EARTHQUAKE & TSUNAMI EARLY WARNING ON THE CASCADIA SUBDUCTION ZONE

A Feasibility Study for an
Offshore Geophysical Monitoring Network

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PREFACE

This study advances efforts to implement earthquake early warning along the U.S. West Coast. An optimized detection and warning system must be adapted to the local geology and particular earthquake risks for a region. Compared to other plate boundaries, residents of subduction zone environments likely benefit the greatest from earthquake early warning because the population is likely to receive the longest warning times. This is because the major inland populations are far from the earthquake source, which lies almost entirely offshore. But subduction zones present a challenge: the geophysical network that detects the earthquake is limited to the land, rather than surrounding the earthquake source region offshore. Subduction zones also pose a second major hazard in the form of a tsunami that is frequently triggered by the offshore earthquake. Therefore, the timeliness, accuracy, and reliability of earthquake and tsunami early warning in subduction zones, such as found in the Pacific Northwest, would be enhanced by offshore geophysical instrumentation. However, offshore instrument networks are technically challenging to design, install, and maintain.

The feasibility and design of an offshore geophysical network for earthquake and tsunami early warning in the Pacific Northwest was evaluated by a team of scientists and engineers at the University of Washington with support from the Gordon and Betty Moore Foundation. The team's goals were to (1) consider the justification for such a system, (2) identify the high-level system specifications, (3) evaluate current and emerging technologies, (4) determine the feasibility and approximate costs of illustrative designs, and (5) make recommendations about the path forward. To inform the study, a workshop of over 100 participants was organized after some preparatory work (Wilcock et al., 2016). Attendees were drawn primarily from academia, but representatives from federal agencies, industry, the emergency management community, and the media were also present (Schmidt et al., 2018). The deliberations and recommendations of the workshop were important in guiding the completion of the study. This report and its supporting documents present the study's results.

The instrument network designs presented here are neither final nor optimized, but rather are illustrative of options that utilize established and emergent approaches. While the report notes the necessity of incorporating an offshore geophysical network into a comprehensive strategy for preparedness, education, warning, and response, it does not present a holistic mitigation plan, nor does it explore in any detail how offshore data would be integrated with existing warning systems that are operated by the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA). This report is best viewed as a resource on the scientific and technical considerations, as well as the societal benefit, for earthquake and tsunami detection in subduction zones, such as in Cascadia and similar locations across the planet with populations at risk.

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ACKNOWLEDGMENTS

This work was funded by the Gordon and Betty Moore Foundation through grant GBMF5231 to the University of Washington. Report editing and layout by Brian Rasmussen and Kim Reading. Graphic design and visualizations by Hunter Hadaway. The authors thank Kate Moran, Diego Arcas, Christian Meinig, and Diego Melgar for thoughtful comments on an early draft.

RECOMMENDED CITATION

Schmidt, D., W. Wilcock, R. LeVeque, F. Gonzales, G. Cram, D. Manalang, M. Harrington, E. Roland, and P. Bodin. *Earthquake and Tsunami Early Warning on the Cascadia Subduction Zone: A Feasibility Study for an Offshore Geophysical Monitoring Network.* Seattle: University of Washington, 2019, 81 pp.

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Executive Summary

Subduction zones are responsible for the largest earthquakes on our planet and generate the largest tsunamis. The nearshore communities of the Pacific Northwest are at great risk from these natural hazards. Early warning systems provide seconds-to-minutes of warning for people and automated systems to take actions that decrease deaths, injuries, and damages. Existing tsunami early warning systems, such as NOAA DART buoys, are designed primarily for far-field tsunamis that propagate across the world's oceans on time scales of hours. Near-source tsunami warning is challenging because nearfield observations are rarely available to characterize the disturbance of the sea surface quickly and to provide an accurate prediction of the immediate impacts. Efforts are underway to obtain rapid near-source tsunami predictions from land-based measurements of earthquake rupture, but the most accurate and complete predictions will require offshore observations. On the U.S. West Coast, earthquake early warning is now provided by terrestrial geophysical networks that contribute data to the ShakeAlert system. But the timeliness and accuracy of the warning are diminished for offshore earthquakes because of the great distance between the offshore source zone and the instruments on land.

