Appendix A. Sources of Historic and Prehistoric Tsunami Data

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A.1 Sources of Historic and Prehistoric Tsunami Data

Historic tsunami and paleotsunami data are important for assessing the tsunami hazard of a region. The past record provides clues to what might happen in the future, such as frequency of occurrence and maximum wave heights. These data can also be used to validate and calibrate tsunami inundation and propagation models and provide guidance for tsunami warning centers.

Tsunamis have been reported since ancient times. The first historically recorded tsunami occurred off the coast of Syria in 2000 B.C. and caused many casualties and destruction. The completeness of the data for a particular region depends on population and settlement patterns and the length of the written record for that area. Paleotsunami data are compiled from geologic evidence found in sediment data. These data can extend the record back several thousand years. This is particularly important for regions where the recurrence intervals of tsunamigenic earthquake sources are longer than the historic record. The Cascadia subduction zone off the U.S. Pacific northwest coast is an example of this type of situation. Evidence for the last large earthquake that generated a major tsunami on this fault zone was in 1700, prior to the written record for that region.

Since tsunami waves are affected by variations in topography and bathymetry near the coast, accurate bathymetric and topographic databases are also necessary for tsunami hazard assessment and are used to validate and calibrate tsunami inundation and propagation models.

The NOAA/National Geophysical Data Center is one of three environmental data centers within the National Environmental Satellite, Data and Information Service (NESDIS). NGDC also operates the World Data Centers for Marine Geology and Geophysics and Solid Earth Geophysics. Operating both World and National Data Centers, WDC/NGDC acquires, processes, and distributes global data for marine and terrestrial environments. WDC/NGDC also has a major role in the post-event data collection (including the compilation, cataloging, and synthesis) of all available information on tsunami sources and effects to support modeling, engineering, planning and educational purposes.

A.1.1 Topography and bathymetry

Tsunami waves are very sensitive to variations in nearshore topography and bathymetry. To accurately model tsunami inundation in a given coastal region, it is therefore necessary to have high resolution digital elevation models (DEM) of merged topography and bathymetry referenced to a common vertical datum. These DEMS are compiled from a variety of data sources, ranging from data collected recently with GPS navigation and multibeam sensors to data collected in the 1800s with lead lines. Currently, the best data available for nearshore areas are collected using airborne Light Detecting and Ranging (LiDAR) technology. In some cases, areas must be resurveyed to provide the data coverage and quality required to construct the DEMs. NOAA is developing accuracy standards for DEMs used as input for tsunami modeling.

If tsunami hazard assessment at a given location involves local earthquake events that would cause vertical displacements (up or down) of the topography and nearshore bathymetry within the inundation zone, then the DEMs used in the tsunami models need to be adjusted for these displacements.

A,1.1.1 NGDC Topography and bathymetry

NGDC supports NOAA's tsunami inundation modeling efforts by developing high-resolution bathymetric/topographic inundation DEMs for select U.S. coastal regions. and the DEMs used in the Method of Splitting Tsunami (MOST) model developed by NOAA's Pacific Marine Environmental Laboratory (PMEL) to simulate tsunami generation, propagation, and inundation.

(http://www.ngdc.noaa.gov/mgg/inundation/tsunami/)

The DEMs are developed using the best available shoreline, bathymetric, topographic, and shoreline-crossing data obtained from numerous federal and state government agencies, academic institutions, and private companies. Data sources include the U.S. National Ocean Service (NOS), the U.S. Geological Survey (USGS), the U.S. Army Corps of Engineers (USACE), the Federal Emergency Management Agency (FEMA), and other federal, state and local government agencies and academic institutions. DEMs are referenced to the vertical tidal datum of mean high water (MHW) and horizontal datum of World Geodetic System 1984 (WGS84). DEM resolution varies from 1/3 arc-second (~10 meters) to 3 arc-seconds (~90 meters).

Data sets used in DEM compilations must be assessed for quality and accuracy both within each dataset, and between datasets to ensure consistency and gradual topographic transitioning along the edges of data sets. The data are collected by numerous methods, in different terrestrial environments, and at various scales and resolutions. For some significant bathymetric and topographic features there are no digital data, necessitating hand digitizing of these features for inclusion in the DEMs.

NGDC has completed grids for Mayaguez, Puerto Rico; Myrtle Beach, South Carolina; Cape Hatteras, North Carolina; Port San Luis, California, and Dutch Harbor, Alaska. The metadata, DEM, and DEM development report for these areas are available online. Figures 1 to 4 show the scheduled year of completion for other U.S. coastal areas.

