Tsunamis

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Tsunamis

Case Studies and Recent Developments

Edited by

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PART II. RECENT DEVELOPMENTS

PREFACE

This book contains 20 papers reflecting the state-of-the-art tsunami research. Most of them were presented at the two international meetings held in 2003: the 21st International Tsunami Symposium, held on July 9 and 10th as a part of IUGG general assembly in Sapporo, Japan, and an International Workshop on Tsunamis in the South Pacific, held on September 25 and 26th in Wellington, New Zealand. More recent work, including the field survey report of the Tokachi-oki earthquake tsunami of September 26, 2003, is also included.

Synolakis and Okal summarize the survey results of International Tsunami Survey Teams, as well as seismological and numerical modelling studies of 15 tsunami events occurred between 1992 and 2002. In this active decade of tsunami disasters, the tsunami community has learned how to organize ITST, describe, document and share the results of surveys. The authors also propose a method to discriminate the seismic tsunamis from landslide tsunamis based on the observed runup heights, and demonstrate it for the recent tsunamis. *Power et al.* report the tsunamis generated by the 2003 Fiordland, New Zealand, earthquake (M 7.2). This earthquake generated two kinds of tsunamis; a local large (4-5 m) tsunami generated by rockslide in a sound, and a smaller tsunami generated by earthquake faulting and detected on tide gauges in Australia.

Three papers discuss volcanic tsunamis in the western Pacific region. *Nishimura et al.* report the tsunami from the 1994 eruption of Rabaul volcanoes. They use a geological method to this modern tsunami deposits and infer the timing and size of tsunamis generated several times in the eruption series. *Pelinovsky et al.* present 35 tide gauge records from the 1883 Krakatau eruption, one of the largest tsunamis instrumentally-recorded all over the world. While the tsunamis in Indian Ocean and Atlantic appear as predicted from ray tracing computations on modern bathymetry, those in Australia, New Zealand and North America do not, indicating that they are not hydrodynamic tsunamis. *Kawamata et al.* report the hydraulic experiments of landslide to estimate the parameters for numerical simulation of two-layer models. They model the 1741 tsunami from landslide of the Oshima-Oshima volcano in Japan Sea to show that the landslide source yields better fit with the observation than an earthquake fault model.

Five papers examine tsunami sources, propagation and coastal behaviour of tsunamis around Japan and Kuril Islands. *Abe* reports seiche periods at 36 bays on Sanriku coast of Japan and compare them with the tsunami amplification factors of each bay from past tsunamis, the 1896 and 1933 Sanriku, 1968 Tokachi-oki and 1960 Chilean tsunamis. He shows that the amplification factors are the largest near the dominant period of incoming tsunamis. *Namegaya and Tsuji* discuss the delayed phase, which appear about 2.6 hours after the first tsunami arrival, of tide gauge records at Miyako from earthquakes off eastern Hokkaido. By making numerical computations for actual and fictitious bathymetry, they conclude that the delayed peak is caused by combination of reflected and edge waves. *Tanioka et al.* summarize the tsunami survey results of the recent 2003 Tokachi-oki earthquake. More than 200 runup height measurements, photographs of actual tsunamis and the descriptions of deposits are presented, as well as a result of numerical simulation at Ootsu harbor where very dense measurements were made. *Satake et al.* review the earthquakes and tsunamis along the Kuril trench from 17th century through the 2003 tsunami. The coastal runup distribution, inversion of tsunami waveforms and tsunami deposits indicate that the tsunami sources along the Kuril trench are variable. *Iliev et al.* report 17 layers of tsunami deposits in the

Holocene. They study the grain size of deposits and diatoms included in the deposits to identify the tsunami origin, use ^{14}C and volcanic ash for dating the tsunamis, and further correlate the tsunamis with those from other Kuril Island and eastern Hokkaido.

Three papers discuss tsunamis on the North and South American coasts, as well as Iberian coasts. *Hatori* compiles tsunami heights along the Aleutian-Alaska coasts, calculates mean tsunami heights squared in each 200-km long segment, and estimates the cumulative tsunami energy since 1788. *Arreaga-Vargas et al.* report the tsunami inundation map for Esmeraldas, Ecuador, based on the inundation modelling from large earthquakes along the Ecuador-Columbia subduction zone. *Mendes-Victor et al.* summarize the European multi-disciplinary and multi-national projects to study the tsunami source of the 1755 Lisbon earthquake. The projects include multi-channel seismic surveys, numerical modelling and paleotsunami studies to examine the tsunami source.

Two papers discuss the waveform analysis of tide gauge records for tsunami forecast and source estimation. *Lee et al.* propose a method to quickly forecast tsunami heights on the Korean coast, based on pre-computed coastal tsunami heights stored on database. Once the source parameters of an earthquake in Japan Sea are estimated, the tsunami heights can be computed based on the superposition principle. *Pires and Miranda* introduce an adjoint method to the inversion of tsunami waveforms. Unlike conventional Green's function approach, this method allows direct estimation of fault parameters from tide gauge records. They demonstrate the method in an idealized sloping beach using the computed waveforms as the observed data.

Three papers are on physical and numerical experiments on submarine landslide and coastal forests. *Fleming et al.* report the design and preliminary results of their tank experiments to study submarine landslides. They use both solid block and granular materials as landslide analogues and adopt various measurement techniques to measure physical quantities. *Harada and Imamura* discuss the effects of coastal forest on tsunami hazard. In addition to the literature surveys to itemize the control factors, they report the results of numerical simulation for various forest width, density, tsunami heights and period, to quantitatively examine the effect of coastal forests. *Imai and Matsutomi* describe their flume experiment to evaluate the fluid forces of tsunami acting on coastal vegetation. They show the temporal variation of drag force, inertia force and wave-making resistance force, as well as estimation of drag and mass coefficients.

The last two papers propose the use non-traditional methods for future tsunami warning systems. *Sasorova et al.* discuss hydro-acoustic signal possibly generated from "dilatant zone" before an earthquake and propose to use such a signal for location of submarine earthquakes and tsunami warning. *Novik et al.* propose to use electromagnetic signals generated by earthquakes for tsunami monitoring and warning. They recommend magnetic recording on the sea surface and atmosphere as well as ocean bottom measurements of seismic, magnetic and temperature.

All the papers were peer-reviewed by at least two colleagues. The editor acknowledges the authors and reviewers to their time and efforts to make this possible.

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November 2004

1992–2002: PERSPECTIVE ON A DECADE OF POST-TSUNAMI SURVEYS

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We present a discussion of the field surveys conducted in the wake of fifteen locally devastating tsunamis in the period 1992-2002. The goal of these surveys has been to gather homogeneous databases of run-up and inundation, for the purpose of documenting precisely the penetration of the waves along the affected beaches. In turn, these can be used as datasets to be matched by numerical simulations of the generation of the tsunamis, their propagation and interaction with the beaches. These surveys have provided new insight into some complex phenomena, such as the existence of a leading depression in an $N-$wave, the importance of beach topography on the local enhancement of run-up, the contribution of underwater landslides to tsunami hazard, and the value of an educated population in terms of the mitigation of human losses. We review a simple and robust algorithm allowing the discrimination between tsunamis generated by dislocations and landslides, based on the aspect ratio of the distribution of run-up on a nearby beach, and the comparison of maximum run-up to the seismic slip involved in the parent earthquake. Some of the techniques developed in these recent post-tsunami surveys can be extended to events dating back a few decades through the interview of elderly witnesses and the surveying of remanent watermarks. When applied to the case of the 1946 Aleutian tsunami, the resulting data require both a large dislocative source to explain the far-field tsunami, and a coeval underwater landslide to account for the near-field run-up values which reached 42 meters at the site of the Scotch Cap lighthouse.

1. Introduction

Over the past twelve years, a number of substantial tsunamis have resulted in significant damage to coastal areas, in the wake of large but not gigantic earthquakes. They have resulted in more than 3000 fatalities, of which 2100 took place during the catastrophic 1998 Aitape tsunami in Papua New Guinea. For the purpose of adequate mitigation of future tsunamis, it is important to understand which factors control most crucially the final characteristics of the flooding, namely run-up and inundation. In turn, their successful modeling requires a reliable database of inundation parameters, against which models can be tested through numerical simulation of the generation of the tsunami, its propagation to the local shores, and its final interaction with the relevant beaches.

