

Tsunamigenic Sea-Floor Deformations

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As important as it is for hazard mitigation, the calculation of three-dimensional tsunami inundation in real time remains a formidable undertaking. Recent advances in hydrodynamics (1) triggered by the availability of high-resolution field and laboratory data have demonstrated that—given reasonable initial data—the predictions of runup

heights are correct to first-order, and therefore, attention has been focused on the effects of the seismic predictions of the fault parameters used for model initialization.

The National Science Foundation recently sponsored a workshop (2) to examine the state-of-the-art of interfacial seismology and its interface with tsunami hydrodynamics. One objective was to ascertain which quantitative features of the early sea-floor deformation can be inferred from teleseismic data, with what accuracy they are believed to be known, and the scientific basis of these inferences. Another objective was to discuss recent developments in the deployment of real-time bottom pressure recorders and seismic instrument arrays for real-time monitoring of tsunami generation, as well as the

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implementation of their data into real-time warning.

Hiroo Kanamori (California Institute of Technology) opened the workshop with an overview of the tectonic motions that generate tsunamis and defined the relevant physical fault parameters. Seismological data provide estimates of the seismic moment (that is, the magnitude M_w), fault width (W), fault length (L), fault slip (D), and rupture duration (L/V), where V is the rupture velocity. For most large subduction zone earthquakes, these parameters have been estimated reasonably well (see table). Kanamori asserted that the rupture time is small in comparison to typical tsunami propagation time scales, for all except perhaps the giant events, and is likely unimportant in the actual tsunami generation.

Certain earthquakes referred to as tsunami earthquakes (3) have slow faulting motion and very long rupture duration, at least three times longer than those listed in the table. These earthquakes probably occur at shallow depths within the sedimentary structure, where entrapped layers with lower rigidity cause greater slip for a given seismic moment. Because of the extreme heterogeneity, accurate modeling is difficult, resulting in large uncertainties in estimated ground deformation. Worse, the spatial and temporal patterns of submarine slumping are presently poorly understood, and it is often difficult to differentiate between slumping events and tsunami earthquakes from teleseismic records.

Tsunami coastal effects are greatly affected by the specific details of the earthquake rupture pattern. Eric Geist [U.S. Geological Survey (USGS)] explained how slip variations in the strike direction lead to variations in tsunami amplitude parallel to the wave front that are preserved during local propagation (4). Slip variations in the dip direction lead to changes in the tsunami wave form, producing *N* waves (that is, leading waves shaped like the letter *N*), whose polarity affect runup dynamics.

Necessary as it is for correctly initializing tsunami models, determining the time history of sea-floor surface elevation remains elusive, for it relies on an understanding of the basic physics of earthquakes. Tom Heaton (California Institute of Technology) discussed Reid's elastic rebound theory and argued against it, using common sense fracture-mechanics considerations; he pointed out that the deformation area estimated from aftershocks often is twice that estimated from geodetic data, begging the question, which one is the more realistic estimate.

Without before and after bathymetric data, the only method for validating the predictions of fracture models on the sea-floor deformation is the inversion of seismic, geo-

detic, or hydrodynamic data. Apostolos Papageorgiou (Rensselaer Polytechnic Institute) presented results from a recent inversion of the $M_w = 9.2$ Great Alaskan Earthquake of 1964. The rupture scenarios used were based on the slip model inferred recently by joint inversion of tsunami and geodetic data. The qualitative characteristics (that is, variation of intensity with time) of the synthesized ground motion in Anchorage were shown to be consistent with eyewitness accounts, raising the possibility of simulating correctly the time history of sea-floor deformation for study of historic events.

Hydrodynamic inversion uses runup or tidal gauge data as input for determining the initial sea-floor displacement that generated the wave motion. Although there have been significant advances, the criteria for regularizing what is an ill-posed problem remain lacking. Nobuo Shuto (Tohoku University) and Kenji Satake (Geological Survey of Japan) have pointed out that the geographic distribution of records is perhaps more im-

M_w	W (km)	L (km)	D (m)	η (m)	L/V (s)
7	30	70	0.6	0.16	23
8	80	200	2.7	0.70	70
9	240	600	9.0	2.30	200
9.5	250	1000	27.0	7.00	330

Estimates of fault parameters for tsunamigenic earthquakes. Here, η is the corresponding vertical sea-floor displacement.

portant than the actual number, although a threshold number of data sources for useful inversions is as yet undetermined.