NGDC maintains and distributes other bathymetric/topographic data collections including the ETOPO2 two-minute gridded global relief database, the Global Land One-km Base Elevation (GLOBE) 30-second gridded land topography data, the Marine Trackline Geophysics database which contains bathymetric, magnetic, gravity and seismic navigation data collected during marine cruises from 1953 to the present, and the National Ocean Service Hydrographic Database (NOSHSD) which provides extensive survey coverage of the coastal waters and Exclusive Economic Zone (EEZ) of the United State and its territories. The NOSHDB (Figure 5) contains hydrographic survey data digitized from smooth sheets completed between 1851 and 1965, and from survey data acquired digitally on NOS survey vessels since 1965.

A.1.2 Tides and sea-level anomalies

The tides have sufficient range along most U.S. coastlines to necessitate taking them into account when doing tsunami hazard assessment. High resolution bathymetric data compiled to develop DEMs for use in tsunami modeling are referenced to different tidal datums. All data must be converted to a common vertical datum, using relative water level information available from tide gages in the area of the DEM. NOAA is currently

assessing the spatial distribution of U.S. tide gage stations that are needed for DEM development.

Another aspect that is included in probabilistic calculations of tsunami wave heights is the variation in background water levels caused by the tides and other sea-level fluctuations. Tsunamis are long sequences of waves that often persist for several days after the first wave in the sequence arrives at a coastal site. Modulating the tsunami wave crests and troughs are the local tides which may be small in range compared with the largest expected tsunamis, but relatively significant for the later waves in the sequence. Assuming a linear superposition of the tsunami waves with the tides, probabilistic calculations can be made of the tidal effects as a function of tsunami amplitude.

Storm-event, seasonal, El Niño and interannual variations in sea level can change the background water level upon which tsunami events occur; they therefore need to be assessed and included in probabilistic calculations for tsunami hazard assessment.

Long-term sea level rise and climate change need to be accounted for in tsunami hazard assessment relevant to decadal and longer time periods. For sea level rise, the primary sources of data are coastal tide gages; these serve to establish new elevation and depth estimates after local earthquake events. Near-coastal GPS measurements help discriminate between long-term tectonic and oceanic changes in local sea level and are also useful immediately after local earthquakes to estimate vertical ground displacement.

A.1.3 Tsunami Wave heights, runup and drawdown

Tsunami waves are sequences of wave crests and wave troughs that can alternately inundate land and expose the nearshore area. The periods of flooding and exposure may last as much as tens of minutes. The amplitudes of these and their duration are modulated by the tides. The dynamics of tsunami waves in very shallow water are such that the wave heights and extent of inundation are often greater if a wave trough precedes the first wave crest. This occurs along the coast adjacent to subduction zones as a result of shallow thrust-fault earthquakes.

Visual recording of tsunamis during events provides some quantitative information of both the inundation and drawdown and can be used to monitor tsunamis in real-time during an event. For hazard assessment, the primary role of these data is the validation of numerical tsunami models in terms of the detailed structure of tsunami bores and other small-scale wave features.

Post-tsunami surveys of high-water marks and debris extent provide information on maximum wave heights, inundation, and current speeds that can again be used for model validation. This provides confidence in the models when applied to the coastal region where the surveys were taken and often for analogous coastal areas as well.

A.1.3.1 NGDC Historic Tsunami and Paleotsunami data

NGDC archives historic tsunami and paleotsunami (in progress, Figure 6) data for the world. The historic tsunami database contains information on tsunami sources, such as source location, date, time, maximum water heights, deaths, injuries, and damage (U.S. dollars at the time of the event). The database also contains information on locations (run-ups) where tsunami effects occurred. The source event table contains information on the generating event (e.g. earthquake, volcano, and landslide). If the event was

generated by an earthquake or volcanic eruption, the event is linked to a table that contains more information on the earthquake (e.g. earthquake magnitudes--Mw, Ms, mb, Ml, Mfa, focal depth, Modified Mercalli Intensity, deaths, injuries, and damage due to the earthquake) or the volcanic eruption (VEI index, morphology, deaths and damage due to the eruption).

A validity is assigned to each source event ranging from 0 for erroneous entries to 4 for definite tsunamis. The validity of tsunami events and runups is based on several factors. For example, tsunamis generated by earthquakes that were instrumentally recorded and recorded on tide gages are assigned a high validity of 4 in the database. Historical events that occurred before the invention of the seismograph or tide gage must be evaluated differently. If the event caused significant effects such as deaths and damage, or was observed in many locations; it is also considered to be a high validity. For example, a tsunami generated by an earthquake in Chile that was observed in Hawaii and California would be assigned a high validity. The number of reliable and independent sources that list a historical event also affects the validity. Historical tsunami events generated by earthquakes are cross-checked with regional and local earthquake catalogs. If the tsunami was reported to have been generated by an earthquake, but there are no listings in the earthquake catalogs, the validity is lowered. For example, if a newspaper article reports a tsunami wave, but there are no sources such as an earthquake that can be related; the tsunami event would be assigned a validity 1. Tsunami events generated by volcanoes are also cross-checked with volcano catalogs.