K. Satake (ed.), Tsunamis: Case Studies and Recent Developments, 1-29.

In this framework, the past decade has seen the development of systematic post-tsunami field surveys by international teams of scientists, generally within a few weeks of the disaster. Although isolated surveys had occasionally taken place following more ancient events [*e.g., Abe et al.,* 1986], the latter had usually concentrated principally on macroseismic effects. Rather, and starting with the 1992 Nicaragua earthquake, specific tsunami surveys have been carried out systematically for a total of fifteen events (Figure 1).

This paper presents a review of each of those surveys, and highlights the most important results obtained in their course, and in particular their influence on the understanding by the tsunami community of the factors affecting the destructive and occasionally lethal power of the waves as they attack the coastal communities. We also discuss a simple algorithm allowing to quantify the distribution of run-up values, as well as our experience in extending the concept of post-tsunami field surveys to historical events.

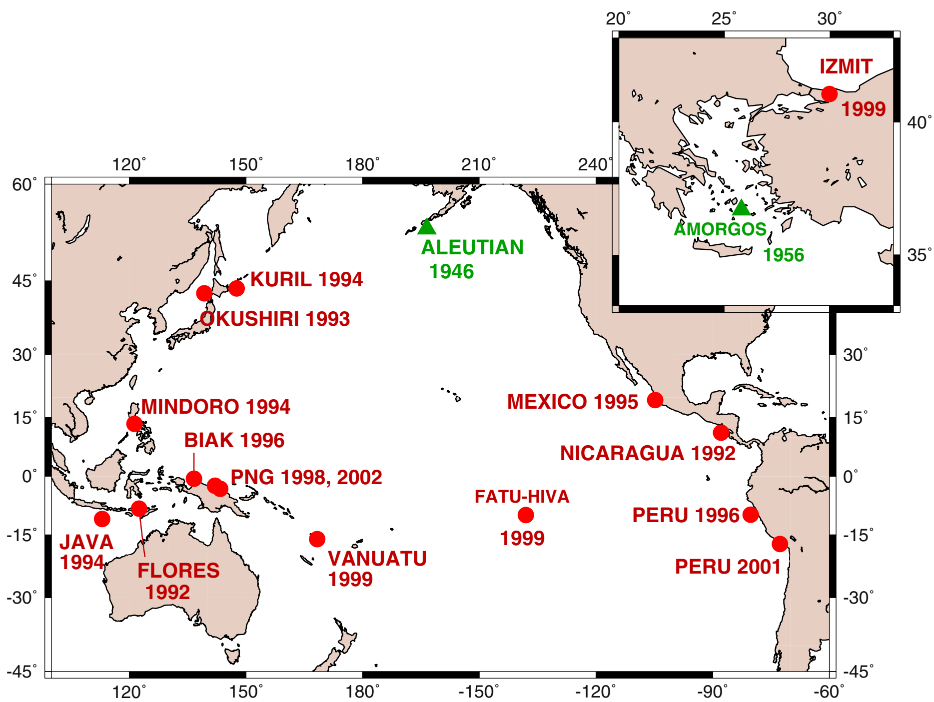


Fig. 1. Map of the Pacific Ocean showing the locations of the tsunami surveys conducted in the past 12 years. The triangles show the source locations for the surveys of historical tsunamis. Note that the 1946 Aleutian survey was taken both in the near and far fields. The inset shows the Aegean Sea, site of the 1999 Izmit and 1956 historical Amorgos surveys.

2. Goals and Methods

The objective of a tsunami field survey is to identify quantitatively the inundation pattern and determine the run-up height distribution along the stricken coastline. Such datasets help better predict what the inundation might be in nearby areas should the same seismic zone rupture at a comparable location in the future, possibly involving an earthquake of a different size. In particular, and through hydrodynamic inversion, the results may help determine if this is the worst-possible event expected in the relevant area and whether the possibility for a transoceanic tsunami exists in a future rupture. Detailed survey results and comparisons with model predictions may also help explain why an event may appear initially anomalous, in the sense that the tsunami damage reported may be incommensurate with the size of the parent earthquake. This type of understanding can lead to the production of inundation maps, similar to those in Hawaii, Japan, and currently in the final stages of completion for parts of California, Oregon, Washington and Alaska. In turn, such maps can help local authorities plan the location of schools, hospitals, fire stations and other critical facilities.

While the scientific rationale behind tsunami surveys is evident, International Tsunami Survey Teams must strike a delicate balance between the necessity to act promptly in order to recover field evidence of an often ephemeral nature, and the obvious priority to be given to search-and-rescue operations in the immediate aftermath of a disaster involving large scale loss of life, shelter, and essential life-sustaining supplies. In this context, we note that most tsunami watermarks are short-lived and may be lost after a single large storm. Similarly, the disposal of debris involving earth-moving equipment may destroy vegetation holding clues to the direction and intensity of tsunami currents. Eyewitnesses usually move to safer areas or are relocated, and sometimes may not welcome being tracked down months later to discuss what may well have been the most painful experience of their lives. In addition, and quite frequently, once an official version of an event circulates, all eyewitnesses report identical information, as it is in human nature for people to trust what they hear or read from the press more than what they see with their own eyes.

In this context, it has been the experience of the international teams that surveys can be successfully conducted within a two- to three-week period from the event, which in general provides a sufficient time window to see the conclusion of search-and-rescue efforts. We wish to emphasize the inobstrusive character of the work of the field survey teams; ITST members have always met the enthusiastic support of the local "lay" people, who have been receptive to the eventual benefits to their communities of the team's work, and usually ask many interesting and difficult questions that further guide in a substantial fashion the team's work.

The essential elements of the database recovered during post-tsunami surveys consist of measurements of *run-up* and *inundation*. We define the former as the maximum vertical elevation of a point located on initially dry land and inundated by the waves, and the latter as the maximum horizontal penetration of the waves in the direction normal to the beach during the flooding (Figure 2). The identification of a data point characterizing water penetration can be made either on the basis of the recognition of a watermark, such as a line of debris deposited by the wave either on land or in vegetation, or through the personal report of an eyewitness to the phenomenon. On occasion, it may be possible to determine neither run-up nor inundation, but only to infer the local flow depth, usually from watermarks on the sides of walls or from debris left dangling on trees or posts.

Once a data point has been identified and its coordinates recorded with GPS technology, run-up is measured using topographic techniques, either by running a traditional leveling transect to the nearby beach, or through three-dimensional laser surveying. In cases of extreme penetration where running a full transect is impractical (*e.g.,* over more than 1 km), run-up can be measured from differential barometric readings taken

Fig. 2.: Photographs illustrating the definition and measurement of vertical flow depth (top left; 1992 Nicaragua tsunami), run-up (top right; 1995 Mexican tsunami), and inundation (bottom; 2001 Peru tsunami).

at the point of maximum penetration and at the shoreline, within a few minutes of each other to minimize the potential for atmospheric perturbation [*e.g., Okal et al.,* 2003*a*]. In all cases, a record is kept of the precise time of the measurements, in order to later effect the tidal corrections necessary to refer measurements to the same still waterline datum at the time of the event.

Post-tsunami surveys also include the geotechnical documentation of dynamic flow over inundated areas, for example the quantification of the amount and direction of sedimentation or erosion, as well as of the granular nature of deposits. Such data can be used to reconstruct quantitatively the currents involved in the inundation [*e.g., Gelfenbaum and Jaffe,* 2003].

An additional element of post-tsunami surveys is the conduct of interviews of eyewitnesses. We seek to record the experience of survivors, both from the standpoint of documenting the physical properties of the waves making up the tsunami (through parameters such as their number and intervals in time, and the occurrence of down-draws leaving no watermarks), and also regarding the human response to the phenomenon, *e.g.,* the recognition by the population of its nature, and the behavior of the individuals with respect to evacuation before or upon arrival of the waves. Such information can be used to identify the most important factors mitigating tsunami hazard [*e.g., Dengler and Preuss,* 2003].