Currently, all tsunami hydrodynamic models use the Harvard CMT solution, the relation for the seismic moment $M = LW\mu D$, where μ is the rigidity, and elastic dislocation theory for predicting the sea-floor displacement. An important issue is the accuracy to which different fault parameters are calculable in real time and as a function of time. The seismologists at the workshop were blind-pollled as to their best guesses of the errors in the estimates of the fault parameters for tsunamigenic events, which rely exclusively on teleseismic records. Even though there is scant evidence for validating fault data in subduction zones (SZs), the guesses were unexpectedly similar: The short-term errors range from 25 to 50%, except for the length and width, where they may be as high as 75%; the error in the distribution of slip and its strikewise variation may be as high as 90%. Errors in longer term estimates are lower by a factor of 2. The best guesses for the rigidity for SZ events varied from 5×10^{11} to 10×10^{11} dyne/cm².

The rise time τ remains elusive; it is defined as the ratio of the barrier interval (a

measure of the heterogeneity of the fault plane) over the rupture velocity V , a stable parameter estimated to be 0.7 to 0.9 of the *S*-wave velocity. It is conjectured that τ can be determined within a factor of 2 for SZ events, except for the pathological silent events, but that its estimate is unimportant to first-order for hydrodynamic simulations.

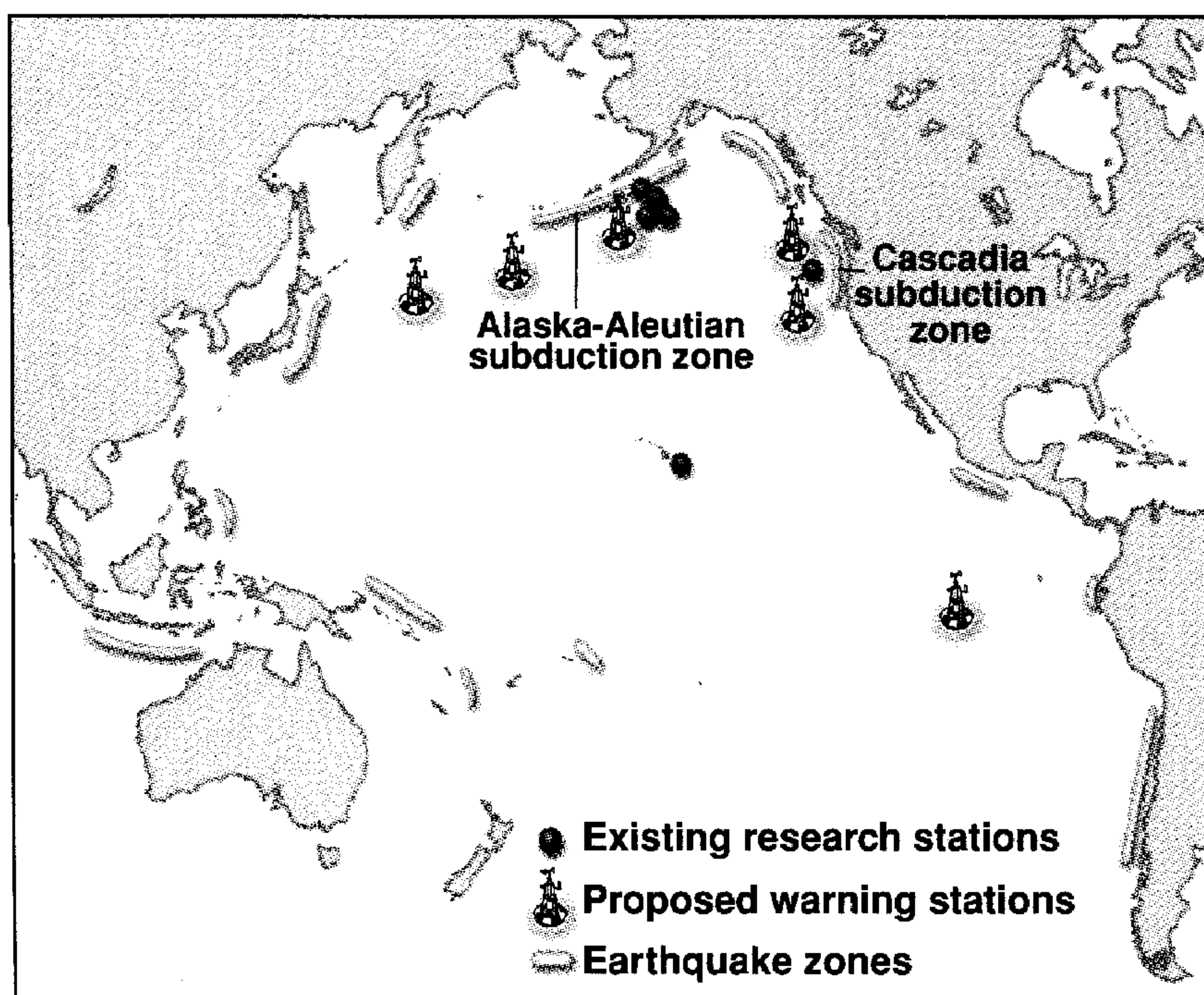
A major problem in real-time tsunami warning is recognizing an anomalous event such as a tsunami earthquake. Emile Okal (Northwestern University) discussed how to extend the real-time estimation of source characteristics of the TREMORS model by measuring the seismic energy carried by *P* waves (5). When coupled with routine real-time estimates of M_w , Okal compares the characteristics of the source at high and low seismic frequencies. On the basis of analysis of the major SZ events of the past few years, it appears possible to uniquely identify tsunami earthquakes as those with a deficiency of up to two orders of magnitude in the ratio of seismic energy E to its moment, E/M .

