W., Lee, C. P., Chen, Y. C., Yen, H. Y., et al. (2006). Giant ionospheric disturbances excited by the $M = 9.3$ Sumatra earthquake of 26 December 2004. *Geophysical Research Letters*, *33*, L02103, 4 pp.

Liu, P. L.-F., Cho, Y.-S., Yoon, S. B., & Seo, S. N. (1994). Numerical simulations of the 1960 Chilean tsunami propagation and inundation at Hilo, Hawaii. In M. I. El-Sabh (Ed.), *Recent Developments in Tsunami Research* (pp. 99–115). Dordrecht: Kluwer.

Liu, P. L.-F., Cho, Y.-S., Briggs, M. J., Synolakis, C. E., & Kânoğlu, U. (1995). Run-up of solitary waves on a circular island. *Journal of Fluid Mechanics*, *302*, 259–285.

Lobkovsky, L. I., Rabinovich, A. B., Kulikov, E. A., Ivashchenko, A. I., Fine, I. V., Thomson, R. E., et al. (2009). The Kuril earthquakes and tsunamis of November 15, 2006 and January 13, 2007: Observations, analysis and numerical modeling. *Oceanology*, *49*, 166–181.

Lockwood, O. G., & Kanamori, H. (2006). Wavelet analysis of the seismograms of the 2004 Sumatra-Andaman earthquake and its application to tsunami early warning. *Geochemistry, Geophysics and Geosystems*, *7*(9), GC001272, 10 pp.

MacInnes, B. T. (2010). Bridging seismology and geomorphology: Investigations of the 2006 and 2007 Kuril Islands tsunamis, *Ph.D. Dissertation,* 188 pp., University of Washington, Seattle.

MacInnes, B. T., Pinegina, T. K., Bourgeois, J., Razhigaeva, N. G., & Kaistrenko, V. M. (2009). Field survey and geological effects of the 15 November 2006 Kuril tsunami in the Middle Kuril Islands. *Pure and Applied Geophysics*, *166*, 9–36.

Manoj, C., Maus, S., & Chulliat, A. (2011). Observation of magnetic fields generated by tsunamis. *Eos, Transactions of the American Geophysical Union*, *92*, 13–14.

Marris, E. (2005). Inadequate warning system left Asia at the mercy of tsunami. *Nature*, *433*, 3–5.

Martin, S. S., Li, L., Okal, E. A., Morin, J., Tetteroo, A., Switzer, A., et al. (2019). Reassessment of the 1907 Sumatra "tsunami earthquake" based on macroseismic, seismological, and tsunami observations, and modeling. *Pure and Applied Geophysics*. https://doi.org/10.1007/s00024-019-02134-2.

Matsutomi, H., & Iizuka, H. (1998). Tsunami current velocity on land and its simple estimation method. *Proceedings of Coastal Engineering, Japan Society of Coastal Engineers*, *45*, 361–365. [in Japanese].

Matsutomi, H., Shuto, N., Imamura, F., & Takahashi, T. (2001). Field survey of the 1996 Irian Jaya earthquake tsunami in Biak Island. *Natural Hazards*, *24*, 199–212.

McAdoo, B. G., Dengler, L., Prasetya, G., & Titov, V. V. (2006). Smong: How an oral history saved thousands on Indonesia’s Simeulue Island during the December 2004 and March 2005 tsunamis. *Earthquake Spectra*, *22*, S661–S669.

McCaffrey, R. (2007). The next great earthquake. *Science*, *315*, 1675–1676.

McCloskey, J., Nalbant, S. S., & Steacy, S. (2005). Earthquake risk from co-seismic stress. *Nature*, *434*, 291.

McNamara, D. E., Ringler, A. T., Hutt, C. R., & Gee, L. S. (2011). Seismically observed seiching in the Panama Canal. *Journal of Geophysical Research*, *116*(B4), B04312, 12 pp.

