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USGS Tsunami Source Working Group (TSWG)

Program and Abstracts of the Second Tsunami Source Workshop: July 19–20, 2010

Compiled by W.H.K. Lee, S.H. Kirby, and M.F. Diggles

Open-File Report 2010-1152

U.S. Department of the Interior
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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia 2010

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Suggested citation
Lee, W.H.K., Kirby, S.H., and Diggles, M.F., compilers, 2010, Program and abstracts of the Second Tsunami Source Workshop; July 19-20, 2010: U.S. Geological Survey Open-File Report 2010-1152, 33 p. [*http://pubs.usgs.gov/of/2010/1152/*].

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Introduction

In response to a request by the National Oceanic and Atmospheric Administration (NOAA) for computing tsunami propagations in the western Pacific, Eric Geist asked Willie Lee for assistance in providing parameters of earthquakes which may be future tsunami sources. The U.S. Geological Survey (USGS) Tsunami Source Working Group (TSWG) was initiated in August 2005. An ad hoc group of diverse expertise was formed, with Steve Kirby as the leader. The founding members are: Rick Blakely, Eric Geist, Steve Kirby, Willie Lee, George Plafker, Dave Scholl, Roland von Huene, and Ray Wells. Half of the founding members are USGS emeritus scientists.

A report was quickly completed because of NOAA's urgent need to precalculate tsunami propagation paths for early warning purposes (Kirby and others, 2005).

It was clear to the group that much more work needed to be done to improve our knowledge about tsunami sources worldwide. The group therefore started an informal research program on tsunami sources and meets irregularly to share ideas, data, and results. Because our group activities are open to anyone, we have more participants now, including, for example, Harley Benz and George Choy (USGS, Golden, Colo.), Holly Ryan and Stephanie Ross (USGS, Menlo Park, Calif.), Hiroo Kanamori (Caltech), Emile Okal (Northwestern University), and Gerard Fryer and Barry Hirshorn (Pacific Tsunami Warning Center, Hawaii). All participants automatically become "members," and if anyone is interested, just send an email to Willie Lee at: *whklee@usgs.gov* for inclusion in our membership list.

To celebrate the fifth anniversary of the TSWG, a workshop is being held in the Auditorium of Building 3, USGS, Menlo Park, on July 19-20, 2010 (Willie Lee and Steve Kirby, Conveners). All talks (except one) will be video broadcast. The first tsunami source workshop was held in April 2006 with about 100 participants from many institutions. This second workshop (on a much smaller scale) will be devoted primarily to recent work by the USGS members. In addition, Hiroo Kanamori (Caltech) will present his recent work on the 1960 and 2010 Chile earthquakes, Barry Hirshorn and Stuart Weinstein (Pacific Tsunami Warning Center) will present their work on tsunami warning, and Rick Wilson (California Geological Survey) will display three posters on tsunami studies by him and his colleagues.

Reference

Kirby, S., Geist, E., Lee, W.H.K., Scholl, D., and Blakely R., 2005, Tsunami source characterization for western Pacific subduction zones; a preliminary report, prepared at the request of the National Oceanic and Atmospheric Administration for their Tsunami Hazards Reduction Program: U.S. Geological Survey Administrative Report.

Scientific Program for the Second Tsunami Source Workshop

Willie Lee and Steve Kirby, Conveners

July 19, 2010 (Monday Afternoon)

1:30 – 1:35 Tom Brocher (Director, USGS Earthquake Science Center): Welcome

1:35 – 1:45 Steve Kirby and Willie Lee (USGS): Introduction to the USGS Tsunami Source Working Group.

1:45 – 2:15 Dave Scholl (USGS): Comparing the contrasting rock frameworks of the Sumatra and south-central Chile convergent margins—insights gained about the sediment subduction setting of great and giant megathrust ruptures.

2:15– 2:45 Roland von Huene (USGS): Subducted ocean crustal relief bracketing the 2010 Chilean earthquake rupture, implications for large earthquake ruptures.

2:45 – 3:30 Poster viewing and Break.

3:30 – 4:30 Special Earthquake Seminar by Hiroo Kanamori (Caltech): Revisiting the 1960 Chilean earthquake (for a general geoscience audience).

July 20, 2010 (Tuesday)

9:00 – 9:30 Holly Ryan (USGS): Selecting a scientifically defensible Aleutian megathrust rupture for the Multi-hazards Demonstration Project tsunami scenario (by Ryan & TSWG).

9:30 – 10:00 Rick Blakely (USGS): Forearc geology from free-air gravity: implications for co-seismic slip during the 2010, 1985, and 1960 Chile earthquakes (by Blakely, Wells, and Keranen).

10:00 – 10:30 Poster viewing and Break.

10:30 – 11:00 Eric Geist (USGS): Tsunami edge waves in relation to the 2010 Chile earthquake.

11:00 – 11:30 Barry Hirshorn (PTWC): Earthquake source characterization for tsunami warning (by Hirshorn & Weinstein).

11:30 – 12:00 Tom Parsons (USGS): Tsunami probability in the Caribbean region (by Parsons and Geist).

12:00 – 1:00 Lunch Break.

1:00 – 1:30 Steve Kirby (USGS): Off-trench earthquakes and their tsunami potential (by Kirby and Wartman).

1:30 – 2:00 Willie Lee (USGS): Reliable earthquake location using grid-search and simplex algorithm.

2:00 – 2:30 George Choy (USGS): Anomalous Eo/Mo earthquakes: Trends and exceptions to the trends (by Choy & Kirby).

2:30 – 3:30 Poster viewing and Break.

3:30 – 5:00 Hiroo Kanamori (Caltech): Comparison of the 2010 Maule earthquake and the 1960 Valdivia earthquake with extensive discussions. {This talk & discussions are informal, without video broadcast.}

Posters (Displayed throughout the Workshop).

Willie Lee and Steve Walter (USGS): The USGS Seismic Data Library in Menlo Park.

George Plafker and J. C. Savage (USGS): Comparisons of Near-Field Tsunami Characteristics of Giant (M>9) Earthquakes in Chile (1960), Alaska (1964), and Sumatra (2004).