The event and runup databases have been significantly improved over the last few years by careful checking of historical entries to flag either poorly identified possible tsunami runups or to verify a meteorological origin for some entries.

The information in the run-up table includes arrival date and time, travel time, maximum water heights, period of the wave, horizontal inundation distance, deaths, injuries, and damage for the specific location. The water height is the maximum height of the water observed above a given reference level such as the height of the tide at the time of the tsunami, or mean lower low water, or sea level if the tide level at the time of the maximum wave was not observed. If the water height was determined from a tide gage, it is the amplitude or half the range.

The events in the database were gathered from scientific and scholarly sources, regional and worldwide catalogs, tide gage reports, individual event reports, diaries, ship's logs, published works, and oral histories. The source material(s) used to compile information on the source event and run-ups are also provided for each entry source event and run-up (complete for U.S., in progress for world). The data are available online via forms-based and interactive map searches (Figure 7).
(http://www.ngdc.noaa.gov/seg/hazard/tsu_db.shtml)

Although the historic and paleo records of tsunamis are extremely valuable for hazard assessment, erroneous conclusions can be drawn from the frequency and recurrence intervals of tsunamis taken from the database. Before the invention of the modern seismograph in 1880, tsunamigenic earthquake locations and magnitudes were determined from descriptions of earthquake damage and tsunami effects. If there were no people in an area to observe the phenomenon, it would not have been recorded. In

addition, the historic record is dependent on a society having written records that were preserved. The amount of documentation for different time periods can be affected by political instability and natural disasters such as fires or floods that destroy archival documents. Until the invention of tide gages in 1832, even if an area was populated and the people had a written language, only significant tsunami events would have been observed. The first instrumental record of a confirmed tsunami occurred on December 23, 1854, when an earthquake off the coast of Japan generated tsunami waves that were registered on tide gages in California and Oregon. In summary, to assess the tsunami history in a region it is important to know the region's history of written language, political stability, and seismograph and tide gage instrumentation.

A.1.4 Offshore tsunami wave heights

Offshore tsunami waves are measured primarily by bottom pressure (BP) gages that report time series in real-time. They also record these data internally for later analysis. It is possible to use BP to estimate wave heights because tsunamis are long gravity waves in which wave heights at the sea surface are directly proportional to BP variations caused by tsunamis.

The open-ocean DART systems deployed by NOAA measure tsunami BP fluctuations, equivalent to a fraction of a centimeter, at 15-second time intervals. Operationally, the observed tides are used to demonstrate that these systems are observing properly and are in calibration. An expanded network of DART systems is being deployed in the Pacific, Atlantic and Indian Oceans. To provide tsunami data quickly after tsunamigenic earthquakes, the DART systems are deployed near potential tsunami sources.

Shallow-water BP systems can also measure tsunamis on the continental shelf; there is an array of submarine cables on the shelf off Japan with BP sensors. The growing array of Coastal Ocean Observing Systems being deployed off the U.S. coast may also include BP systems. Since such systems near the U.S. coast have not been deployed as yet, their value to tsunami studies will be for future events.

Harbor and coastal tide gages measure tsunami wave heights at particular locations and are used during tsunami events to provide Tsunami Warning Centers with direct tsunami observations in impact zones. These water level observations are compared with the tsunami heights generated by numerical models and are thereby used to tune and verify such models, as well as estimate the characteristics of the tsunami sources. Since these gages are most often placed at protected sites inside harbors, they do not report tsunami wave heights within the surrounding area. However, assimilating these data into coastal tsunami models provides a method for estimating the latter. The tide gages also provide data on tsunamis that are generated by local earthquakes and landslides.

Under special circumstances altimetric satellites have measured tsunamis, when the satellites happened to pass over tsunamis during the brief time when the tsunamis were propagating in the open ocean. There are research projects underway to see whether GPS technology can be used to measure tsunamis. Such new technology may eventually augment the data being provided by the operational DART and tide gage networks.

A.1.4.1 NGDC Offshore tsunami wave heights

In the 1980s, NOAA's PMEL developed deep ocean tsunameters for the early detection, measurement, and real-time reporting of tsunamis in the open ocean. The tsunameters were developed by PMEL's Project DART (Deep-ocean Assessment and Reporting of Tsunamis, http://nctr.pmel.noaa.gov/Dart/index.html). A DART system consists of a seafloor bottom pressure recording (BPR) system capable of detecting tsunamis as small as 1 cm, and a moored surface buoy for real-time communications. The existing and planned DART locations are shown in Figure 8.