In addition to photographic documentation of the damage inflicted by the tsunami, and whenever possible, a full video recording of the interview of witnesses is taken and permanently archived, after obtaining informed consent on their part.

Another aspect of the work of International Tsunami Survey Teams is their outreach to local communities. By working closely with community leaders and local teachers, we seek to hold meetings in town and church halls, schools, hospitals, etc., in which we make presentations to the local populations. In a more casual fashion, we never cease to talk to groups of residents, who simply congregate around the scientists during the surveys (Figure 3). Not surprisingly, we have found considerable differences in the level of sensitivity to tsunami hazards among the populations of various regions. In the most earthquake-prone areas, such as the coast of Peru, the local residents feel many earthquakes every year, and most of them have been or will be exposed to a perceptible tsunami in their life times. As a result, the concept of tsunami hazard is passed along by ancestral tradition, and the populations are well educated in this respect; the reflex of self-evacuation upon noticing an anomalous behavior of the sea is well developed, to the extent, for example, that it contributed significantly to the reduction of the death toll, during the 2001 Camaná, Peru tsunami [*Okal et al.,* 2002*a*]. In areas less exposed to tsunamis, there is obviously a lower awareness of tsunami hazard, and a greater education effort is warranted.

In this general framework, the message from the ITST strives to repeat a few fundamental facts regarding tsunamis and their mitigation, namely (i) that tsunamis are a natural phenomenon which is part of the normal geological processes occurring in the Earth, and that they do and will recur; (ii) that any local earthquake felt strongly enough to disrupt people's activities could produce significant changes in sea level and should dictate evacuation of low-lying areas; and (iii) that any withdrawal of the sea is the harbinger of the destructive return of an inundating wave and should trigger an immediate evacuation of the beaches. Based on local topography, we seek to give

Fig. 3. Outreach to local communities by members of the International Tsunami Survey Teams. *Top:* Drs. J.C. Borrero (left) and E.A. Okal (right) give a presentation at the San Juan Batista public school on Juan Fernández Island, Chile, during the 1946 Aleutian survey in the far field. *Bottom:* Dr. C. Ruscher (with hat) answers questions at a spontaneous gathering with local residents during the 1999 Vanuatu survey.

guidelines as to the spatial extent of an adequate evacuation, and emphasize the need to remain vigilant for several hours, as tsunamis consist of multiple waves whose period cannot be safely evaluated from the first arrivals. We also strive to distribute pamphlets, if possible translated in a local language, which summarize tsunami hazards and simple rules for their mitigation, and we generally attempt to leave a master copy with local officials and school teachers.

To local government officials and civil defense authorities, we also stress the importance of a sensible control on the development of real estate in low-lying areas, and of the value of keeping the population aware of tsunami hazard through various exercises, such as the yearly drills conducted for example in Japan and Peru.

On a more formal level, the teams have enthusiastically sought to include members from the affected countries, in order to provide opportunities for *in situ* training during and after the survey, thus establishing the basis of closer international cooperation in science. Local scientists also contribute regularly to the data analyses and are joint authors of most publications resulting from field surveys. Repeatedly, scholars from the home countries have later pursued graduate studies abroad (*e.g.,* in the United States, Japan or New Zealand) in the wake of their participation in International Tsunami Survey Teams.

3. Individual tsunami surveys

In this section, we detail the fifteen surveys taken by International Tsunami Survey Teams since 1992, and in particular emphasize the fundamental contributions which each of them has brought to the advancement of our understanding of tsunami hazard.

3.1. NICARAGUA, 02 SEPTEMBER 1992; $M_0 = 3.4 \times 10^{27}$ dyn-cm [*Dziewonski et al., 1993a*]; INITIAL FIELD REPORT: *Satake et al.* [1993].

With more than 160 people killed along the coast of Nicaragua, this was the first tsunami in over a decade to result in a substantial number of casualties. This, and its clear nature as a "tsunami earthquake", motivated a number of detailed surveys, which became the model for all subsequent field work by the International Tsunami Survey Teams in the aftermath of later tsunamis. We recall that "tsunami earthquakes" were defined by *Kanamori* [1972] as events whose tsunamis have far greater amplitude than expected from their conventional magnitudes.

The seismic characteristics of the earthquake have been described in a number of publications [*Kanamori and Kikuchi,* 1993; *Satake,* 1994; *Velasco et al.,* 1994; *Kikuchi and Kanamori,* 1995]. Its strong deficiency in high-frequency energy release is best illustrated by its low body-wave magnitude, $m_b = 5.3$, which resulted in the earthquake not being felt along certain segments of coastline, and thus in the absence of natural warning for the impending disaster. *Newman and Okal* [1998] computed their lowest value of the parameter $\Theta = \log_{10} E^E / M_0$ as -6.30 for that event (this parameter expresses the dimensionless ratio of estimated radiated energy to seismic moment; under generally accepted scaling laws, it is expected to be an invariant ($\Theta = -4.90$) related to source strain release). In addition, *Okal et al.* [2003*b*] documented the deficient hydroacoustic ("T") waves of the 1992 Nicaragua earthquake. *Okal and Newman* [2001] noted the absence of comparable or larger interplate thrust earthquakes along the Nicaragua subduction zone.

Results from the field survey are given by *Abe et al.* [1993]. They confirm substantial values of run-up, reaching 8–10 m and spread over a 290–km long segment of coastline, extending from the Honduran border to the Costa-Rican one. These first datasets based on modern surveys were impossible to model using the then-available simulation codes, which would stop the wave evolution calculations at some threshold depth (*e.g.,* 5 or 10 m), and essentially treat the shoreline as a rigid and fully reflecting vertical wall. In practice, those simulations predicted run-up values too low by close to an order of magnitude, when based on dislocation models acceptable from the seismological standpoint [*Imamura et al.,* 1993]. By contrast, *Titov and Synolakis* [1993] presented a largely successful simulation based on a prototype algorithm handling the full interaction of the wave with an initially dry beach.

3.2. FLORES, INDONESIA, 12 DECEMBER 1992; $M_0 = 5.1 \times 10^{27}$ dyn-cm [*Dziewonski et al.,* 1993*b*]; INITIAL FIELD REPORT: *Yeh et al.* [1993].

The parent earthquake of this tsunami took place in the Flores Sea, north of the Sunda arc, and represented subduction of the proposed Banda block below the Australian plate, under a complex regime of back-arc compression probably associated with the incipient collision between continental Australia and the Sunda trench farther East [*Beckers and Lay,* 1995; *Hidayat et al.,* 1995].

The field survey conducted in the aftermath of the tsunami [*Tsuji et al.,* 1995*a*] documented several intriguing results: while it established a maximum run-up of 4–5 m on most of the Northern coast of Flores Island, it revealed catastrophic values of up to 26 m at some localities (Rangrioko) in Northeastern Flores. Underwater surveys by *Plafker* [1997] showed that the latter resulted from submarine landslides triggered locally by the earthquake.

In addition, a remarkable observation on the nearly circular island of Babi showed that the maximum run-up (7.2 m) was observed in the lee of the tsunami, following a process of convergence of the tsunami waves behind the circular obstruction [*Yeh et al.,* 1993; *Imamura et al.,* 1995*a*], which was successfully reproduced in the laboratory by *Briggs et al.* [1995], and simulated numerically by *Yeh et al.* [1994] and *Tinti and Vannini* [1995].

Finally, it was noticed at the community of Wuring, off Maumere on the northern coast of Flores, that a strong overland flow had over-run a peninsula, illustrating the vulnerability of such features due to bathymetric focusing of tsunami energy by shallow structures.

3.3. HOKKAIDO-NANSEI-OKI, 12 JULY 1993; $M_0 = 4.7 \times 10^{27}$ dyn-cm [*Dziewonski et al.,* 1994]; INITIAL FIELD REPORT: *Shuto et al.* [1993].