Rick Wilson (CGS) and others: Development of new databases for tsunami hazard analysis in California.

Rick Wilson (CGS) and others: New maximum tsunami inundation maps for use by local emergency planners in the State of California, USA..

Rick Wilson (CGS) and others: The 2010 Chilean tsunami on the California coastline.

Aurelie Guilhem and Doug Dreger (U.C. Berkeley): Towards a realtime earthquake source determination and tsunami early warning in Northern California

Ray Wells, Rick Blakely, and Dave Scholl, (USGS): Subduction zone structure revealed by free-air gravity and its relation to slip in great earthquakes - evidence from recent events

Seismicity of the Earth 1900-2007, U.S. Geological Survey Scientific Investigations Map 3064, 2010.

Jakob Wartman, Steve Kirby, Kita Saeko, and George Choy: A global outer-rise/outer-trench-slope (OR/OTS) earthquake study: Trends and exceptions to the trends, 2009 Fall AGU Poster.

List of Participants in the 2nd Tsunami Source Workshop, July 19-20, 2010

This list is prepared from the signed up sheets for the Workshop. However, some participants did not sign in. In particular, over 100 people attended the Earthquake Seminar given by Prof. Hiroo Kanamori, which was a part of the Workshop.

We wish to thank the webcast and projection team: Susan Garcia, Sam Arriola, Luke Blair and Scott Haefner, for their excellent work.

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Abstracts for The Second Tsunami Source Workshop

All USGS authors were required to submit an abstract for publication approval, as the workshop's program and abstracts will be released as a USGS Open-File Report.

Abstracts are arranged in the order of presentation at the Workshop. The last two posters are by USGS authors that have publication approval already, as they had been released before.

1. Comparing the Contrasting Rock Frameworks of the Sumatra and South-Central Chile Convergent Margins — Insights Gained About the Sediment Subduction Setting of Great and Giant Megathrust Ruptures

By David W. Scholl, USGS Emeritus

Textbooks commonly show that a wide (>50-100 km) body of accreted ocean-floor sediment is characteristic of underthrust margins. But modern offshore data demonstrate that large accretionary masses only occur along ~25 percent of the global length of subduction zones and only along those bordered by trenches that for many tens of millions of years have been thickly (>1-1.5 km) filled with sediment. The accretionary margin thickens and widens seaward. The seaward end of the margin's framework of older basement rock thus lies much closer to the coastal area than the trench. A prominent example of an accretionary margin is the greater Sumatra (Andaman-Sumatra-west Java) subduction zone. This lengthy margin repeatedly nucleates great ($M_w \geq 8$) or giant ($M_w \geq 9$) megathrust earthquakes, for example, the giant December 26, M_w9.0 event of 2004 and the nearby great M_w8.8 rupture of March 2005.

The more typical structural fabric of a convergent margin is characterized by the seaward continuation of coastal basement rock nearly to the trench axis. These nonaccreting or erosive margins gradually narrow and thin. A typical example of a nonaccreting margin is the Chile subduction zone. The south-central sector of this margin, between the Juan Fernandez Ridge to the north (33° S) and the South Chile Rise to the south (46° S), is bordered by a trench thickly flooded (>1.5-2.0 km) with glacial-age sediment. Offscraping of these deposits has built a narrow (10-25 km wide) frontal prism at the seaward end of the margin's late Paleozoic (~300 Ma) basement rock. This specific sector of the global length of subduction zones spawned the largest instrumentally recorded megathrust earthquake, the giant M_w9.5 of 1960, and, 50 years later, the destructive M_w8.8 rupture of February 27, 2010. Charles Darwin, upon his arrival in Chile in 1835, was greeted by an earlier earthquake of similar magnitude.

Evidently, with respect to the tendency of a sector of subduction zone to break in great and giant megathrust earthquakes, the fabric and fabrication of the margin's rock and sedimentary architecture are not determining factors. The accretionary greater Sumatra and nonaccretionary south-central Chile subduction zones are, however, both bordered by a sediment-charged trench. Subduction of the greater part of the trench fill inserts a 1-2-km thick layer of clastic material into the subduction channel that separates the upper and lower plates at both convergent margins. Megathrust rupturing occurs within or along the top of the subduction channel. Two decades ago Larry Ruff (1989) posited that sediment subduction tends to smooth interplate roughness, thus facilitating lateral continuation of between-plate rupturing, a circumstance that identifies occurrence areas of repeated great and giant megathrust earthquakes. The contrasting rock frameworks of the high-magnitude earthquake habitats of the greater Sumatra and south-central Chile subduction zones—yet similar settings of abundant sediment subduction—are consistent with the Ruff conjecture.

Reference

Ruff, L.J, 1989, Do trench sediments affect great earthquake occurrence in subduction zones?: Journal of Pure and Applied Geophysics, v. 129, nos. 1/2, p. 263-282.

2. The 2010 Great Chilean Earthquake and Modern Geophysical Data

By Roland von Huene, USGS Emeritus

The high-quality modern geophysical data acquired before the 2010 Chilean earthquake greatly facilitated an understanding of the geology that may have constrained earthquake rupture. The 2010 Chilean rupture was bracketed by subducting ocean crust features clearly resolved in multibeam bathymetry. On the north is a volcanic ridge continuing landward beneath the margin as a ridge in the plate interface. The subducted ridge is 1 to 3 km high, and the upper plate above it has clear sea-floor expression. The southern feature is a well-imaged fracture zone across the sea floor but is not well constrained once it subducts. The 20-km-wide fracture zone is flanked by rugged sea floor, and its thinned crust is weakened by multiple fractures. Both the northern and southern bracketing features have been earthquake asperities in the past, showing that subducted lower plate relief can be an asperity at one time as well as a barrier at another.

The Alaska margin's Kodiak segment also has subducting relief that corresponds with the 1964 earthquake nucleation and slip. However, the geophysical data are not nearly as good as those along Chile. The adjacent 1938 Shumagin rupture area corresponds with the subducted Zodiak deep-sea fan. If this is a repeated rupture area, the contrast in physical properties between sediment types may separate adjacent rupture areas. Modern geophysical data like those along the Chilean margin can advance understanding of earthquakes by combining the specific tectonics of a fault zone and the dynamics of its rupture from seismology.