For coastal residents, earthquake early warning helps ensure that individuals secure themselves prior to severe ground shaking and avoid injury, so that they are then able to evacuate areas at risk from the tsunami. Offshore instruments would improve earthquake early warning accuracy and reduce the mischaracterization of earthquakes. For many coastal communities, seconds matter, because the tsunami may arrive before an evacuation can be completed. A tsunami early warning can be more accurate and timely if it is informed by an earthquake early warning, as this information can be used to initiate predictive models that forecast the height, arrival time, and inland flooding of the incoming tsunami wave. Offshore instruments can also detect and warn of tsunamis that might be triggered from submarine landslides that produce no discernable shaking or slow earthquakes that produce diminished shaking relative to their magnitude and fail to alert coastal residents of a potential tsunami risk.

Installing instruments in subduction zones presents logistical and engineering challenges because the offshore source zone is inaccessible and inhospitable. A variety of instruments can be used to detect an emergent earthquake and tsunami, with ocean bottom seismometers and pressure gauges being the most established. Research is needed to understand whether seafloor pressure gauges are sufficient to measure an emergent tsunami within the source zone or whether they must be complemented by direct observations of sea surface displacement.
One technical challenge when building an offshore system is providing reliable power and communications. Cabled systems are the most mature technology for enabling both earthquake and tsunami early warning from offshore instruments, but at considerable upfront cost. Moored buoys are well demonstrated for tsunami warning, but their latency is likely too large for earthquake early warning. A hybrid approach that uses multiple technologies, such as a combination of cabled and buoy systems, may be ideal because benefits of each technology can be maximized while the risks and costs minimized. Emerging technologies may provide new solutions, but significant research and development is required to evaluate these approaches and demonstrate that they are scalable.

The implementation of an offshore instrument network will require the cooperation and support of many, diverse stakeholders. Extensive research and development is needed to ensure that an offshore system is optimally designed and well implemented. Early warning systems must be developed in synergy with other planning, mitigation, and educational activities to maximize regional preparedness, response, and resilience.