This tsunami remains to this date the last catastrophic one to affect Japan, with 198 fatalities confirmed on the small island of Okushiri. The Aonae peninsula at the southern tip of the island was completely over-run by the waves, despite the presence of a

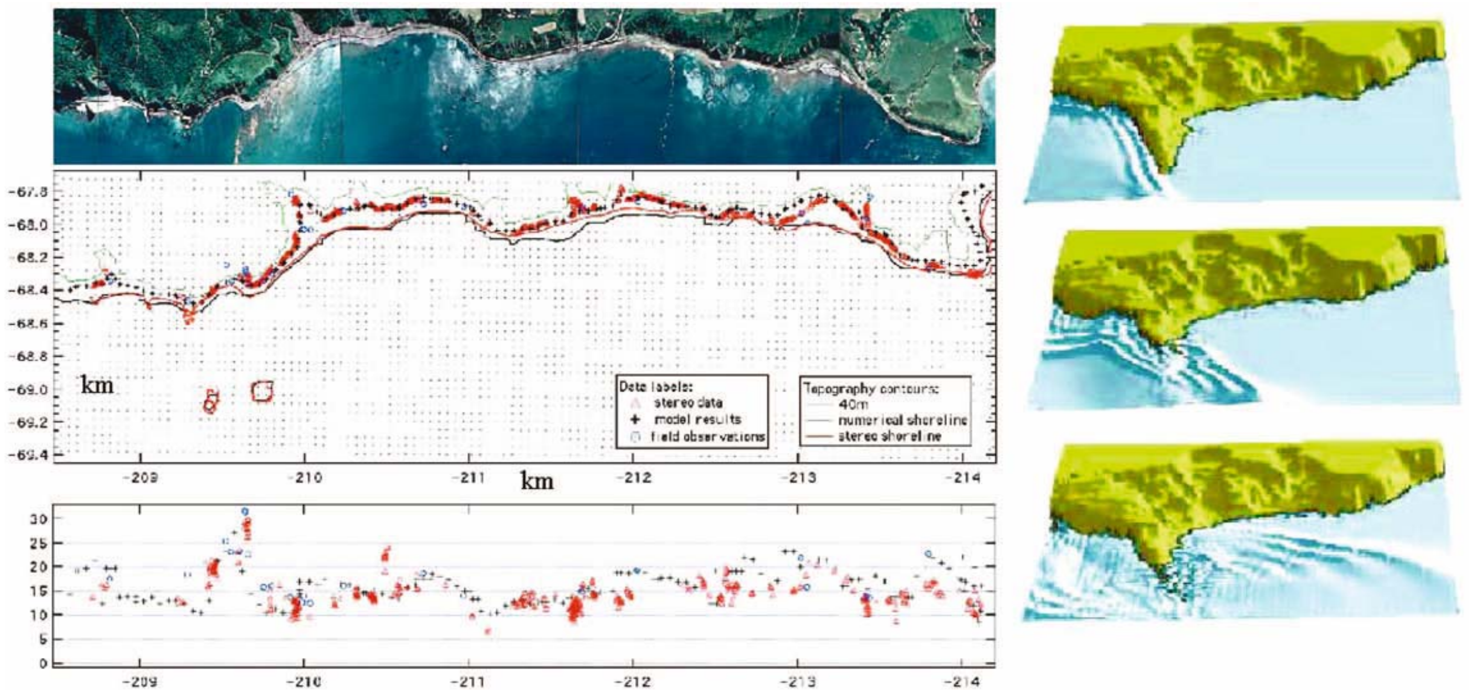


Fig. 4. Modeling of the Hokkaido-Nansei-Oki tsunami on the island of Okushiri. *Left:* Aerial view (top) of damage along the Western coast of Okushiri Island; map (center) showing inundation points measured in the field (open circles) and interpreted from stereographic aerial pictures (triangles), compare to the result of modeling (crosses); cross-section (bottom) showing measured and modeled values of run-up (in meters). *Right:* Video snapshots showing modeling of the inundation and over-run of the Southern-most tip of Okushiri island at Aonae. After *Titov and Synolakis* [1997].

7−m high protection wall. Seismological investigations of the parent earthquake were carried out by *Tanioka et al.* [1995*a*] and *Kuge et al.* [1996]. Post-tsunami field surveys [*Shuto et al.,* 1993; *Shuto and Matsutomi,* 1995] documented run-up reaching 31 m at a river gully near Monai on the Western shore of the island, emphasizing the importance of the topography at the receiving shore on the eventual amplitude of run-up.

Based on the DCRC-17a source model of *Takahashi et al.* [1995], the modeling by *Titov and Synolakis* [1997] of those maximum run-up values and of the inundation flow over the Aonae peninsula using the MOST code [*Titov and Synolakis,* 1998] was the first successful demonstration of the capability, for simulation techniques, to reproduce the highly non-linear interaction of the wave with originally dry land (Figure 4).

The Okushiri tsunami was relatively unique in the extreme proximity of the source region to the island which left practically no time for the residents to escape the onslaught of the waves. This tragedy had a profound effect on the evolution of mitigation strategies, notably concerning sea walls, shoreline development and vertical evacuation.

3.4. JAVA, 02 JUNE 1994; $M_0 = 5.3 \times 10^{27}$ dyn-cm [*Dziewonski et al.,* 1995*a*]; INITIAL FIELD REPORT: *Synolakis et al.* [1995].

This was the second "tsunami earthquake" of the 1990s, characterized once again by an extreme deficiency in energy-to-moment ratios (*Newman and Okal*'s [1998] parameter $\Theta = -6.01$). The absence of ground shaking proved lethal to the population (223 killed by the tsunami, none by the earthquake), put helped evaluate the wave damage. *Tanioka and Satake* [1996] suggested that a sloping ocean bottom in the epicentral area could have enhanced tsunami generation through the contribution of horizontal displacement of the sea bottom. *Abercrombie et al.* [2001] proposed that the earthquake involved slip over a subducting seamount, which had provided a single locking asperity along an otherwise aseismic subduction segment [*Okal and Newman,* 2001], an idea originally expressed in Japan by *Lallemand and Le Pichon* [1987].

The field survey [*Tsuji et al.,* 1995*b*] identified run-up amplitudes reaching 14 m at Rajekwesi, and documented the importance of the local topography, capable of amplifying and funneling tsunami energy, notably over so-called pocket beaches.

3.5. SHIKOTAN, KURIL ISLANDS, 04 OCTOBER 1994; $M_0 = 3.0 \times 10^{28}$ dyn-cm [*Dziewonski et al.,* 1995*b*]; INITIAL FIELD REPORT: *Pelinovsky et al.* [1995].

This earthquake was at the time the second largest in the Harvard CMT catalogue; it was not, however a subduction event, but rather involved tearing of the subducting slab along a nearly vertical fault plane [*Tanioka et al.,* 1995*b*]. It produced very strong shaking resulting in the opening of large fissures in the ground, and led to environmental damage due to leakage from oil storage tanks. The resulting tsunami was surveyed by *Yeh et al.* [1995], with run-up in the range of 5 to 9 m; none of the 12 deaths were directly attributable to the tsunami. However, most of the locations surveyed on Shikotan Island lacked significant accumulation of tsunami deposits, indicating a lack of universal correlation between substantial inundation and sedimentation.

The distribution of run-up was made relatively complex by the intricate geography of the islands and straits in the region, but was nevertheless successfully modeled by *Yeh et al.* [1995] and *Titov* [1996], even though *Piatanesi et al.* [1999] have suggested that the surveyed dataset is insufficient to resolve the two conjugate fault planes of the focal mechanism.

3.6. MINDORO, PHILIPPINES, 14 NOVEMBER 1994; $M_0 = 5.1 \times 10^{26}$ dyn-cm [*Dziewonski et al.,* 1995*b*]; FIELD REPORT: *Imamura et al.* [1995].

This relatively moderate earthquake, characterized by a strike-slip mechanism, generated a significant tsunami, featuring run-up as high as 7.3 m. While some of the large run-up values could be attributable to local landslides (as in the case of Flores (1992), but on a smaller scale), the survey conducted by *Imamura et al.* [1995*b*] revealed local on-land deformations departing from the expected field of static displacements, and highlighted the importance of the horizontal displacement of a coastline traversed by a strike-slip fault as a possible mechanism of generation of a local tsunami, as modeled by *Tanioka and Satake* [1996] and more recently *Legg et al.* [2003]. Finally, it pointed out the existence of complex and powerful flow regimes at the mouths of rivers, due both to the tsunami and the presence of cracks on the river bed, as exemplified at Wawa, on the Baruyan River, where a 4000-ton barge was moved 1.6 km inland.