3. Revisiting the 1960 Chilean Earthquake

By Hiroo Kanamori, Caltech (This work is in collaboration with Dr. Luis Rivera)

The 1960 Chilean earthquake is considered to be the largest earthquake in the last century, with M_w =9.5. This is in contrast to M_w=9.2 for the 1964 Alaskan earthquake. However, the determination of M_w for the Chilean earthquake was made with only a relatively small number of records, and because of the uncertainties in the source geometry, instrument constant, source finiteness etc., M_w is inevitably subject to large uncertainties. Since the difference of 0.3 in M_w translates to a factor of 3 in moment, if M_w =9.5 is correct, it has an important implication for tsunami excitation, the depth extent of faulting, and the strength of shaking on shore. Also, most studies using static deformation data suggest M_w =9.2, and the difference between the seismic and static estimates has been a matter of considerable debates. In view of these outstanding questions, we re-examined some of the existing seismic data using more recent knowledge on the dip angle, depth, and source finiteness.

Important new information came from the Isabella Benioff strainmeter of the 1960 Chilean earthquake. This is one of the most important historical seismograms because the first observations of the free oscillations of the Earth were made from this record (Benioff and others, 1961). Smith (1966) compared the normal mode spectra of the 1960 Chilean earthquake and the 1964 Alaskan earthquake observed with the Isabella strain meter. He concluded that the energy contained in the Chilean earthquake spectra recorded at Isabella is about 25 times larger than that of the Alaskan earthquake. However, since the fault geometries of these earthquakes were not well understood at the time, the spectral data could not be interpreted in terms of the source strength (e.g., seismic moment). With the help of Dr. Stewart Smith, we examined this data set by computing the extensional strain and spectrum at Isabella using the most up-to-date source geometries and the rupture finiteness. This is a relative comparison using the data obtained at the same location, with the same instrument and the same analysis method, and is more robust than the results obtained from individual records for each earthquake. The result suggests that the seismic moment of the Chilean earthquake is about 3 to 5 times larger than that of the Alaskan earthquake, which is consistent with many of the previous results.

Another important observation on the Isabella record which has not been investigated yet is the unusually large G wave and toroidal mode. Since the orientation of the Isabella strain rod is only 4.5° from the great circle path from Chile, the large amplitude G waves and toroidal modes are not expected if the mechanism of the 1960 Chilean earthquake is the traditional thrust mechanism. To explain this observation, significant right-lateral slip must be invoked.

These results together with the seismicity during a period of 32 hours preceding the main shock, the unusual nature of the immediate foreshock 15 min before the main shock, and some macro-seismic descriptions of the onset of the main shock suggest that the 1960 Chilean earthquake appears to have involved a long and extensive nucleation process and is very different from the ordinary megathrust events we have experienced during the past 50 years.

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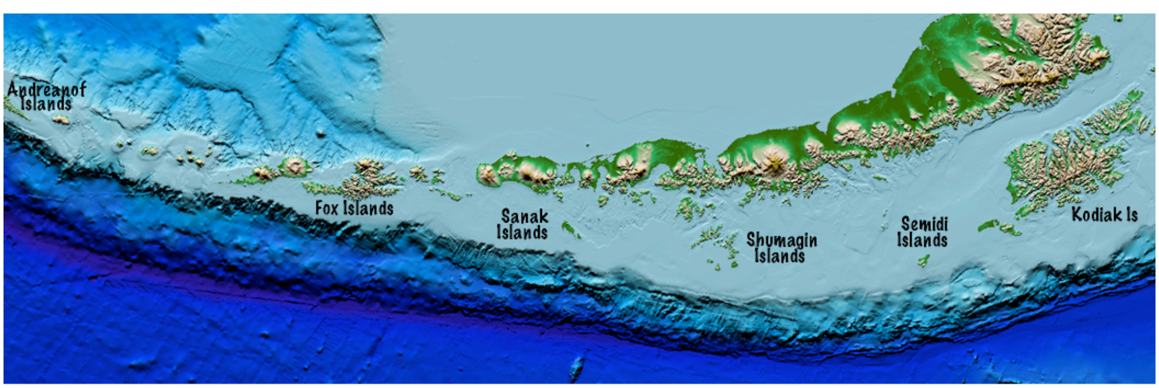
Smith, S., 1966, Free oscillations excited by the Alaskan earthquake: Journal of Geophysical Research, v. 71, p. 1183-1193.

4. Selecting a Scientifically Defensible Aleutian Megathrust Rupture for the Multi-Hazards Demonstration Project Tsunami Scenario

By Holly Ryan and the Tsunami Source Working Group, USGS

The main goal of the Multi-hazards Demonstration Project is to help communities reduce losses from natural hazards affecting southern California. A tsunami scenario is being planned for emergency managers in 2013 that will involve a tsunami striking the coast of California, resulting in damage to coastal structures and injuries to residents there. Owing to directivity effects, the most hazardous pan-Pacific tsunami that could have an impact on the Port of Los Angeles would be one spawned by a M_w>9 earthquake beneath the eastern Aleutian subduction zone. An earthquake of this magnitude requires a multisegment rupture of a significant area of the megathrust from west of the Fox Islands to Kodiak Island. In order to select the most probable earthquake source for the tsunami scenario, we present data that support (or not) a throughgoing rupture of the eastern Aleutian megathrust.

Historic megatsunamis have been spawned to the west of the proposed scenario area during the 1957 Andreanof earthquake and to the east during the 1964 Alaskan earthquake; the 1964 event ruptured both the Prince William Sound and Kodiak Island asperities. In the area between the 1957 and 1964 ruptures, global positioning system (GPS) data presently show little to no strain accumulation as measured on the Shumagin and Sanak Islands. Conversely, GPS data show that the subduction zone beneath a portion of the Fox and Semidi Islands is locked (Freymueller and others, 2008). We present a possible scenario for a multisegment rupture beneath the eastern Aleutian arc based on the historical earthquake record, gravity and magnetic data, and seismic reflection profiles. The scenario requires rupture across weakly locked segments of the arc. Questions that we would like to address include: Is there a minimum separation between locked segments that will allow an earthquake to break through a rupture-impeding patch? Can strain accumulation be time varying? Do earthquakes tend to rupture the same segments?