Introduction

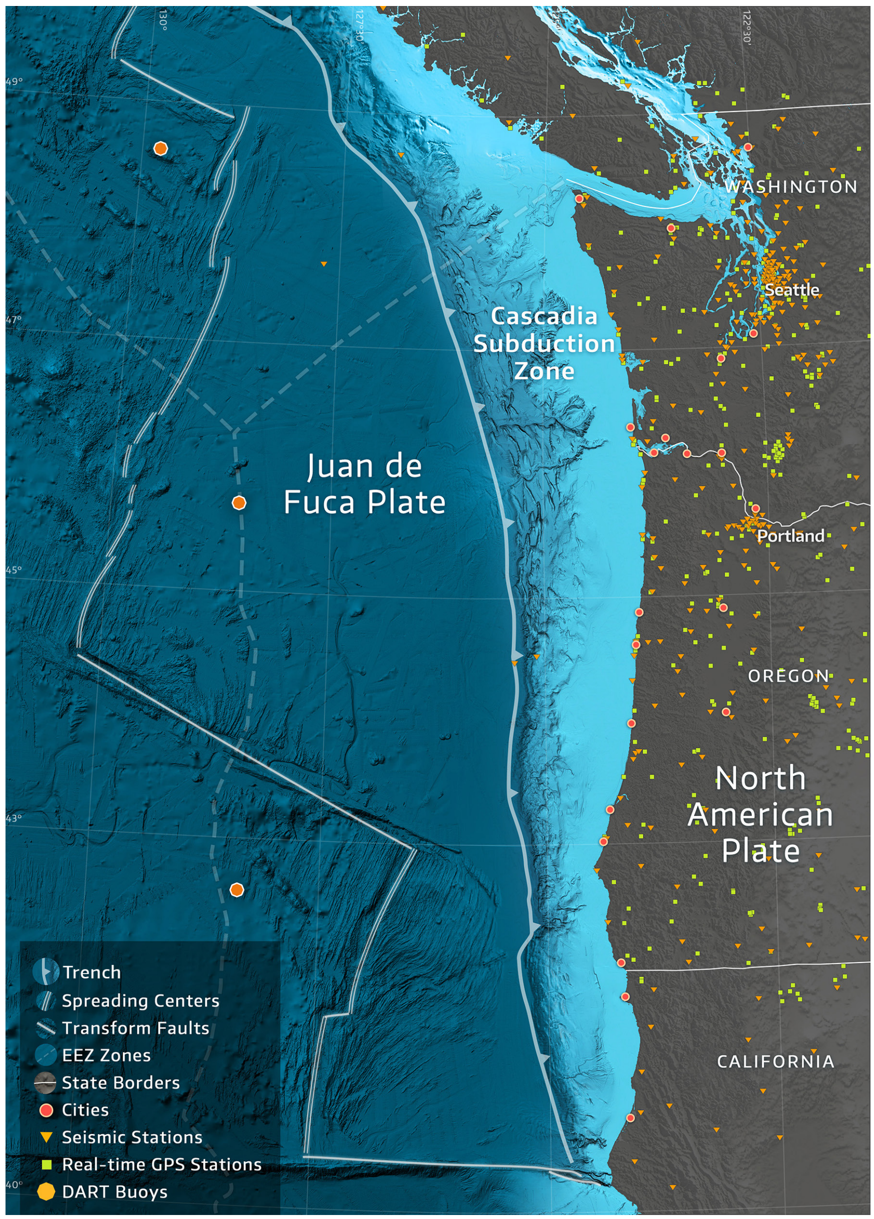
The western parts of Northern California, Oregon, Washington, and British Columbia will experience a major earthquake and tsunami that will cause extensive property damage and loss of life. The source of the threat to the Pacific Northwest is the Cascadia subduction zone, which marks the boundary between the North American continental plate and the Juan de Fuca oceanic plate. As these two plates converge at a rate of 1.5 inches/year, the Juan de Fuca plate slides beneath the North American plate. The major fault that forms between these two plates remains locked for many hundreds of years, allowing stress to build in the Earth's crust. Eventually, the fault will fail and the plates will lurch past each other, producing an earthquake as large as magnitude 9. During the event there will be several minutes of violent shaking strong enough to knock people off their feet and destroy many buildings. The vertical movement of the seafloor during this event will raise the sea surface suddenly, initiating a large tsunami. Tsunami waves will strike the nearby coast of the Pacific Northwest 10–20 minutes after the earthquake begins. Wave heights may be 10–50 feet at exposed coastal locations proximal to the source, with secondary arrivals continuing to inundate the coast for many hours. Subduction zone earthquakes are particularly devastating because they are often compound natural disasters. The earthquake generates a tsunami and produces widespread regional destruction that challenges emergency responses and hinders post-event recovery.

While scientists know that stress is accumulating now and will eventually result in a large earthquake and tsunami, it is not known when this event will occur. The USGS estimates the probability is 10–14% (up to a 1-in-7 chance) that an earthquake of magnitude 8 or greater will occur on the Cascadia subduction zone in the next 50 years (Petersen et al., 2002). Independent studies report similar probabilities in the range of 11–17% in the next 50 years (Kulkarni et al., 2018; Onur and Seemann, 2004). The geologic record of paleoseismic deposits offshore suggests that the probabilities may be higher (21–42%) on the southern section of the subduction zone (Goldfinger et al., 2012). For comparison, the lifetime odds of a male being diagnosed with prostate cancer or a female being diagnosed with breast cancer (1-in-8; Howlander et al., 2019) are about the same odds as for a resident of the Pacific Northwest experiencing a major subduction zone earthquake in their lifetime. Unlike these diseases, however, when an earthquake strikes, it will affect the well-being, infrastructure, and economy of the entire region instantly; 100% of the population will be impacted. There are simple strategies our society can take to mitigate the potential impacts of a large earthquake and tsunami in the Pacific Northwest. All, however, require advanced planning and infrastructure investment by state and federal governments, in partnership with the private sector.