3.7. MANZANILLO, MEXICO, 09 OCTOBER 1995; $M_0 = 1.15 \times 10^{28}$ dyn-cm [*Dziewonski et al.* ,1997*a*]; INITIAL FIELD REPORT: *Borrero et al.* [1997].

This earthquake was the largest one to affect the Mexican coastline since the devastating 1932 series, but remained significantly smaller than the latter's mainshock [*Pacheco et al.,* 1997; *Zobin,* 1997], a conclusion upheld by *Ortíz et al.*'s [1998] modeling of tidal gauge records.

During the field survey, *Borrero et al.* [1997] documented on a photograph taken by a coastal resident the leading depression (down-draw) expressing the first phase of interaction of the tsunami with a local beach (Figure 5). This is believed to be the first documented observation of this phenomenon, which had been predicted theoretically, for an adequate focal geometry, by *Tadepalli and Synolakis* [1994, 1996], and which is rooted in the dipolar nature, involving both subsidence and depression, of the ground deformation during the earthquake. It confirms the challenge to the paradigm of the soliton model for the leading waveform of an earthquake-generated tsunami.

3.8. BIAK, INDONESIA, 17 FEBRUARY 1996; $M_0 = 2.4 \times 10^{28}$ dyn-cm [*Dziewonski et al.,* 1997*b*]; INITIAL FIELD REPORT: *Imamura et al.* [1997].

This very large earthquake took place along a segment of the New Guinea Trench with no previously documented large scale seismicity, leading *Okal* [1999] to suggest a regime of subduction through large events separated by long recurrence times, the previous one tentatively dated to 1914. The tsunami was damaging throughout Northwestern Irian Jaya, and in particular on Biak Island, where run-up reached 7.7 m. The field work of the ITST [*Matsutomi et al.,* 2001] documented for the first time the feasibility

Fig. 5. *Right:* Initial down-draw during the early phases of the 1995 Mexican tsunami at Tenacatita Bay (photograph courtesy of J. Lehemen). *Left:* Same location photographed later during the survey by the ITST (note the balustrade damaged by the earthquake).

of obtaining a database of current velocities, estimated from differences in inundation depths upstream and downstream of obstacles such as house walls, based on an application of Bernouilli's theorem [*Matsutomi and Iizuka,* 1998].

3.9. CHIMBOTE, PERU, 21 FEBRUARY 1996; $M_0 = 2.2 \times 10^{27}$ dyn-cm [*Dziewonski et al.,* 1997*b*]; INITIAL FIELD REPORT: *Bourgeois et al.* [1996].

This represents the last of the recent "tsunami earthquakes" characterized by a deficient energy-to-moment ratio ($\Theta = -5.94$); as in the case of the Nicaragua and Java events described above, no other large subduction earthquakes are known along that section of the Northern Peru coastline [*Okal and Newman,* 2001]. The earthquake also showed a spectacular deficiency in hydroacoustic T waves at teleseismic distances [*Okal et al.,* 2003*b*]. The field survey [*Bourgeois et al.,* 1999] documented run-up in the 2 to 5 m range over a 250–km stretch of coast, and the total run-over of a flat, 1.5–km wide isthmus separating the local bays at Chimbote and Samanco.

The run-up of the tsunami along the Peruvian coast, as well as in some bays of the Marquesas Islands, was successfully modeled by *Bourgeois et al.* [1999] and *Heinrich et al.* [1998], after allowing for a low value of source rigidity, in order to reflect the anomalous character of the earthquake [*Ihmlé et al.,* 1998]. *Satake and Tanioka* [1999] modeled regional tidal gauge records to constrain the width of the fault.

3.10. AITAPE, PAPUA NEW GUINEA, 17 JULY 1998; $M_0 = 3.7 \times 10^{26}$ dyn-cm [*Dziewonski et al.,* 1999]; INITIAL FIELD REPORT: *Kawata et al.* [1999].

Despite the relatively small size of the parent earthquake, this tsunami resulted in over 2100 fatalities, officially surpassed in the 20th century only by the 1933 Sanriku, Japan tsunami. The field survey was organized within two weeks of the disaster and confirmed exceptional run-up heights, reaching 15 m at Arop, but concentrated on a 25–km stretch of coastline outside which the effects of the tsunami were benign. As documented in detail in *Synolakis et al.* [2002], the combination of excessive amplitude and concentration of the run-up was quickly recognized as incompatible with any simulation model based on the excitation of the tsunami by the seismic dislocation; in addition, the earthquake did not feature a slow source comparable to those of documented "tsunami earthquakes" [*Newman and Okal,* 1998; *Synolakis et al.,* 2002].

Finally, witness reports generally indicated that the tsunami had arrived at least 10 minutes later than predicted by all acceptable models of propagation from the earthquake source [*Davies et al.,* 2003]. Based on the identification of a hydroacoustic signal recorded near Wake Island and featuring an anomalous combination of amplitude and duration, *Okal* [1998; 2003] proposed that the tsunami had been generated by an underwater landslide, itself triggered by the earthquake with a delay of 13 minutes. A number of ship-based surveys, using seismic refraction and remotely operated submersibles [*e.g., Sweet and Silver,* 2003] later identified a 4–km^3 slump contained in a bowl-shaped amphitheater located 25 km from the coast, which was used as the source of the tsunami in several successful numerical simulations of run-up along the Sandaun coast [*Heinrich et al.,* 2000; *Synolakis et al.,* 2002; *Imamura and Hashi,* 2003].

Results from the post-tsunami field survey thus led to the identification of a submarine landslide as the source of the devastating 1998 Papua New Guinea tsunami, and renewed sensitivity was aroused in the tsunami community for the hazards created by underwater landslides [*Bardet et al.,* 2003]. As a result, the level of hazard posed by relatively moderate earthquakes (typically at the magnitude 6 level) must be re-examined upwards, on a case-by-case basis [*Borrero et al.,* 2001].

3.11. IZMIT, TURKEY, 17 AUGUST 1999; $M_0 = 2.9 \times 10^{27}$ dyn-cm [*Dziewonski et al.,* 2000*a*]; INITIAL FIELD REPORT: *Altınok et al.* [1999].

The devastating Izmit earthquake [*e.g., Barka et al.,* 2002], which killed upwards of 18,000 people, was accompanied by a significant tsunami which inflicted additional destruction to coastal areas at the Eastern end of the Sea of Marmara, including environmental damage due to a major oil spill at a refinery in Izmit. A database of results from tsunami surveys is given by *Altınok et al.* [2001], who attribute the origin of the tsunami principally to the activation of underwater normal faults located at pull-apart basins offsetting the main strike-slip fault, and documented by seismic refraction [*Altınok et al.,* 1999], with additional contributions from localized coastal slumps.

The modeling of the 1999 Izmit tsunami, proposed by *Yalçıner et al.* [2000], has led to a better understanding of tsunami risk in the Sea of Marmara [*Yalçıner et al.,* 2002], where a major earthquake with potentially catastrophic effects on the Istanbul metropolis is generally expected in the next decades [*Parsons et al.,* 2000].

3.12. FATU HIVA, MARQUESAS, 13 SEPTEMBER 1999; FIELD SURVEY: *Okal et al.* [2002*b*].

Without any warning (earthquake tremor, acoustic rumbling, etc.), a series of two waves reaching 5 m in amplitude inundated the beach front in the village of Omoa on the island of Fatu Hiva, and inflicted severe damage to the local school. Miraculously, there were no victims among the estimated 85 children attending school that afternoon. The cause of this local tsunami was an aerial landslide resulting from the collapse of a weathered cliff, 3 km from the village (Figure 6). The resulting survey [*Okal et al.,* 2002*b*] provided a volume estimate of (2 to 5) $\times 10^6$ m^3 for the slide, and successful simulations were carried out by *Hébert et al.* [2002] and *Okal et al.* [2002*b*]. To our knowledge, the landslide was not detected instrumentally anywhere in the Pacific Basin, and this event thus constitutes the first surveyed occurrence of an "aseismic tsunami".