Reference

Freymueller, J.T., Woodard, H., Cohen, S., Cross, R., Elliott, J., Larsen, C., Hreinsdottir, S., and Zweck, C., 2008, Active deformation processes in Alaska, based on 15 years of GPS measurements, *in* Freymueller, J.T., Haeussler, P.J., Wesson, R., and Ekstrom, G., eds., Active Tectonics and Seismic Potential of Alaska: Washington, D.C., American Geophysical Union, Geophysical Monograph 179, p. 1-42.

5. Forearc Geology from Free-Air Gravity—Implications for Coseismic Slip During the 2010, 1985, and 1960 Chile Earthquakes

By Richard Blakely, Ray Wells, and Katie Keranen, USGS

The M_w 8.8 Chilean megathrust earthquake of 2010 occurred along the Chile trench between the Juan Fernandez Ridge and the Mocha Fracture Zone. Finite fault models of coseismic slip show that the 2010 rupture filled the gap between slip that occurred in the M_w 9.5 Valdivia earthquake of 1960 and the M_w 8.0 Valparaiso earthquake of 1985. We examine the distribution of coseismic slip in these earthquakes (which together ruptured the megathrust over a distance of 1,500 km) and compare the slip to crustal structure of the forearc as revealed by free-air gravity.

Gravity anomalies along the forearc consist of a profound gravity low along the trench and a paired gravity high along the Coast Range. Together, the two anomalies approximately bound the megathrust seismogenic zone. The structure of the anomalies appears to correlate with seismic behavior. Gravity and coincident multichannel seismic (MCS) profiles across the margin show that the trench gravity minimum is commonly displaced landward from the bathymetric trench axis and that the offset is proportional to the amount of sediment in the trench. Gravity offsets increase sharply south of the Juan Fernandez Ridge, where MCS data show a large increase in sediment thickness. The greatest slip during the 1960 and 2010 earthquakes occurred where gravity predicts thickest trench sediments.

Gravity and bathymetric gradients along the slope and shelf also outline a characteristic deep-sea terrace and its slope basins. The terrace rises southward toward the Concepción gravity high, caused by a Paleozoic plutonic terrane extending offshore to the trench. South of the Concepción high, forearc basin gravity lows extend to the triple junction and mark the locus of highest slip during the 1960 earthquake. The Concepción gravity high was a region of lesser slip in both 2010 and 1960 and acted as a boundary between high-slip regions, at least during this seismic cycle. Teleseismic finite fault slip models for the 2010 earthquake are variable but typically show two high-slip regions offshore, one near Concepción and one farther north, with more than 10 m of slip. Both coincide with offshore basins, but high slip extends onshore beneath the Coast Range gravity high in most models. These models are likely to evolve as more geodetic data become available, but it appears that forearc geology, as manifested by gravity anomalies, partially controlled the location of greatest slip during the 1960, 1985, and 2010 Chilean megathrust earthquakes.

6. Tsunami Edge Waves in Relation to the 2010 Chile Earthquake

By Eric Geist, USGS

Edge waves are a particular type of coastal wave trapped by refraction that propagate parallel to the coastline and share similar characteristics to Love waves in seismology (Sezawa and Kahai, 1939). In combination with scattering and resonance resulting from propagation along an irregular coastline, edge waves generally create a complex waveform in which the offshore amplitude, runup, and timing of the largest wave oblique to the earthquake rupture and in the far-field are difficult to predict (Geist, 2009). Instrumental (tide gauge) measurements of the broadside tsunami directly across from the rupture zone of interplate thrust earthquakes are typically dominated by the direct, nontrapped arrival (Geist, 2009). However, ancillary evidence from the 2010 Chile tsunami, including eyewitness observations of large-amplitude late arrivals and multiple onshore flow directions, suggest that edge waves broadside from the rupture zone may have been particularly strong for this tsunami.

The theoretical understanding of edge waves is based on simple shelf and slope geometries. Edge waves occur in distinct modes (*n*), with the fundamental mode (*n*=0), also known as the Stokes mode, the most commonly observed. For a semi-infinite sloping beach of slope β, the dispersion relation is (Ursell, 1952; Liu and others, 1998)

$$\omega_n^2 = gk_n \sin(2n+1)\beta, \qquad (2n+1)\beta < \pi/2, \tag{1}$$

where ω is the angular frequency and *k* the wavenumber. Snodgrass and others (1962) developed the propagation characteristics of edge waves along a flat shelf and distinguished between the discrete edge wave modes and leaky modes that occupy a continuous spectrum. Ishii and Abe (1980) consider a more complex case of edge waves along a stepped continental margin profile with an intervening linear slope and compare their results (dispersion relation and amplitude of fundamental mode edge wave) with those from the vertical step profile. The amplitude η of edge wave modes for a semi-infinite sloping beach is based on Laguerre polynomials $L_n(x)$ of order *n* and is of the form (González and others, 1995)

$$\eta_n(x,y) = Ae^{i(k_n y - \omega_n t)} e^{-k_n x} L_n(x). \tag{2}$$

For more general offshore slopes, the amplitude function is a solution to the confluent hypergeometric equation (Kummer's equation) (Ishii and Abe, 1980; Mei, 1989). In the case where the initial disturbance is located near the coast with the long axis oriented parallel to the coast, the fundamental mode edge wave (*n*=0) dominates (Liu and others, 1998; Fujima and others, 2000). This case is apropos for typical interplate thrust earthquakes, in which the vertical displacement field spans across and is oriented subparallel with the coastline.

Edges waves associated with the 2010 Chile tsunami are particularly prominent in numerical models of tsunami propagation, owing to the proximity of the initial disturbance to the coast and the relative smoothness of the coastline. Different slip distributions for the earthquake are examined in relation to the observations of edge waves in an attempt to understand why these waves are dominant in the broadside regime.