Meining, C., Stalin, S. E., Nakamura, A. I., González, F. I., & Milburn, H. B. (2005). Technology developments in real-time tsunami measuring, monitoring and forecasting. *Proceedings of OCEANS 2005, MTS/IEEE*, *93*, 1673–1679.

Miller, D. J. (1960). The Alaska earthquake of July 10, 1958: Giant wave in Lituya Bay. *Bulletin of the Seismological Society of America*, *50*, 253–266.

Nalbant, S., Steacy, S., Sieh, K., Natawidjaja, D., & McCloskey, J. (2005). Updated earthquake hazard in Sumatra. *Nature*, *435*, 756–757.

Nettles, M., Ekström, G., Dziewoński, A. M., & Maternovskaya, N. (2005). Source characteristics of the great Sumatra earthquake and its aftershocks. *Eos, Transactions of the American Geophysical Union*, *86*(18), U43A−01 [abstract].

Newman, A. V., & Okal, E. A. (1998). Teleseismic estimates of radiated seismic energy: The E/M_0 discriminant for tsunami earthquakes. *Journal of Geophysical Research*, *103*, 26885–26898.

Newman, A. V., Feng, L., Fritz, H. M., Lifton, Z. M., Kalligeris, N., & Wei, Y. (2011). The energetic 2010 $M_w = 7.1$ Solomon Islands tsunami earthquake. *Geophysical Journal International*, *186*, 775–781.

Newman, A. V., Hayes, G., Wei, Y., & Convers, J. (2011). The 25 October 2010 Mentawai tsunami earthquake, from real-time discriminants, finite-fault rupture, and tsunami excitation. *Geophysical Research Letters*, *38*(5), L05302, 10 pp.

Ni, S., Kanamori, H., & Helmberger, D. V. (2005). Energy radiation from the Sumatra earthquake. *Nature*, *434*, 582.

Nöggerath, J., Geller, R. J., & Gusiakov, V. K. (2011). Fukushima: The myth of safety, reality of geoscience. *Bulletin of Atomic Scientists*, *67*(6), 36–37.

Occhipinti, G., Lognonné, P., Kherani, A. A., & Hébert, H. (2006). Three-dimensional waveform modeling of ionospheric signature induced by the 2004 Sumatra tsunami. *Geophysical Research Letters*, *33*, L20104.

Okal, E. A. (1993). WM_m: An extension of the concept of mantle magnitude to the *W* phase, with application to real-time assessment of the ultra-long component of the seismic source. *Eos, Transactions of the American Geophysical Union*, *74*(33), 344 [abstract].

Okal, E. A. (2003). *T* waves from the 1998 Papua New Guinea earthquake and its aftershocks: Timing the tsunamigenic slump. *Pure and Applied Geophysics*, *160*, 1843–1863.

Okal, E. A. (2007). Seismic records of the 2004 Sumatra and other tsunamis: A quantitative study. *Pure and Applied Geophysics*, *164*, 325–353.

Okal, E. A. (2013). From 3-Hz *P* waves to ${}_0S_2$: No evidence of a slow component to the source of the 2011 Tohoku earthquake. *Pure and Applied Geophysics*, *170*, 963–973.

Okal, E. A. (2017). The excitation of tsunamis by deep earthquakes. *Geophysical Journal International*, *209*, 234–249.

Okal, E. A., & Borrero, J. C. (2011). The “tsunami earthquake” of 22 June 1932 in Manzanillo, Mexico: Seismological study and tsunami simulations. *Geophysical Journal International*, *187*, 1443–1459.

Okal, E. A., & MacAyeal, D. R. (2006). Seismic recording on drifting icebergs: Catching seismic waves, tsunamis and storms from Sumatra and elsewhere. *Seismological Research Letters*, *77*, 659–671.

Okal, E. A., & Newman, A. V. (2001). Tsunami earthquakes: The quest for a regional signal. *Physics of the Earth and Planetary Interiors*, *124*, 45–70.

Okal, E. A., & Saloor, N. (2017). Historical tsunami earthquakes in the Southwest Pacific: An extension to $\Delta > 80^\circ$ of the Energy-to-Moment parameter Θ. *Geophysical Journal International*, *210*, 852–873.