As a result of this disaster, the school was rebuilt more than 1 km inland, in what one would hope represents a reversal of the recent trend towards development of beachfront real estate in the Marquesas.

3.13. VANUATU, 26 NOVEMBER 1999; $M_0 = 1.7 \times 10^{27}$ dyn-cm [*Dziewonski et al.,* 2000*b*]; FIELD SURVEY: *Caminade et al.* [2000].

This event, discussed in detail by *Pelletier et al.* [2000], took place behind the main Vanuatu arc, and featured a thrusting mechanism. The field survey documented run-up

Fig. 6. 1999 Tsunami at Fatu Hiva, Marquesas. *Top:* View of the village of Omoa, inundated by the wave. *Bottom:* Landslide at Vaifaite, 3 km from Omoa, photographed by the ITST 22 days after the event. The landslide (labeled "NEW") is approximately 300 m across and 250–300 m tall. It expresses the ongoing erosion of the island, with older episodes expressed in the morphology of the cliff, while the central part of the picture (labeled "NOT YET") constitutes permanent hazard.

reaching 6–7 m on Pentecost Island and 7–8 m on Ambryn. It is probable that small-scale landslides contributed locally to the larger values. From the standpoint of tsunami mitigation and warning, the 1999 Vanuatu event served as a spectacular illustration of the value of education of the coastal populations. The story of the village of Baie Martelli is a case in point: only a few months before the event, the villagers had been shown on portable, battery-operated television sets, a video based on the 1998 Papua New Guinea disaster, stressing the need to evacuate coastal areas following any strong earthquake, and especially in the event of anomalous variations in sea level. When the earthquake struck, in the middle of the night, and a villager reported a withdrawal of the sea, the entire village was evacuated before the tsunami destroyed it totally; out of a population of 300, the only five victims were elderly invalids who could not evacuate, and a drunken man, who would not.

3.14. CAMANA, PERU, 23 JUNE 2001; $M_0 = 4.7 \times 10^{28}$ dyn-cm [*Ekström et al.,* 2003]; FIELD REPORT: *Okal et al.* [2002*a*].

This earthquake remains, to this day, the largest event in the past 39 years, as documented by the Harvard CMT catalogue, and *Kanamori* [1977]. While exhibiting a trend towards slowness ($\Theta = -5.48$), the event did not qualify as a "tsunami earthquake", and its tsunami was adequately modeled as due to a standard seismic dislocation. The tsunami affected the coastal communities from Ilo in the South to Tanaca in the North and resulted in 86 people killed or reported missing in the coastal area. Most of the inundation and damage took place in the Camaná river delta area.

One of the major results from the initial field survey [*Okal et al.,* 2002*a*] was that this death toll could have been much greater, had the tsunami struck during a Summer night, when the beach would have been packed with vacationers. The survey team was also impressed with the level of education and sensitivity to hazard of the local population, especially in fishing communities with a deeply rooted ancestral tradition. Indeed most of the victims at Camaná were farm workers from the hinterland.

Another highlight of the international surveys following the event [*Dengler et al.,* 2003] was the access to a video of the arrival of the tsunami in the bay of Matarani harbor, documenting a small initial positive wave (not exceeding a few tens of cm, and thus within the range of tidal oscillations), followed by a strong down-draw, emptying the bay and grounding many boats for a period of about 20 minutes, during which the bay developed complex patterns of vortical flow. This video, filmed by a television cameraman before he was ordered to evacuate the harbor (and thus missed filming the subsequent inundation) is one of a handful of existing films of the actual motions of water in a harbor during a tsunami. Finally, a systematic investigation of the tsunami deposits in the Camaná delta revealed a large variation in thickness and layering, even on the small scale of the delta, stretching approximately 10 km along a generally rectilinear shoreline [*Dengler et al.,* 2003].

3.15. WEWAK, PAPUA NEW GUINEA, 08 SEPTEMBER 2002; $M_0 = 2.9 \times 10^{27}$ dyn-cm [*G. Ekström,* pers. comm., 2002]; FIELD REPORT: *Borrero et al.* [2003].

In contrast to the 1998 disaster, which occurred only 135 km to the Northwest, the 2002 earthquake was a larger seismic source, which did more significant damage onland, killing five persons , but resulted in a much weaker tsunami (maximum run-up on the coast: 3.5m), observed on a longer stretch of coast [Borrero et al., 2003]. This confirmed, if need be, that the 1998 tsunami was generated by an exceptional source — the underwater landslide — absent from the 2002 scenario.

4. The use of regional run-up datasets as identifiers of tsunami sources

In a recent contribution, *Okal and Synolakis* [2004] have shown that datasets of run-up amplitudes in the near field can be used to identify the nature (dislocation or landslide) of the source of a tsunami based on the analysis of the aspect ratio of the distribution of run-up along beach, and of the maximum run-up measured in the near field, scaled by the co-seismic slip Δu on the fault plane. Specifically, given a distribution $\zeta(y)$ of run-up values along a beach oriented in the y direction, these authors fit by trial and error a function of the type

$$\zeta(y) = \frac{b}{\left(\dfrac{y-c}{a}\right)^2 + 1} \qquad (1)$$

and define the two dimensionless quantities $I_1 = b/\Delta u$ and $I_2 = b/a$. They propose that these behave as invariants, characteristic of the class of tsunami source considered (dislocation *vs.* landslide), but largely independent of the exact parameters describing such sources. They are motivated by the intuitive observation that maximum run-up (hence b) should be principally controlled by the amount of deformation of the sea floor, and hence by the slip Δu on the fault, while its distribution (hence a) should reflect the lateral extent of the source. Noting the fundamentally different distribution fields of underwater deformation for dislocations and landslides, and in particular that the strain release in an earthquake is limited inherently by the strength of crustal rocks, *Okal and Synolakis* [2004] showed that I_2 (as well as I_1 when Δu is sufficiently well known) can be used as a *discriminant* of the nature of a tsunami source (Figure 7). This was supported by the systematic processing of more than 70 simulations of regional tsunamis using both kinds of sources, and letting their geometric parameters vary widely. A simple rule of thumb is that dislocations sources cannot feature aspect ratios I_2 greater than 10^{-4}.

Figure 8 presents the application of this approach to seven profiles obtained from the above modern surveys (and the 1946 Unimak field survey; see Section 5. below). We eliminated those surveys taken along contorted shorelines or those featuring islands, where in both cases the definition of the coordinate y is difficult. These results clearly identify the 1998 Papua New Guinea and 1946 Aleutian tsunamis as the only ones requiring a non-dislocative source to model their tsunamis in the near field (Figure 7). In particular, Figures 8*b* and 8*c* illustrate the fundamentally different nature of the run-up distribution for the two Papua New Guinea events: the 1998 Aitape tsunami, generated by a landslide, and the 2002 Wewak one, resulting form a standard dislocation.

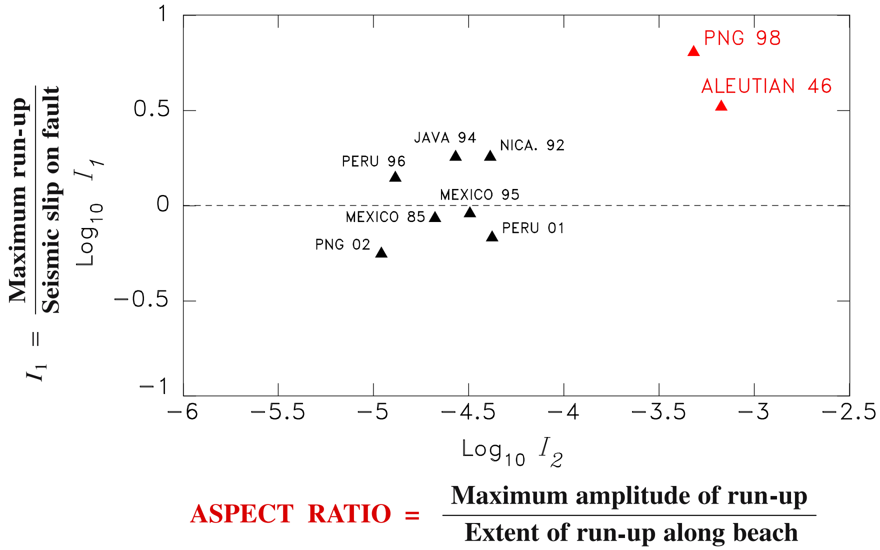


Fig. 7. Plot of the dimensionless parameters I_1 and I_2 obtained by regressing the distribution of run-up along near-field beaches for a number of tsunamis surveyed by the ITSTs. This figure clearly identifies the 1998 Papua New Guinea and 1946 Aleutian tsunamis as the only ones with $I_1 > 2$; $I_2 > 10^{-4}$, thus requiring generation by a landslide rather than by the earthquake dislocation. After *Okal and Synolakis* [2004].