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Ursell, F., 1952, Edge waves on a sloping beach: Proceedings of the Royal Society of London, A, v. 214, p. 79-97.

7. Earthquake Source Characterization for Tsunami Warning

By Barry F Hirshorn and Stuart Weinstein, The Pacific Tsunami Warning Center

The Pacific Tsunami Warning Center (PTWC), located in Ewa Beach, Hawaii, is responsible for issuing tsunami warnings to the coastal populations of Hawaii, the Pacific Basin (exclusive of the U.S. West Coast and Canada), the Caribbean Basin (exclusive of Puerto Rico), and, on an interim basis, the Indian Ocean.

The PTWC must therefore rapidly detect, locate, and characterize the source of any potentially tsunamigenic earthquake as soon after the initiation of rupture as possible. Automated paging systems alert on-duty scientists to any M_w 5.5 or larger earthquake occurring worldwide. Real time phase associators provide preliminary hypocenters for review by the on-duty scientists. We then calculate a suite of traditional amplitude-based magnitudes such as M_b, M_S, as well as the broadband P-wave moment magnitude, M_{wp}, from the P or pP wave broad band velocity seismograms (Tsuboi and others, 1995, 1999). This method is based on the assumption that the integrated far-field p-wave displacement is a proxy for the earthquake's source time function, and works well for regional and teleseismic events (Tsuboi and others, 1999; Whitmore and others 2002; Hirshorn and Tsuboi, 2004).

However, for some complex earthquakes, for example the M_w 8.4 (GCMT) Peru earthquake of June 21, 2001, M_{wp} underestimates M_w if the first moment release is not the largest. In addition, for truly Great earthquakes, like the M_w 9.5 Chile event of 1960, this method will severely underestimate M_w. For these larger earthquakes, duty scientists also routinely estimate M_m, a very long period surface wave magnitude based on mantle waves with periods in the range 50–410 s (Okal and Talandier, 1989). We have also recently begun testing the W-phase method (Kanamori and Rivera, 2008) to enable rapid M_w estimation (and CMT determination) for Great earthquakes, and for slow ("Tsunami") events. To detect slow earthquakes, we also compare multiple magnitude estimates at different periods, $M_w(M_m)$ as a function of period, and the appearance of M_{wp}'s "pseudo" source time function (a proxy for the source time function without rigorous corrections for path and reciever effects).

PTWC duty scientists also compute the quantity $\log_{10}(Er/Mo)$, known as "Theta," where Mo is the seismic moment (Aki, 1966). Newman and Okal (1998) showed that Theta is anomalously small for tsunami earthquakes. In addition we are testing (personal communication) Andy Newman's cumulative energy method which is also helpful for detecting slow "Tsunami" events.

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8. Tsunami Probability in the Caribbean Region

By Tom Parsons and Eric L. Geist, USGS

We calculated tsunami-runup (in excess of 0.5 m) probability at coastal sites throughout the Caribbean region. We applied a Poissonian probability model because of the variety of uncorrelated tsunami sources in the region. Coastlines were discretized into 20-km by 20-km cells, and the mean tsunami runup rate was determined for each cell. The ~500-year empirical record compiled by O'Loughlin and Lander (2003) was used to calculate an empirical tsunami probability map, the first of three constructed for this study. However, it is unclear whether the 500-year record is complete, so we conducted a seismic moment-balance exercise, using a finite element model of the Caribbean-North American plate boundaries and the earthquake catalog, and found that moment could be balanced if the seismic coupling coefficient is c=0.32.

Modeled moment release was therefore used to generate synthetic earthquake sequences to calculate 50 tsunami runup scenarios for 500-year periods. We made a second probability map from numerically calculated runup rates in each cell. Differences between the first two probability maps based on empirical and numerical-modeled rates suggest that each captured different aspects of tsunami generation; the empirical model may be deficient in primary plate-boundary events, whereas numerical model rates lack back-arc fault and landslide sources. We thus prepared a third probability map using Bayesian likelihood functions derived from the empirical and numerical rate models and their attendant uncertainties to weight a range of rates at each 20-km by 20-km coastal cell. Our best-estimate map gives a range of 30-year runup probability from 0 to 30 percent regionally.

9. Large Off-trench Earthquakes and Their Tsunami Potentials

By Stephen Kirby, Jakob Wartman, and George Choy, USGS

Earthquakes that occur seaward of trenches and distant from triple junctions are generally associated with flexure of oceanic lithosphere in the outer-rise/outer-trench-slope region and hence represent the seismic moment release component of flexural strain rate. Such earthquakes are generally very shallow, occurring within 5 to 20 km of the sea floor, depending on the plate age and other factors, and are the result of normal faulting that occurs above the outer plate bending fiber. About one in six off-trench events occur at greater depths and represent compressional failure at depths below the 3-D neutral flexural surface. Such events tend to occur close to the trench, whereas the shallower normal-faulting earthquakes occur from the outer rise to the mid-outer-trench slope. Compressional events, owing to their greater depth of occurrence and much smaller maximum moment magnitudes ($M_w \leq 7.2$) and cumulative moment release (< 1 percent of total moment for normal-faulting shocks) represent little or no tsunami hazard.

Great ($M \geq 8$) off-trench normal-faulting earthquakes are rare (with 5 confirmed in the instrumental era: 1917 Tonga *M*~8; 1933 Japan *M*8.6; 1977 Banda *M*8.3; 2007 Kuriles *M*8.1; and 2009 Tonga *M*8.1) and their ground-motion effects usually do not affect the nearest shores because of their great distances offshore. Their geohazard importance stems from producing large tsunamis. The plate-tectonic settings of these events share some common features: (i) All have occurred in subduction systems in which convergence rates are greater than about 65 mm/a and the incoming oceanic plate is old (Mesozoic), thermally mature, and, by inference, mechanically thick. Sea-floor bending strains and strain rates estimated from these observations are high. (ii) Large outer-rise gravity anomalies attest to high bending stresses in these source regions. (iii) Focal mechanisms indicate that the ruptures cross ocean spreading fabric at angles greater than 30 degrees and, in the two cases for which there are high-resolution swath maps available, they have fault scarps with significant relief and individual scarp lengths >100 km. (iv) For those events for which seismological constraints on depth and/or focal mechanisms are available, they show that these earthquakes are very shallow normal-faulting ruptures (< 20 km below the sea floor). These common features of great off-trench earthquakes are consistent with a model of shallow seismic deformation by large-scale bending at high stresses and strain rates. That such events occur in deep water and involve steeply-dipping (≥45°) dip-slip ruptures is consistent with the larger tsunami runups and greater damage and loss of life than are expected from megathrust earthquakes of comparable magnitudes.