Okal, E. A., Piatanesi, A., & Heinrich, P. (1999). Tsunami detection by satellite altimetry. *Journal of Geophysical Research*, *104*, 599–615.

Okal, E. A., Fryer, G. J., Borrero, J. C., & Ruscher, C. (2002). The landslide and local tsunami of 13 September 1999 on Fatu-Hiva (Marquesas Islands; French Polynesia). *Bulletin de la Société Géologique de France*, *173*, 359–367.

Okal, E. A., Dengler, L., Araya, S., Borrero, J. C., Gomer, B., Koshimura, S., et al. (2002). A field survey of the Camaná, Peru tsunami of June 23, 2001. *Seismological Research Letters*, *73*, 904–917.

Okal, E. A., Fritz, H. M., Raveloson, R., Joelson, G., Pančošková, P., & Rambolamanana, G. (2006a). Madagascar field survey after the December 2004 Indian Ocean tsunami. *Earthquake Spectra*, *22*, S263–S283.

Okal, E. A., Sladen, A., & Okal, E. A.-S. (2006b). Rodrigues, Mauritius and Réunion Islands field survey after the December 2004 Indian Ocean tsunami. *Earthquake Spectra*, *22*, S241–S261.

Okal, E. A., Fritz, H. M., Raad, P. E., Synolakis, C. E., Al-Shijbi, Y., & Al-Saifi, M. (2006c). Oman field survey after the December 2004 Indian Ocean tsunami. *Earthquake Spectra*, *22*, S203–S218.

Okal, E. A., Borrero, J. C., & Synolakis, C. E. (2006d). Evaluation of tsunami risk from regional earthquakes at Pisco, Peru. *Bulletin of the Seismological Society of America*, *96*, 1634–1648.

Okal, E. A., Talandier, J., & Reymond, D. (2007). Quantification of hydrophone records of the 2004 Sumatra tsunami. *Pure and Applied Geophysics*, *164*, 309–323.

Okal, E. A., Fritz, F. M., & Sladen, A. (2009). 2004 Sumatra tsunami surveys in the Comoro Islands and Tanzania, and regional tsunami hazard from future Sumatra events. *South African Journal of Geology*, *112*, 343–358.

Okal, E. A., Fritz, H. M., Synolakis, C. E., Borrero, J. C., Weiss, R., Lynett, P. J., et al. (2010). Field survey of the Samoa tsunami of 29 September 2009. *Seismological Research Letters*, *81*, 577–591.

Okal, E. A., Kirby, S. H., & Kalligeris, N. (2016). The Showa Sanriku earthquake of 1933 March 2: A global seismological reassessment. *Geophysical Journal International*, *206*, 1492–1514.

Okal, E. A., Hyvernaud, O., Paris, A., Hébert, H., & Heinrich, P. (2019). Ancillary records of the Krakatau eruption and tsunami of 22 December 2018. *Geophysical Research Abstracts*, *21*, EGU2019–11563 [abstract].

Paris, A., Okal, E. A., Guérin, C., Heinrich, P., Schindelé, F., & Hébert, H. (2019). Numerical modeling of the June 17, 2017 landslide and tsunami events in Karrat Fjord, West Greenland. *Pure and Applied Geophysics*. https://doi.org/10.1007/s00024-019-02123-.

Pelinovsky, E., Zahibo, N., Dunkley, P., Edmonds, M., Herd, R., Talipova, T., et al. (2004). Tsunami generated by the volcano eruption on July 12–13, 2003 at Montserrat, Lesser Antilles. *Science of Tsunami Hazards*, *22*, 44–57.

Pelletier, B., Régnier, M., Calmant, S., Pillet, R., Cabioch, G., Lagabrielle, Y., et al. (2000). Le séisme d'Ambryn-Pentecôte du 26 novembre 1999 ($M_w = 7,5$): données préliminaires sur la séismicité, le tsunami et les déplacements associés. *Comptes-Rendus de l'Académie des Sciences (Paris), Série 2*, *331*, 21–28.