The edited BPR Data from 1986 to 2004 are available online from NGDC. The edited data were collected from a DART buoy BPR and historic BPRs (ie. no communication with a surface buoy). The data from the buoys include several signals, including tides and earthquake waves. In the open ocean, tsunamis are very small (a few centimeters), but tides can be large (~1 meter) and earthquake waves can be very large (several meters). Therefore, to see the tsunami, the data need to be filtered to remove signals of tidal or earthquake frequencies. NGDC is in the process of providing a way to do this online. (http://www.ngdc.noaa.gov/seg/hazard/DARTData.shtml)

The real-time DART Data are available from the NOAA National Data Buoy Center. (http://www.ndbc.noaa.gov/dart.shtml)

A.1.5 Nearshore Currents

Nearshore tsunami currents are indirectly inferred by their effects, such as the movement of coral and rocks of various sizes and the erosion and deposition of sediment. Direct observations of tsunami currents will occur eventually on the continental shelf as more coastal ocean observing systems are installed and maintained over time. While these systems will include shore-sited Doppler radars that measure offshore currents, the sensitivity of these systems to the small tsunami currents offshore where the radars are most effective is open to question. Presently, the most detailed estimates of nearshore tsunami currents as functions of location and time are obtained from numerical models tuned to the observed tsunami wave heights.

A.1.6 Sediment Transport

Sediment transport modifies the nearshore bathymetry and beach topography over time, sometimes making substantial changes in these within days as the result of major storms, or tsunamis. Other transport processes have longer timescales, such as the seasonal variations in currents, tides and waves. Societal responses to coastal erosion and deposition include the construction of seawalls and other protective structures and the dredging of entrance channels and harbors. These changes in the character of the coastal areas can have major implications for the potential impact of tsunamis.

Measuring littoral drift is done indirectly via periodic surveys of land elevation and nearshore water depths, for example using GPS and LIDAR technologies. The net changes in these can be ascribed to sediment transport. In principle, this same procedure could be applied before and after a tsunami to estimate the net sediment transport caused by the tsunami. Doing so requires up-to-date topography and bathymetry at the onset of

the tsunami. Post-event surveys of sediment deposits provide information on the strength of the tsunami currents and the extent of inundation.

A.1.7 References

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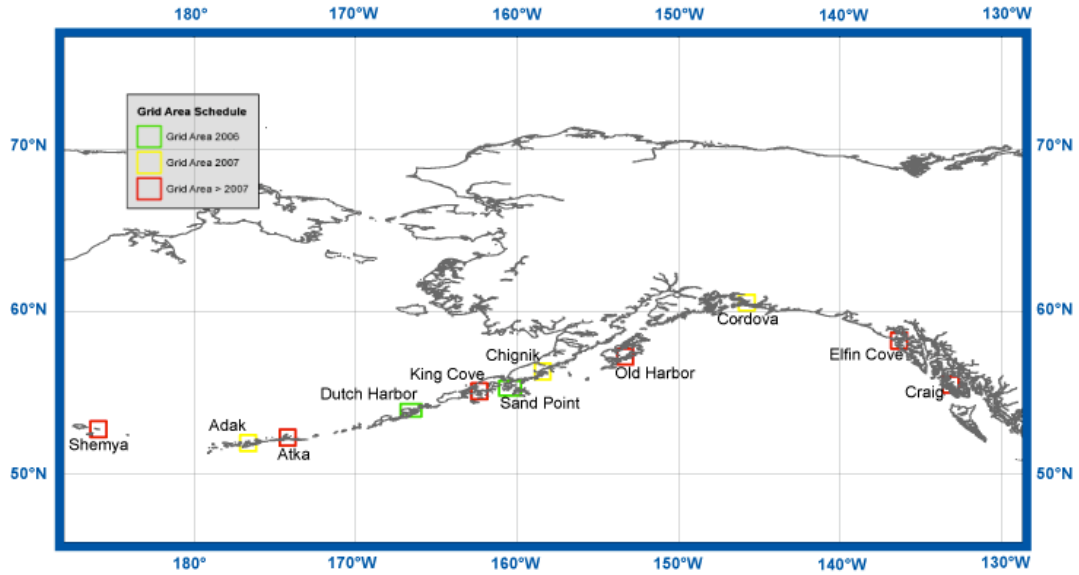

Figure 1. Gridding schedule for Alaska.