5. Extension to historical events: The case of the 1946 Aleutian tsunami

Some of the techniques used by the International Tsunami Survey Teams can be extended to build quantitative data bases of run-up and inundation for historical events. When available, historical archives can be used successfully, as demonstrated by the reconstruction of the effects of the 1700 Cascadia tsunami in Japan [*Satake et al.,* 1996; *Atwater et al.,* 2004]. In their absence, and for more recent events, we have found that many elderly residents throughout the Pacifi c had kept vivid memories of the damages wrought by the 1946 Aleutian tsunami, both in the near and far fi elds, to the extent that quantitative information on run-up and inundation could be recovered more than 50 years after the fact (Figure 9).

However, in dealing with historical events, the surveyor is faced with the additional challenge of assessing the reliability of the recollection provided by a necessarily elderly witness, whose memory may be failing. In particular, it is of paramount importance to establish beyond doubt the association of a recollection with the correct tsunami. As detailed in *Okal et al.* [2002*c*], this may involve techniques of "cross-examination" of the witnesses regarding time of the day (which often is characteristic of a given tsunami on a particular island) and age of the witness (expected to vary significantly between candidate events, due to the general rarity of destructive tsunamis). We discuss here the application of this approach to two historical tsunamis.

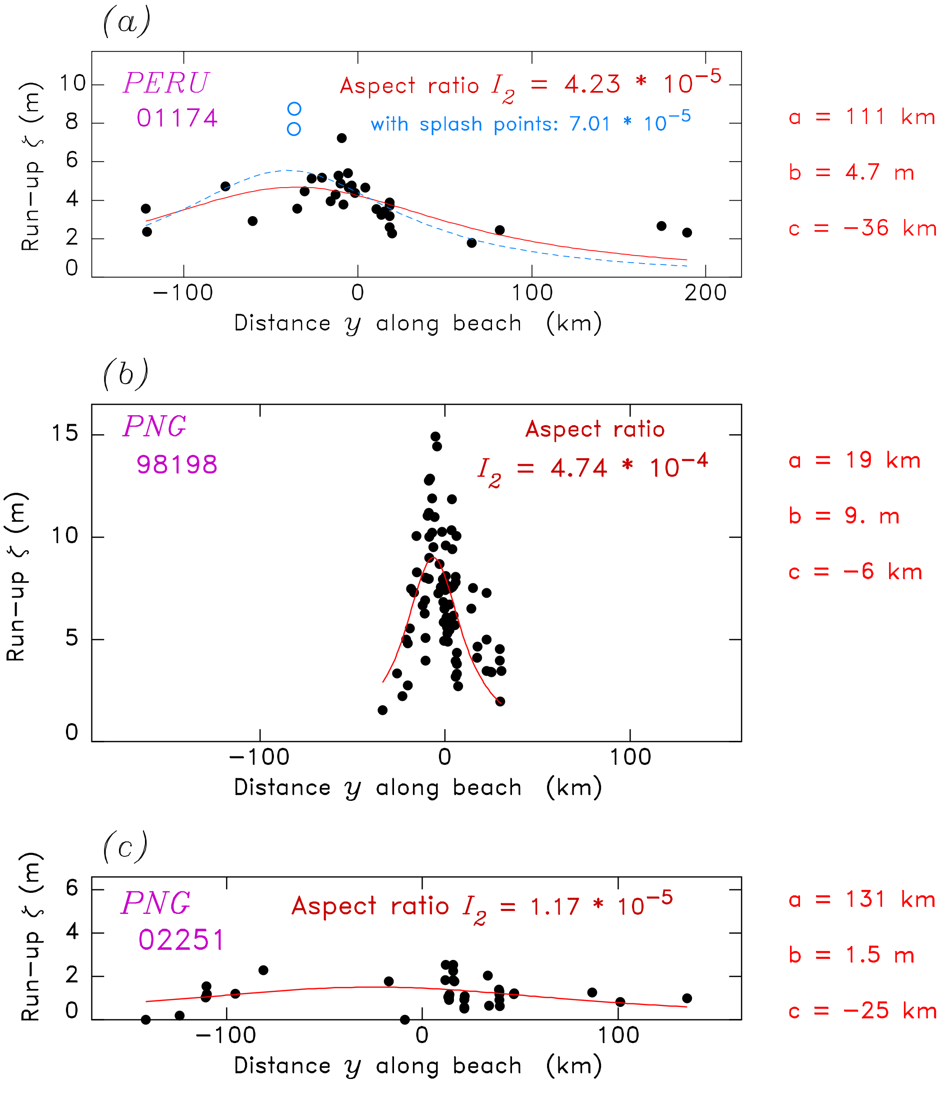


Fig. 8. Field survey profiles of run-up fitted to an equation of the form (1). *(a):* 2001 Peruvian tsunami. The solid dots are the individual measurements; the red line the best-fitting function of the type (1). Open symbols are run-up values affected by splashing against a steep cliff, which should be discarded from the data. *(b):* Same as (a) for the 1998 Papua New Guinea tsunami. *(c):* Same as (a) for the 2002 Papua New Guinea tsunami. All three diagrams are plotted using the same horizontal and vertical scales, to allow direct comparisons between events. The striking contrast between the distributions of the 1998 and 2002 events in Papua New Guinea expresses the anomalous character of the 1998 event, which features $I_2 > 10^{-4}$ and requires a non-dislocative source. After *Okal and Synolakis* [2004].

5.1. UNIMAK, ALEUTIAN IS., 01 APRIL 1946; $M_0 = 9 \times 10^{28}$ dyn-cm [*López and Okal,* 2002].

The case of the 1946 Aleutian tsunami remains a challenge to the seismological and tsunami communities. The earthquake, featuring a conventional magnitude of only 7.4 [*Gutenberg and Richter,* 1954] is deceptively small in regard of the catastrophic tsunami which it generated, in both the near field, where it eradicated the Scotch Cap