Peltier, W. R., & Hines, C. O. (1976). On the possible detection of tsunamis by a monitoring of the ionosphere. *Journal of Geophysical Research*, *81*, 1995–2000.

Plafker, G. L. (1997). Catastrophic tsunami generated by submarine slides and backarc thrusting during the 1992 earthquake on Eastern Flores I., Indonesia. *Geological Society of America, Abstracts with Program*, *29*(5), 57 [abstract].

Pollitz, F., Banerjee, P., Bürgmann, R., Hashimoto, M., & Choosakul, N. (2006). Stress changes along the Sunda trench following the 26 December 2004 Sumatra-Andaman and 28 March 2005 Nias earthquakes. *Geophysical Research Letters*, *33*(6), L06309, 4 pp.

Power, W., Clark, K., King, D. N., Borrero, J., Howarth, J., Lane, E. M., et al. (2017). Tsunami runup and tide-gauge observations from the 14 November 2016 $M = 7.8$ Kaikōura earthquake, New Zealand. *Pure and Applied Geophysics*, *174*, 2457–2473.

Prasetya, G., Husrin, S., Kongko, W., Istyanto, D., Hidayat, R., Asvaliantina, V., et al. (2019). The 22nd December 2018 Anak Krakatau Tsunami in Sunda Straits, Indonesia. *Geophysical Research Abstracts*, *21*, EGU2019–12276 [abstract].

Press, F., & Harkrider, D. G. (1966). Air-Sea waves from the explosion of Krakatoa. *Science*, *154*, 1325–1327.

Rabinovich, A. B. (2019). Twenty-seven years of progress in the science of meteorological tsunamis following the 1992 Daytona Beach event. *Pure and Applied Geophysics*, submitted.

Rabinovich, A. B., & Thomson, R. E. (2007). The 26 December 2004 Sumatra tsunami: Analysis of tide gauge data from the world ocean, Part I. Indian Ocean and South Africa. *Pure and Applied Geophysics*, *164*, 261–308.

Rabinovich, A. B., Lobkovsky, L. I., Fine, I. V., Thomson, R. E., Ivelskaya, T. N., & Kulikov, E. A. (2008). Near-source observations and modeling of the Kuril Islands tsunamis of 15 November 2006 and 13 January 2007. *Advances in Geosciences*, *14*, 105–116.

Ruff, L. J. (1989). Do trench sediments affect great earthquake occurrence in subduction zones? *Pure and Applied Geophysics*, *129*, 263–282.

Ruff, L. J., & Kanamori, H. (1980). Seismicity and the subduction process. *Physics of the Earth and Planetary Interiors*, *23*, 240–252.

Satake, K., Shimazaki, K., Tsuji, Y., & Ueda, K. (1996). Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700. *Nature*, *379*, 246–249.

Shuto, N., & Matsutomi, H. (1995). Field survey of the 1993 Hokkaido-Nansei-Oki earthquake tsunami. *Pure and Applied Geophysics*, *144*, 406–449.

Smith, W. H. F., Scharroo, R., Titov, V. V., Arcas, D., & Arbic, B. K. (2005). Satellite altimeters measure tsunami. *Oceanography*, *18*, 11–13.

Solov'ev, S. L., & Go, C. N. (1984). Catalogue of tsunamis on the Eastern shore of the Pacific Ocean. *Canadian Translations. Fisheries and Aquatic Sciences*, *5078*, 293. pp.

Stein, R. S., Barka, A. A., & Dieterich, J. H. (1997). Progressive failure on the North Anatolian fault since 1939 by earthquake stress triggering. *Geophysical Journal International*, *128*, 594–604.

Stein, S., & Okal, E. A. (2005). Size and speed of the Sumatra earthquake. *Nature*, *434*, 581–582.

Stein, S., & Okal, E. A. (2007). Ultra-long period seismic study of the December 2004 Indian Ocean earthquake and implications for regional tectonics and the subduction process. *Bulletin of the Seismological Society of America*, *97*, S279–S295.