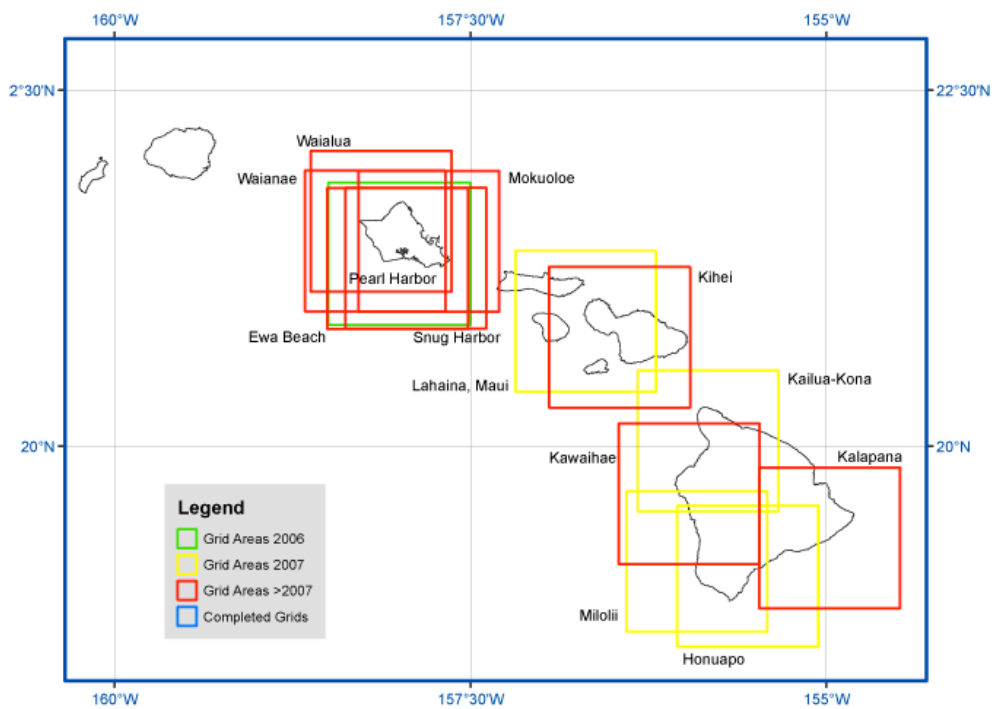

Figure 2. Gridding schedule for Hawaii.