When implemented into TREMORS, this method could automatically identify exceptionally efficient tsunami generation in adequate time for warning.

Two major current developments in real-time tsunami warning are TriNet and CREST. TriNet is a wide-dynamic-range seismic network being constructed jointly by the California Institute of Technology, USGS, and the California Division of Mines and Geology. Kanamori asserted that if ground-motion data longer than 100 s can be retrieved, then the sea-floor deformation can be estimated quickly and provide key information for near-field tsunami warning; however, the systems' ability to detect such long-period strong ground motion has not been tested.

The Consolidated Reporting of Earthquakes and Tsunamis (CREST) was initiated in 1996 through the tsunami hazard mitigation implementation plan of the National Oceanographic and Atmospheric Administration (NOAA). According to Dave Oppenheimer (USGS), the USGS will be upgrading the seismic equipment and monitoring facilities of seismic networks operating in Cascadia, Alaska, and Hawaii, with 24-bit data loggers and broadband and strong-motion sensors. A total of 60 CREST sites will be installed or upgraded in the U.S. Pacific states. This equipment will provide rapid, reliable, and relevant seismic data to

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Existing and planned tsunami monitoring stations. The network focuses on regions posing a direct threat to coastal communities of the United States. Research stations do not report in real time. Two of the six real-time reporting stations are scheduled for deployment in July 1997.

the tsunami warning centers that will be exchanged among them by way of the Internet and dedicated intranets.

In 1986, NOAA's Pacific Marine Environmental Laboratory started measuring tsunamis in the Pacific with the use of bottom-pressure recorders (BPRs), which store data but do not report in real time; the systems were deployed for up to 15 months at water depths of up to 5 km and can detect 1-mm changes in sea level that last longer than 2 min. Frank Gonzalez (NOAA) discussed NOAA's plans (6) to deploy a six-buoy tsu-

displacement for real-time warning.

Overall, despite significant advances over the past 5 years, the following issues remain troublesome, and progress is needed for reliable tsunami warnings. (i) There is lack of quantitative information on sediment layers overlying tsunamigenic faults and about how these layers affect directly the generation of tsunamis. (ii) A consistent methodology for differentiating between submarine slumping and tsunami-earthquake events needs to be developed. (iii) The distribution of friction in the fracture zone of tsunamigenic events

nami monitoring network of a real-time reporting version, for operational hazard assessment and warning (see figure). The first two buoys are scheduled for deployment in 1997, south of the Shumagin Islands in the Alaska-Aleutian SZ and west of the Cascadia SZ.

The installation of BPRs for real-time warning has also been progressing in Japan, where the National Research Institute for Earth Science and Disaster Prevention (NIED) has installed an optical submarine cable for earthquake and tsunami monitoring in Sagami Bay; S. I. Iwasaki (NIED) explained that its main objective is the inference of the sea-floor

needs to be better calculated either through measurement or theory. (iv) The effects of onshore small-scale topography and focus-inducing large-scale bathymetry and areas at risk from exceptional runup need to be further identified to allow for more targeted real-time warnings. (v) Better methods for identifying the strikewise and slipwise slip distribution need to be developed.

Yet, there is wide consensus that the seismic moment, the hypocentral location, and the dip and strike angles, if known from fault characteristics, are reliably determinable in the short term for first-order initialization of hydrodynamic computations and are sufficient for differentiating between small and large events, except in the Okal-style atypical events. The key for better data, better warnings, and faster results is the deployment of strategically located BPRs with redundancy built in and the use of satellite communications as soon as cost-effective.

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