Sweet, S., & Silver, E. A. (2003). Tectonics and slumping in the source region of the 1998 Papua New Guinea tsunami from seismic reflection images. *Pure and Applied Geophysics*, *160*, 1945–1968.

Synolakis, C. E., & Kânoğlu, U. (2015). The Fukushima accident was preventable. *Philosophical Transactions of the Royal Society (London)*, *373A*, 20140374. 23 pp.

Synolakis, C. E., & Okal, E. A. (2005). 1992–2002: Perspective on a decade of post-tsunami surveys. Advances in Natural and Technological Hazards. In K. Satake (Ed.), *Tsunamis: Case studies and recent developments* (Vol. 23, pp. 1–30). Berlin: Springer.

Synolakis, C. E., Imamura, F., Tsuji, Y., Matsutomi, H., Tinti, S., Cook, B., et al. (1995). Damage, conditions of East Java tsunami analyzed, Eos. *Transactions of the American Geophysical Union*, *76*(26), 257–264.

Synolakis, C. E., Yalçıner, A. C., Borrero, J. C., & Plafker, G. L. (2002). Modeling of the November 3, 1994 Skagway, Alaska tsunami. Solutions to Coastal Disasters. In L. Wallendorf & L. Ewing (Eds.), *Proceedings of the American Society of Civil Engineers* (Vol. 78, pp. 915–927).

Synolakis, C. E., Bardet, J.-P., Borrero, J. C., Davies, H. L., Okal, E. A., Silver, E. A., et al. (2002). The slump origin of the 1998 Papua New Guinea tsunami. *Proceedings of the Royal Society (London), Series A*, *458*, 763–789.

Tadepalli, S., & Synolakis, C. E. (1994). The run-up of N-waves. *Proceedings of the Royal Society (London), Series A*, *445*, 99–112.

Tadepalli, S., & Synolakis, C. E. (1996). Model for the leading waves of tsunamis. *Physical Review Letters*, *77*, 2141–2145.

Tanioka, Y., & Satake, K. (1996). Tsunami generation by horizontal displacement of ocean bottom. *Geophysical Research Letters*, *23*, 861–864.

Taylor, F. W., Briggs, R. W., Frohlich, C., Brown, A., Hornback, M., Papabatu, A. K., et al. (2008). Rupture across arc segment and plate boundaries in the 1 April 2007 Solomons earthquake. *Nature Geoscience*, *1*, 253–257.

Thomson, R. E., Rabinovich, A. B., Kulikov, E. A., Fine, I. V., & Bornhold, B. D. (2001). On numerical simulation of the landslide-generated tsunami of November 3, 1994 in Skagway Harbor, Alaska. In G. Hebenstreit (Ed.), *Tsunami research at the* *end of a critical decade* (pp. 243–282). Dordrecht: Kluwer Academic Publishers.

Tinti, S., & Vannini, C. (1995). Tsunami trapping near circular islands. *Pure and Applied Geophysics*, *144*, 595–620.

Tinti, S., Manucci, A., Pagnoni, G., Armigliato, A., & Zaniboni, F. (2005). The 30 December 2002 landslide-induced tsunamis in Stromboli: Sequence of the events reconstructed from the eyewitness accounts. *Natural Hazards Earth Systems Science*, *5*, 763–775.

Tinti, S., Armigliato, A., Manucci, A., Pagnoni, G., Zaniboni, F., Yalçıner, A. C., et al. (2006). The generating mechanisms of the August 17, 1999 İzmit Bay (Turkey) tsunami: Regional (tectonic) and local (mass instabilities) causes. *Marine Geology*, *225*, 311–330.

Titov, V. V., & Synolakis, C. E. (1993). A numerical study of wave run-up of the September 2, 1992 Nicaraguan tsunami. In Y. Tsuchiya & N. Shuto (Eds.), *Proceedings of the Tsunami Symposium, International Union of Geology and Geophysics Japan Society of Civil Engineers,* (pp. 627–635). Wakayama, Japan.