These common features of source regions for great off-trench earthquakes are used to identify potential sites for future great off-trench earthquakes that share the above attributes. More than 15,000 km in total of subduction margin in the western subduction margin of the Pacific Plate and the northeastern Indian Plate subduction margin in eastern Indonesia share these characteristics. Methods are also suggested for estimating the rates of slip accumulation and average recurrence times of such earthquakes. These estimates suggest millennial return times in any one trench sector and global occurrences of great off-trench earthquakes every few decades, as has been observed.

10. Reliable Earthquake Location Using Grid-Search and Simplex Algorithm

By W.H.K. Lee, USGS Emeritus

Most tsunamis are generated by shallow earthquakes offshore, and accurate earthquake locations are important to study their tectonic settings and propagation paths.

Most commonly used algorithms for locating earthquakes on computers are based on an inverse formulation (Geiger, 1912). Numerous software implementations have been made using the Geiger method, which applies the Gauss-Newton nonlinear optimization technique to find the origin time and hypocenter by iterative linearized steps starting from a trial solution (for example, Lee and Stewart, 1981). Recent advances in earthquake location methods are mostly concentrated on obtaining the best relative locations for a group of earthquakes using high-quality data (including waveforms) recorded by a dense seismic network (for example, Waldhauser and Ellsworth, 2000; Richards and others, 2006). However, Geiger-like location programs do not work well for poorly constrained earthquakes, because the available arrival times may not be sufficient to solve the inverse problem, and the chosen trial solution may lead to a local minimum.

A physical problem involving observations is much more easily solved by a forward or direct formulation, if the large amounts of computations required can be managed. Recently, computers became fast enough that the forward approach has been explored (for example, Sambridge and Kennett, 2001; Oye and Roth, 2003; Lee and Baker, 2006). Computation is intensive, but a robust solution can be found in about 100 seconds on a PC for a typical case, along with a 3-D residuals map for visualizing the solution’s uncertainty. This direct approach has three major advantages over the inverse formulation: (1) a global minimum in the solution space can be obtained, (2) the computation is simple and straightforward, and (3) it can be adapted to perform either an L1-norm or L2-norm minimization.

A general software package was developed specifically for locating earthquakes occurring before 1963, when the available phase data were highly variable in quality, the distributions of the recording stations were highly nonuniform, and many earthquakes occurred outside existing seismic networks (Lee and Baker, 2006). It is called JLOC, and was coded in Java by Doug Dodge. Instead of a brute grid search, we use the downhill simplex algorithm to search the neighborhood of thousands of grid points that coarsely cover the solution space. The downhill simplex algorithm was chosen for its robustness (Press and others, 1986).

I have applied it to locate two earthquakes—the 1920 offshore Hualien earthquake and the 1907 offshore Sumatra earthquake. Although the uncertainty is still large, the relocated hypocenters are reliable because the entire solution space (10º x 10º x 300 km) was searched at a 10-km interval grid and the simplex algorithm was used to “home in” the final solution by L1-norm minimization and rejection of outliers. In the case of the 1907 offshore Sumatra earthquake, the relocated hypocenter differs significantly from the Gutenberg and Richter (1954) location and is consistent with the observed tsunami data (Kanamori and others, in press).

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11. Anomalous E_s/M_o Earthquakes: Trends and Exceptions to the Trends

By George L. Choy and Stephen H. Kirby, USGS

Global studies of shallow earthquakes (magnitude > 5.5 and depth < 70 km) have found that, for a given seismic moment M_o, the radiated energy E_S of an earthquake can range over two orders of magnitude. The global distribution of events that are either anomalously elevated or anomalously depleted in energy turns out to be nonrandom and may provide insight into the variation of seismogenic conditions. Recent work has found that earthquakes with unusually elevated radiated energy (as measured by apparent stress $\tau_a > 1.0$ MPa, where $\tau_a = \mu E_S / M_0$) are characteristic of high-deformation tectonic settings such as intraplate near regions of plate reorganization and intraslab at slab bends or slab collisions, an observation which can lead to improving estimates of seismic hazard potential. In contrast, the overall population of thrust earthquakes in the vicinity of subduction zones has the lowest average τ_a among plate-boundary earthquakes. This is consistent with the idea that the plate interface is generally a mature fault, having suffered large cumulative slip over time. Nevertheless, within the population of subduction plate-boundary earthquakes, there is considerable variability in the E_s/M_o ratio. For instance, the subset of very large ($M > 7.5$) earthquakes with anomalously low E_s/M_o ratio (or, equivalently, a magnitude differential $\Delta M > 0.5$, where ΔM is the difference between energy magnitude M_e and moment magnitude M_w) has been associated with destructive tsunami events involving slow rupture. In contrast, a global reconnaissance of the radiated energies of more than 1,500 large shallow thrust earthquakes that occurred from 1987 to 2008 at subduction zones found 152 earthquakes with anomalously high energy radiation (that is, having $\tau_a > 1.0$ MPa or, equivalently, ΔM values less than about –0.2). High-energy events occur in high-deformation regimes such as collisions of oppositely subducting slabs, submerged continent-continent collisions, and regions of slab distortion. Some of these events may be intraslab on the basis of their greater depths compared to shallower events that are presumed to be on subduction boundaries.