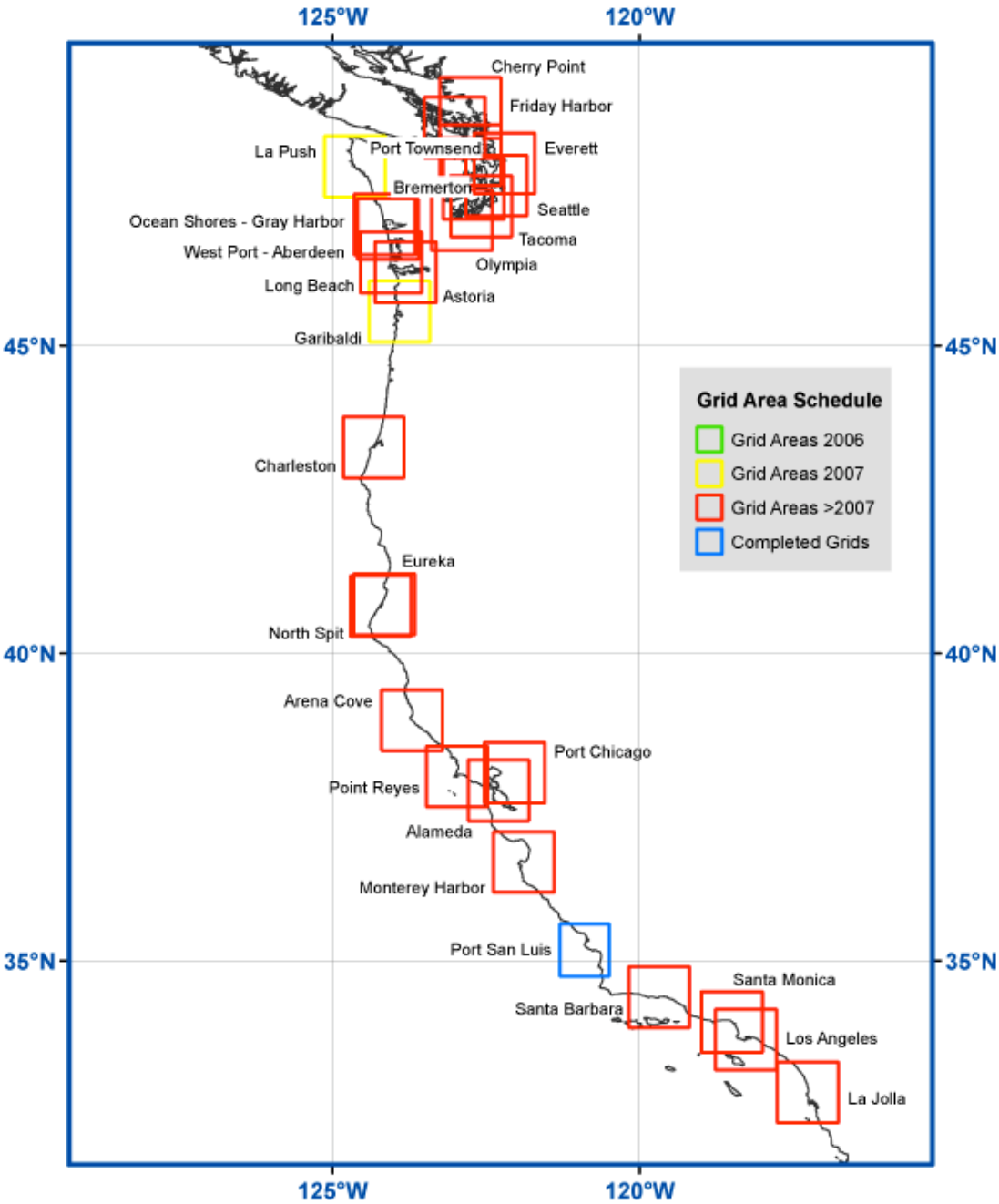

Figure 3. Gridding schedule for U.S. west coast.

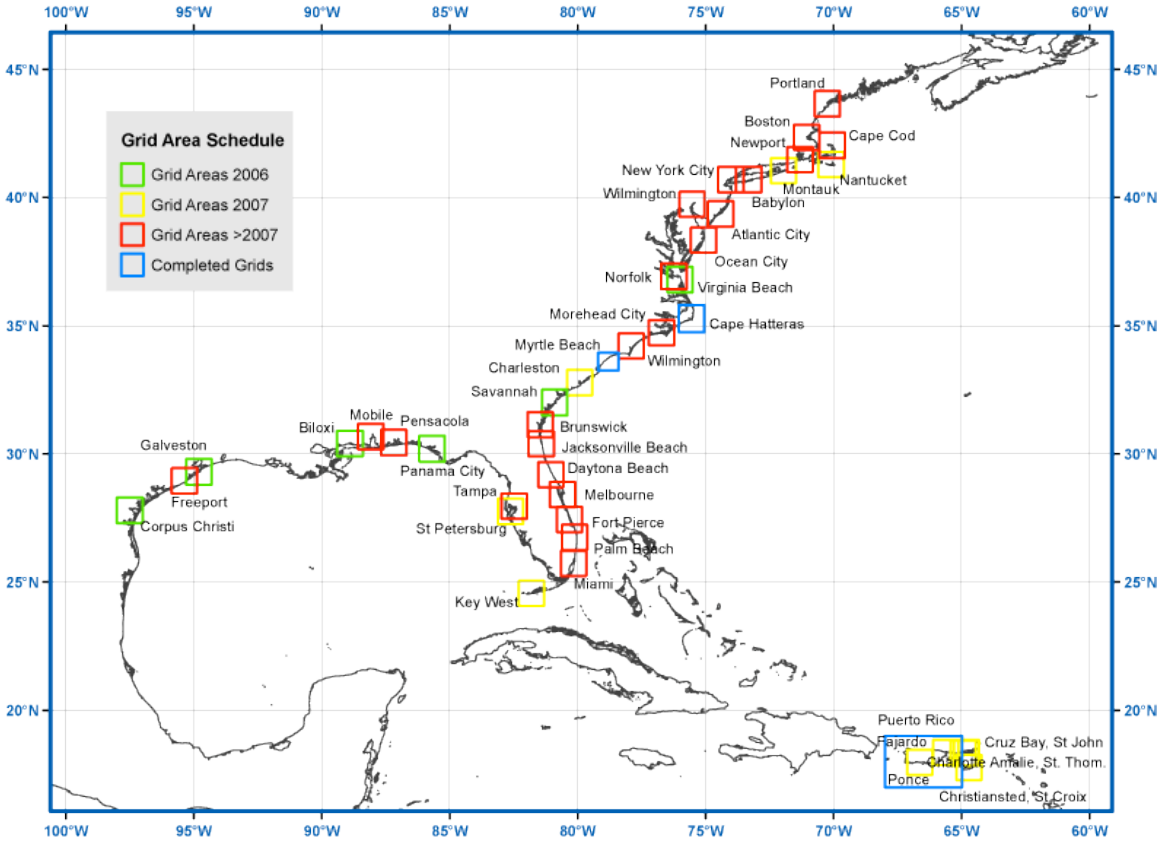

Figure 4. Gridding schedule for U.S. east coast and Caribbean.