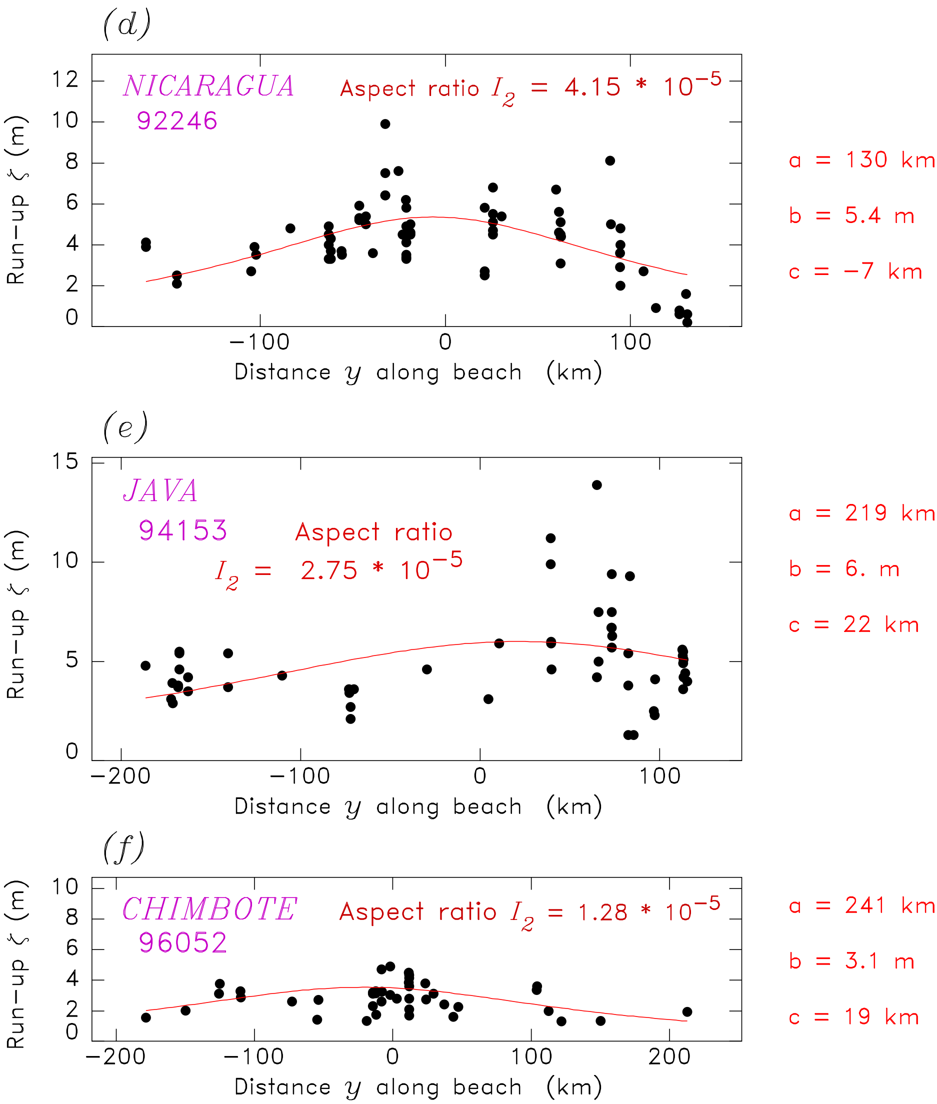
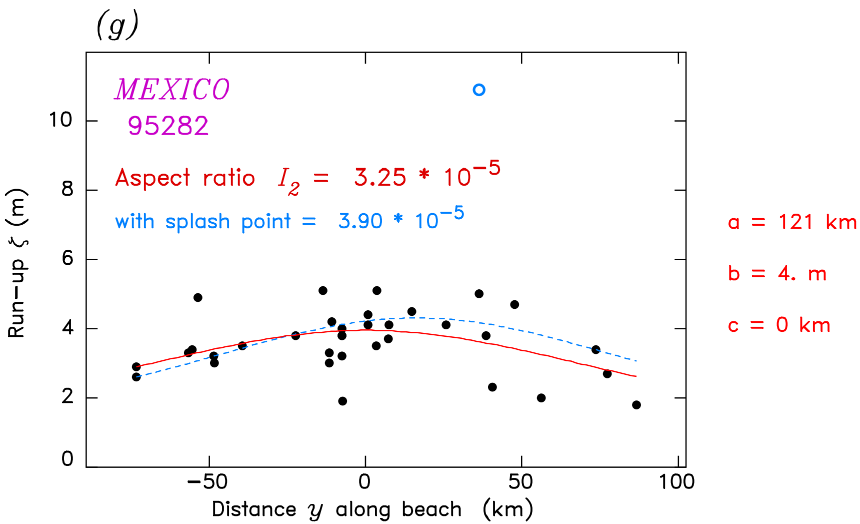


Fig. 8 (ctd.). Same as Figure 8*(a)* for the "tsunami earthquakes" of Nicaragua (1992), Java (1994), and Chimbote, Peru (1996).



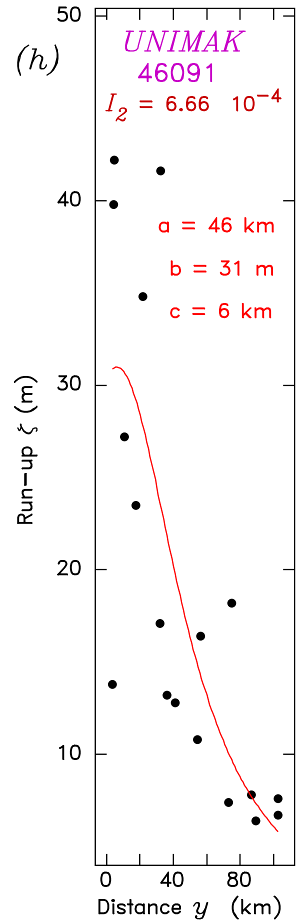


Fig. 8 (ctd.). Same as Figure 8*(a)* for the 1995 Mexico tsunami *(g)* and the 1946 Aleutian tsunami *(h)*. All frames *(a − h)* in Figure 8 share the same ratio of vertical-to-horizontal scales, allowing direct comparison of aspect ratios.

lighthouse, and in the far field, where it killed 159 people in Hawaii, and wrought significant damage in the Marquesas, and probably as far as Antarctica [*Fuchs,* 1982]. It was recognized early on by *Kanamori* [1972] as a "tsunami earthquake" featuring exceptionally slow rupture. During several campaigns of field work in 1999-2002, described in detail in *Okal et al.* [2002*c*; 2003*a*], we were able to successfully compile a database of 57 far-field and 29 near-field run-up measurements through the interview of 69 witnesses aged 59 to 89 at the time of the interview [*Okal et al.,* 2002*c*; 2003*a*]. These field surveys produced two fundamental results: in the near field, we revised to a maximum of 42 m the amplitude of run-up at Scotch Cap, and established that it decays relatively fast along the coast of Unimak Island. These two observations require the involvement of a major underwater landslide as they indicate an aspect ratio $I_2 = 6.7 \times 10^{-4}$ and a ratio of maximum run-up to seismic slip $I_1 = 3.4$ both in excess of those theoretically acceptable for any dislocation [*Okal and Synolakis,* 2004]. The presence of a landslide in the source of the 1946 tsunami is also supported by anecdotal testimony from retired fishermen. In contrast, in the far field, and based principally on our results at Juan Fernández Island, we document a very pronounced directivity, which cannot be reconciled with a landslide source, and requires a substantial dislocation.

A detailed seismological reassessment of the 1946 Aleutian earthquake established that it involved bilateral rupture over a fault extending at least 200 km, and that it featured one of the slowest ruptures ever documented, with *Newman and Okal*'s [1998] parameter Θ reaching -7.0 [*López and Okal,* 2002]. Using simulations based on an estimated seismic moment of $M_0 = 9 \times 10^{28}$ dyn-cm (suggested from the evolution of mantle wave spectral amplitudes with frequency, as recorded on broad-band instruments at Pasadena), *Hébert and Okal* [2003] have successfully reproduced the directivity in run-up amplitudes surveyed in the far field, and *Titov et al.* [2003] have similarly, but with the help of a different code, modeled the inundation at Hilo, Hawaii, as reported by *Shepard et al.* [1946].

The model emerging from these studies is that of a complex process, comprising an extremely slow and very large earthquake (required to explain the far field tsunami, as well as for example, the distribution of aftershocks), and of a coeval landslide responsible for the exceptional amplitude of run-up in the near field.

5.2. AMORGOS, GREECE, 09 JULY 1956; $M_0 \approx 5 \times 10^{27}$ dyn-cm [this study].

This relatively large earthquake was followed by a locally destructive tsunami, with maximum run-up reported to have reached 30 m on the Southern coast of the island of Amorgos. *Ambraseys* [1960] suggested that the source of the tsunami must have involved underwater landslides off the Eastern coast of Amorgos. There is considerable disagreement on the exact focal mechanism of the earthquake [*Shirokova,* 1972; *Ritsema,* 1974], suggesting the possibility of a composite rupture, in the general framework of extensional neotectonics in the the back-arc Aegean Basin. A number of marine surveys [*Ambraseys,* 1960; *Perissoratis and Papadopoulos,* 1999] have suggested the involvement of an underwater slump as a source of the tsunami.

We have initiated a tsunami survey through the interview of a dozen elderly witnesses on the island of Amorgos in the Summer of 2003, and compiled a preliminary dataset of 6 run-up measurements. Its peaked character on the Eastern coast of Amorgos would