Titov, V. V., & Synolakis, C. E. (1997). Extreme inundation flow during the Hokkaido-Nansei-Oki tsunami. *Geophysical Research Letters*, *24*, 1315–1318.

Titov, V. V., & Synolakis, C. E. (1998). Numerical modeling of tidal wave runup. *Journal of Waterway, Port, Coastal and Ocean Engineering*, *124*, 157–171.

Titov, V. V., González, F. I., Bernard, E. N., Eble, M. C., Mofjeld, H. O., Newman, J. C., et al. (2005). Real-time tsunami forecasting: Challenges and solutions. *Natural Hazards*, *35*, 41–58.

Titov, V. V., Rabinovich, A. B., Mofjeld, H., Thomson, R. E., & González, F. I. (2005). The global reach of the 26 December 2004 Sumatra tsunami. *Science*, *309*, 2045–2048.

Titov, V. V., Kânoğlu, U., & Synolakis, C. E. (2016). Development of MOST for real-time tsunami forecasting. *Journal of Waterway, Port, Coastal and Ocean Engineering*, *142*, 03116004, 16.

Tsuji, Y., Matsutomi, H., Imamura, F., Takeo, M., Kawata, Y., Matsuyama, M., et al. (1995). Damage to coastal villages due to the 1992 Flores Island earthquake tsunami. *Pure and Applied Geophysics*, *144*, 481–524.

Tyler, R. H. (2005). A simple formula for estimating the magnetic fields generated by tsunami flow. *Geophysical Research Letters*, *32*(9), L09608, 4 pp.

Wallace, R. E., Pararas-Carayannis, G., Valenzuela, R., & Taggart, J. N. (1977). Earthquake and tsunamis of August 16, 1976, Mindanao, Philippines. *Geological Society of America Abstracts with Program*, *9*, 523 [abstract].

Ward, S. N. (1980). Relationships of tsunami generation and an earthquake source. *Journal of Physics of the Earth*, *28*, 441–474.

Wang, J., Ward, S. N., & Xiao, L. (2015). Numerical simulation of the December 4, 2007 landslide-generated tsunami in Chebalis Lake, Canada. *Geophysical Journal International*, *201*, 372–376.

Wessel, P., & Smith, W. H. F. (1991). Free software helps map and display data. *Eos, Transactions of the American Geophysical Union*, *72*, 441–446.

Whitmore, P., Benz, H., Bolton, M., Crawford, G., Dengler, L., Fryer, G., et al. (2008). NOAA/West Coast and Alaska Tsunami Warning Center Pacific Ocean response criteria. *Science of Tsunami Hazards*, *27*(2), 1–21.

Ye, L., Kanamori, H., Avouac, J.-P., Li, L., Cheung, K. F., & Lay, T. (2016). The 16 April 2016, $M_w = 7.8$ ($M_s = 7.5$) Ecuador earthquake: A quasi-repeat of the 1942 $M_s = 7.5$ earthquake and partial re-rupture of the 1906 $M_s = 8.6$ Colombia–Ecuador earthquake. *Earth and Planetary Science Letters*, *454*, 248–258.

Yeh, H., Imamura, F., Synolakis, C. E., Tsuji, Y., Liu, P. L.-F., & Shi, S. (1993). The Flores Island tsunami. *Eos, Transactions of the American Geophysical Union*, *74*, 369–373.

Yeh, H., Liu, P. L.-F., Briggs, M., & Synolakis, C. E. (1994). Propagation and amplification of tsunamis at coastal boundaries. *Nature*, *372*, 353–355.

Yeh, H., Titov, V. V., Gusiakov, V., Pelinovsky, E., Khramushin, V., & Kaistrenko, V. (1995). The 1994 Shikotan tsunamis. *Pure and Applied Geophysics*, *144*, 855–874.

Yuan, X., Kind, R., & Pedersen, H. (2005). Seismic monitoring of the Indian Ocean tsunami. *Geophysical Research Letters*, *32*(15), L15308, 4 pp.

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