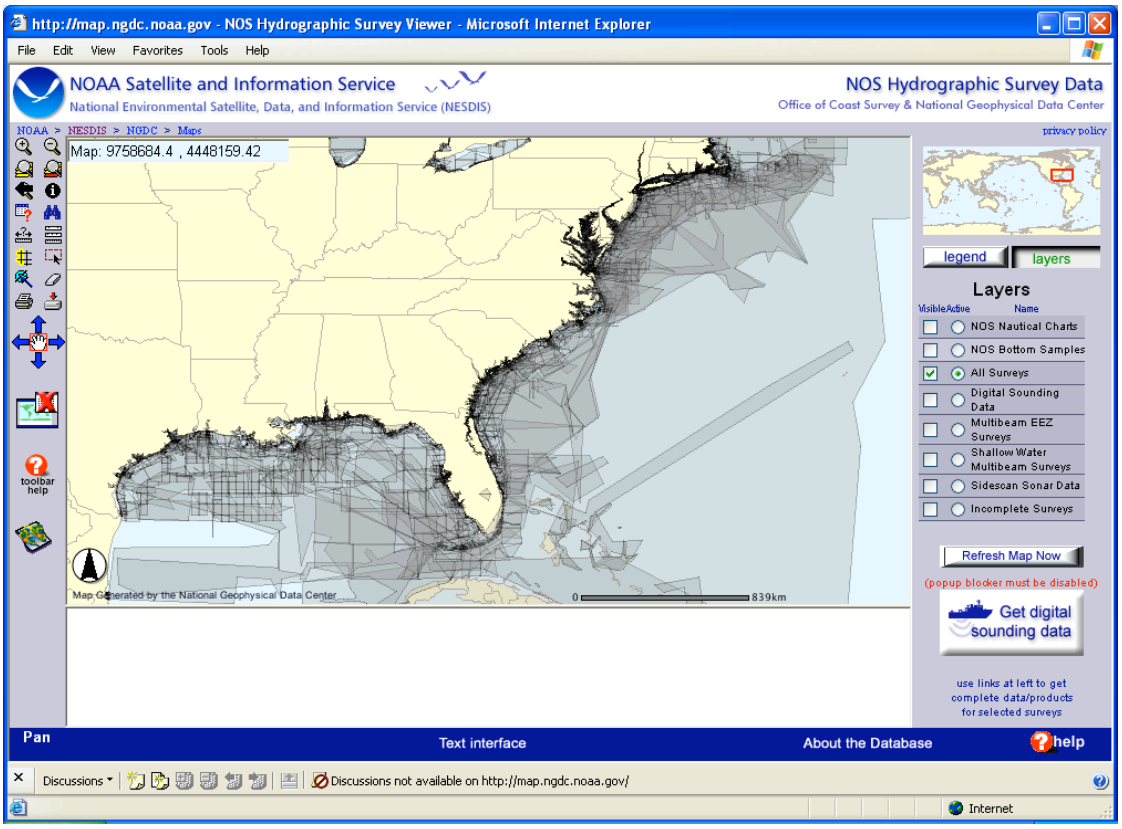

Figure 5. NOS Hydrographic survey data for U.S. east coast.

Figure 6. Map showing Cascadia Subduction Zone and tsunami deposit locations in the NOAA/NGDC tsunami runup database.