This reconnaissance also found 308 additional earthquakes with anomalously low E_s/M_o comparable to that associated with slow tsunami earthquakes. The majority of low-energy thrust events occur beneath forearc basins and not beneath frontal prisms, where some tsunami earthquakes are suspected to have originated. They are nearly always located at the top surface of a Wadati-Benioff zone that can be interpreted as the slab interface. They are found in three regimes, not all of which are tsunamigenic. Class I are the large events ($M > 7.5$) located near sediment-poor trench axes that have been associated with tsunami earthquakes involving slow rupture. Class II are smaller events deeper and further from the trench axis at sediment-rich subduction zones. Class III are events downdip of subducted fracture zones and ridges that may provide the mechanism to transport sediments down the plate interface. The locations of anomalously high- and low-energy subduction events do not typically commingle. The systematic spatial patterns for thrust, as well as normal-fault and strike-slip earthquakes, suggest anomalous E_s / M_o is an expression of stress and frictional conditions along and within a subduction boundary.

12. The USGS Seismic Data Library in Menlo Park

By Willie Lee and Steve Walter, USGS

The U.S. Geological Survey (USGS) Seismic Data Library is being reestablished in Menlo Park, California, in order to support the research being conducted by the USGS Tsunami Source Working Group. It turns out that the seismograms of pre-1990 earthquakes from the world's subduction zones are important to researchers seeking to understand where future tsunamigenic earthquakes might occur and how big they might be.

The USGS Seismic Data Library was first established as a "project" in the early 1970s, when the Earthquake Mechanism Laboratory of the National Oceanic and Atmospheric Admnistration (NOAA) in San Francisco merged with the USGS National Center for Earthquake Research in Menlo Park. Willie Lee was assigned as its project chief in 1976, and the library grew to be one of the largest archives of seismograms, seismic station bulletins, and related materials from around the world. Following an internal reorganization of the USGS, this Data Library was abandoned around 1996. The seismogram collection of WWSSN (Oliver and Murphy, 1971) with about 5 million 70-mm film chips was sent to the USGS Albuquerque Seismological Lab (ASL), and seismograms from the California Seismic Network (Calnet) were moved to USGS storage. Some of the seismic station bulletins (mostly pre-1940) were saved by Lee to the extent that his garage could hold, and the rest of the holding—including large quantities of magnetic tapes and punched cards, and most of the seismic station bulletins—was discarded.

In 2009 the Data Library acquired a nearly complete collection of more than 18,000 35-mm microfilms of the WWSSN seismograms from the Pasadena Seismic Laboratory spanning the period from 1964 to 1977. They are equivalent to the 70-mm film chips at ASL, but are on film rolls. We also have a good subset of the microfilms from the Historical Seismogram Filming Project (in which about 500,000 seismograms from 1890s to 1963 were microfilmed; Lee and others, 1988)—about 460 16-mm film rolls, and around 600 35-mm film rolls. In order to view and digitize this collection of microfilm records, we recently purchased a Konica-Minolta MS7000 Microform Scanner, which is designed to view and scan microfilm rolls.

More recently, we obtained a collection of worldwide seismic station bulletins from the University of California Berkeley Seismological Laboratory. Combined with what Lee had saved in his garage, this will make a fairly complete collection, probably the most complete set in the United States. Because of lack of funding, most of this collection is yet to be sorted and cataloged.

Modern digital seismograms of adequate global coverage are available only since 1990, and we must use the WWSSN and historical seismograms to study earthquakes before 1990. At present, USGS Golden has a complete collection of the historical seismograms, and USGS Albuquerque has a complete collection of the WWSSN seismograms. Although not 100-percent complete, we have both the WWSSN and historical seismograms in Menlo Park. In addition, we have an extensive collection of seismic station bulletins that are necessary to make use of these seismograms. Our effort is also supporting of the international SeismoArchives project (*http://www.iris.edu/seismo/*; Lee and Benson, 2008).

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13. Comparisons of Near-Field Tsunami Characteristics of Giant (*M*>9) Earthquakes in Chile (1960), Alaska (1964), and Sumatra (2004)

By George Plafker and J.C. Savage, USGS Emeriti

The M_W 9.5 Chile earthquake sequence (May 21–22, 1960), the largest instrumentally recorded seismic event in history, was generated by a megathrust rupture of the southern end of the Peru-Chile Arc about 850 km long and 60–150 km wide down dip. Within Chile, the earthquake and tsunami took more than 2,000 lives and caused ~$550 million in property damage. The trans-Pacific tsunami killed an additional 230 people and caused an estimated $125 million damage in Japan, Hawaii, and the Philippine Islands. Regional coseismic surface displacements occurred over ~170,000 km^2 between the Chile Trench and volcanic arc.

The displacements are characterized by a broad asymmetric downwarp of as much as –2.3 m between the mainland coast and the volcanic arc and a contiguous zone of upwarp of as much as 5.8 m that includes part of the Arauco Peninsula on the mainland coast and several offshore islands. The aftershock distribution suggests that the zone of uplift extends seaward to the Chile Trench. Dislocation models of the vertical surface displacements and seismic data indicate average and maximum megathrust slip was about 20.3 m and 54 m, respectively, and average landward dip is estimated at ~20°. Coseismic offshore vertical displacements generated a near-field tsunami with measured runups to 15 m in Chile and the largest and most destructive trans-Pacific tsunami of modern times. At Isla Guafo and Isla Mocha the direction and timing of waves with the highest runup (15 m), together with dislocation models of the vertical displacements, are suggestive of one or more local intraplate splay fault sources at or near the edge of the continental shelf superimposed on the overall broad upwarp due to megathrust slip at depth.

The giant M_W 9.2 Alaska (March 27, 1964) and Sumatra (December 26, 2004) earthquakes are broadly similar to the Chile event in that (1) they ruptured major segments of the eastern Aleutian Arc (800 km long by 250–350 km wide) and Sunda Arc (1,200+ km long by 150–200 km wide) and (2) coseismic uplift offshore generated major near-field and far-field tsunamis to 13 m high in Alaska and as much as 36 m in Sumatra, where the 2004 event generated the deadliest tsunami in recorded history (169,000 deaths on Sumatra and 63,000 elsewhere throughout the Indian Ocean region). They differ significantly from the Chile event in that (1) they have much wider forearc and shelf regions (200+ km), (2) megathrust dips are much shallower (9º or less), (3) calculated maximum slip of 20–30 m is about 50 percent of that in the Chile event, and (4) major coseismic splay faults were involved in uplift and tsunami generation in the Alaska forearc and are inferred within the Sumatra forearc from intraplate seismicity and tsunami arrival times, heights, and periods recorded on Sumatra.