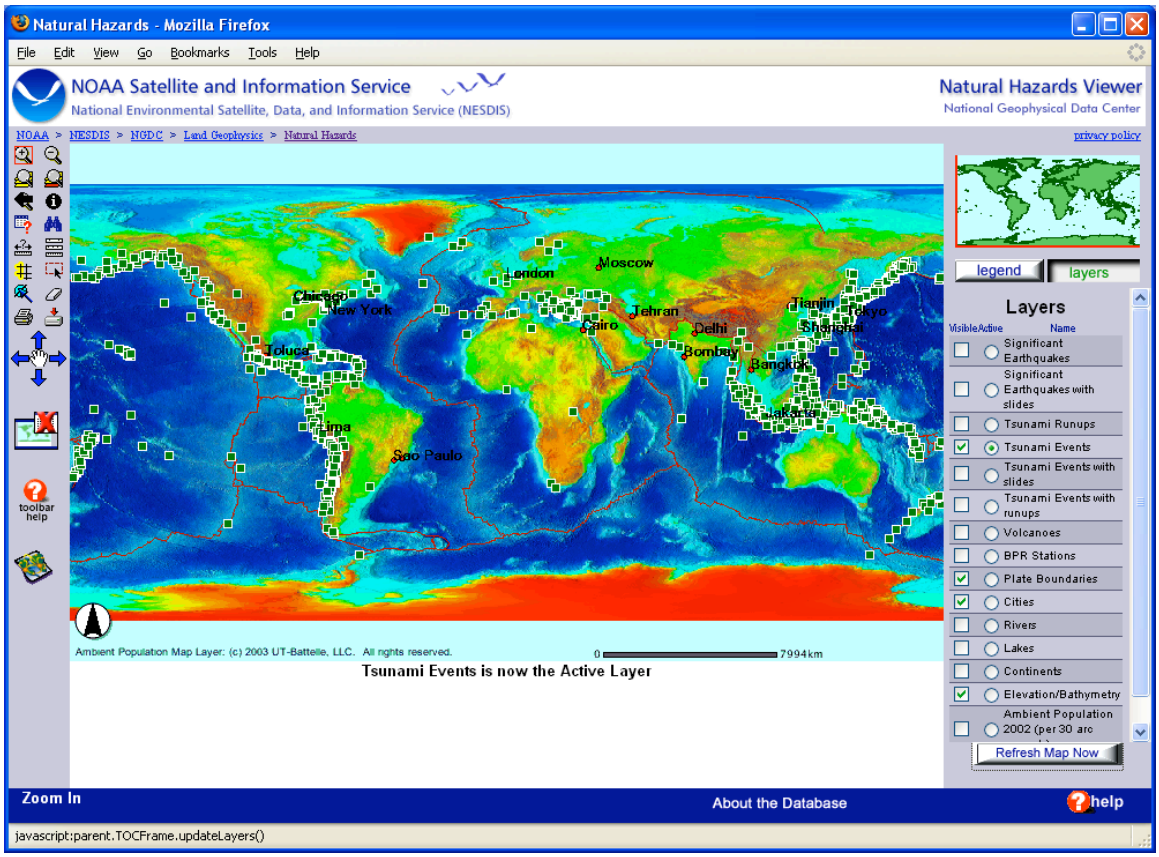

Figure 7. NGDC interactive web map displaying tsunami events.

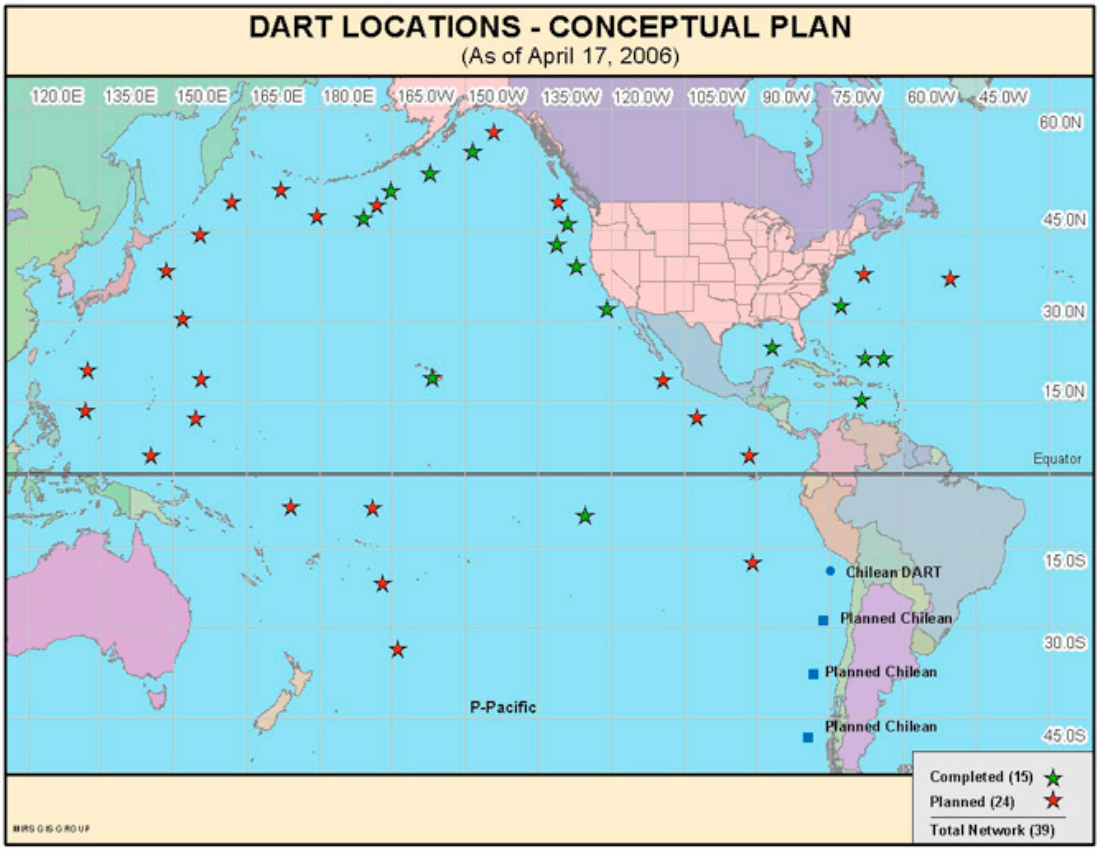

Figure 8. Completed and planned DART locations.