The data for all three of these giant earthquakes show that a fraction of the total fault slip can be partitioned between the gently dipping megathrust and intraplate splay faults that break relatively steeply to the surface. For tsunami generation, this means that the initial wave at the source can be higher and closer to shore than it would be for slip entirely on the megathrust, thereby significantly increasing hazards to inhabitants and property on nearby shores.

14. Development Of New Databases For Tsunami Hazard Analysis In California

By Rick I. Wilson[1], Aggeliki Barberopoulou[2], Jose C. Borrero[2,3], William A. Bryant[1], Lori A. Dengler[4], James D. Goltz[5], Mark R. Legg[6], Terilee McGuire[1], Kevin M. Miller[5], Charles R. Real[1], Costas E. Synolakis[2], and Burak Uslu[7]

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The California Geological Survey (CGS) has partnered with other tsunami specialists to produce two statewide databases to facilitate the evaluation of tsunami hazard products for both emergency response and land-use planning and development. A robust, State-run tsunami deposit database is being developed that compliments and expands on existing databases from the National Geophysical Data Center (Global) and the USGS (Cascadia). Whereas these existing databases focus on references or individual tsunami layers, the new State-maintained database concentrates on the location and contents of individual cores/trenches that sample tsunami deposits. These data provide an important observational benchmark for evaluating the results of tsunami inundation modeling. CGS is collaborating with and sharing the database entry form with other states to encourage its continued development beyond California's coastline so that tsunami deposits can be evaluated on a regional basis.

CGS is also developing an Internet-based, tsunami-source-scenario database and forum where tsunami source experts and hydrodynamic modelers can discuss the validity of tsunami sources and their contribution to hazard assessments for California and other coastal areas bordering the Pacific Ocean. The database includes all distant and local tsunami sources relevant to California starting with the forty scenarios evaluated during the creation of the recently completed statewide series of tsunami inundation maps for emergency-response planning. Factors germane to probabilistic tsunami hazard analyses (PTHA), such as event histories and recurrence intervals, are also addressed in the database and discussed in the forum. Discussions with other tsunami-source experts will help CGS determine what additional scenarios should be considered in PTHA for assessing the feasibility of generating products of value to local land-use planning and development.

15. New Maximum Tsunami Inundation Maps for Use by Local Emergency Planners in the State of California, USA

By Rick I. Wilson[1], Aggeliki Barberopoulou[2], Kevin M. Miller[3], Jim D. Goltz[3], and Costas E. Synolakis[2]

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A consortium of tsunami modelers, geologic-hazard-mapping specialists, and emergency-planning scientists has produced maximum-tsunami-inundation maps for California, covering most residentially and transient-populated areas along the State's coastline. The new tsunami-inundation maps are an upgrade over the existing maps for the State, improving on the resolution, accuracy, and coverage of the maximum anticipated tsunami-inundation line. Thirty-three separate map areas covering nearly one-half of California's coastline were selected for tsunami modeling using the Method of Splitting Tsunami (MOST) model. Based on a preliminary evaluation of over fifty local and distant tsunami-source scenarios, those with the maximum expected hazard for a particular area were input to MOST. The MOST model was run with a nearshore bathymetry-topographic grid resolution varying from three arc-seconds (90 m) and one arc-seconds (30 m), depending on availability. Maximum tsunami "flow depth" and inundation layers were created by combining all modeled scenarios for each area. A method was developed to define better the location of the maximum inland penetration line using higher-resolution digital onshore topographic data from interferometric radar sources. The final inundation line for each map area was validated using a combination of digital stereo photography and fieldwork. One-hundred and thirty inundation maps were made available at *www.tsunami.ca.gov*. Local governmental agencies have used these tsunami inundation maps to develop or update their evacuation routes and emergency response plans. The State will continue to evaluate the tsunami-inundation hazard for the State by comparing the existing mapping and modeling results to inundation modeling using newly completed high-resolution (10 m) bathymetry-topographic grids, ongoing evaluation of tsunami sources (seismic and submarine landslide), and comparison to the location of recorded paleotsunami deposits.

16. The 2010 Chilean Tsunami on the California Coastline

By *Rick I. Wilson[1], Lori A. Dengler[2], Mark R. Legg[3], Kate Long[4], and Kevin M. Miller[4]

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At 2:55 AM PDT, a little over four hours after the Chilean earthquake origin time, the West Coast Alaska Tsunami Warning Center placed the entire California coast in a Tsunami Advisory. The Advisory forecast tsunami amplitudes ranging from approximately 0.3 to 1.4 meters and strong currents in bays and harbors. Hourly conference calls were held with the county operational areas and most counties cleared beaches and limited access to harbor areas. The highest amplitudes were predicted for San Luis Obispo County and areas south. The tsunami initially arrived at San Diego at 12:02 PM on February 27, and moved progressively up the coast over the next hour and a half. Peak recorded amplitudes (above normal tidal conditions) at tide gauge locations in the State ranged from 0.12 meters in San Francisco Bay to a high of 0.91 meters at Santa Barbara; the largest observed amplitudes were over one meter at Pismo Beach. At most locations, the strongest surges were recorded within the first two hours but for some locations, like Crescent City and Santa Barbara, the largest surge occurred 5–6 hours after the initial onset. At many locations, the tsunami activity lasted for more than a day, and in some areas it exacerbated ambient flooding from severe storm activity. Harbors in southern and central California received the most impact by estimated tsunami currents ranging from five to 15 knots, with minor to moderate damage occurring in several areas. The damage to docks, boats, and harbor infrastructure in California is estimated to be several million dollars. Estimated (from videos and eye-witness accounts) and recorded (instrumented) tsunami-current velocities could provide an important validation and (or) calibration tool for numerical tsunami-modeling methods and databases of existing model runs.