Actions that can help the region prepare and mitigate potential losses from a subduction zone earthquake and tsunami include updating building codes to reflect our evolving understanding of the hazard, constructing vertical evacuation structures on the coast where tsunami evacuation is hindered by geographic barriers, retrofitting unreinforced buildings, hardening infrastructure and transportation systems, educating the population, and developing post-disaster response and recovery plans. There is the potential to minimize injuries, deaths, and damage by taking pre-emptive actions in the seconds before strong ground shaking arrives or the minutes before tsunamis arrive on the coast. Early warning systems, such as the USGS ShakeAlert (Given et al., 2014), are designed to inform the public of an impending event, based on real time seismic data, so that people and automated systems can take appropriate actions.

Early warning systems are most effective when designed to sense the beginning of an earthquake or tsunami as quickly as possible, maximizing the warning time. Because the events initiate offshore, tsunamis and offshore earthquakes represent challenging natural events to detect, characterize, and warn the public about in real time. The USGS ShakeAlert system currently relies on land-based seismic networks (Figure 1), which have diminishing

Figure 1. The Pacific Northwest with geological features, political boundaries, and existing onshore geophysical instrumentation labeled. The source zone for the subduction zone earthquake and tsunami is below the continental shelf and slope, located between the coastline and the trench (thick blue line with teeth).



Early warning systems are most effective when designed to sense the beginning of an earthquake or tsunami as quickly as possible, maximizing the warning time.

sensitivity to earthquakes that initiate offshore. The early detection of offshore events by the ShakeAlert system are often mischaracterized or have high rates of false negatives. NOAA operates a tsunami warning system that uses earthquake source estimates and observations of wave heights from buoy and coastal tide gauge data across the Pacific. Tsunami warnings issued from global or regional terrestrial earthquake sensing systems alone are often too slow and lack enough detail to warn vulnerable local communities when the tsunami is generated near shore.

Direct measurements of tsunamis by existing NOAA DART (Deep Ocean Assessment and Reporting of Tsunamis) buoys (Bernard and Meinig, 2011), which are located primarily in deep-water regions, detect and characterize well tsunamis that originate in distant areas of the Pacific. Tsunami warnings for nearshore events in Cascadia are inferred from earthquake source data, as well as new DART nearfield technology that is now undergoing ocean trials. Ocean Networks Canada has recently installed bottom pressure recorders and coastal radars that can detect tsunamis from nearshore events off Vancouver Island. Otherwise, there are few instruments offshore that could observe a tsunami generated near shore, and provide an immediate and accurate warning for coastal residents of Washington, Oregon, and Northern California. Coastal residents are advised to move to higher ground upon feeling an earthquake, but many may be unfamiliar with proper courses of action, particularly during summer months when tourism increases coastal populations. Residents may not take action because they assume that shaking is not significant enough, or they are not fully aware of what is happening.

A fast and accurate earthquake early warning could be provided by an offshore instrument network (Figure 2). This system could also provide the first in-situ observations of local tsunami initiation and serve as a tsunami early warning system for Pacific Northwest communities. Offshore seismic observations could provide up to 15 seconds of additional time before the ground starts shaking, and provide more accurate location and magnitude

There are few instruments offshore that could observe a tsunami generated nearshore and provide an immediate and accurate warning for coastal residents.

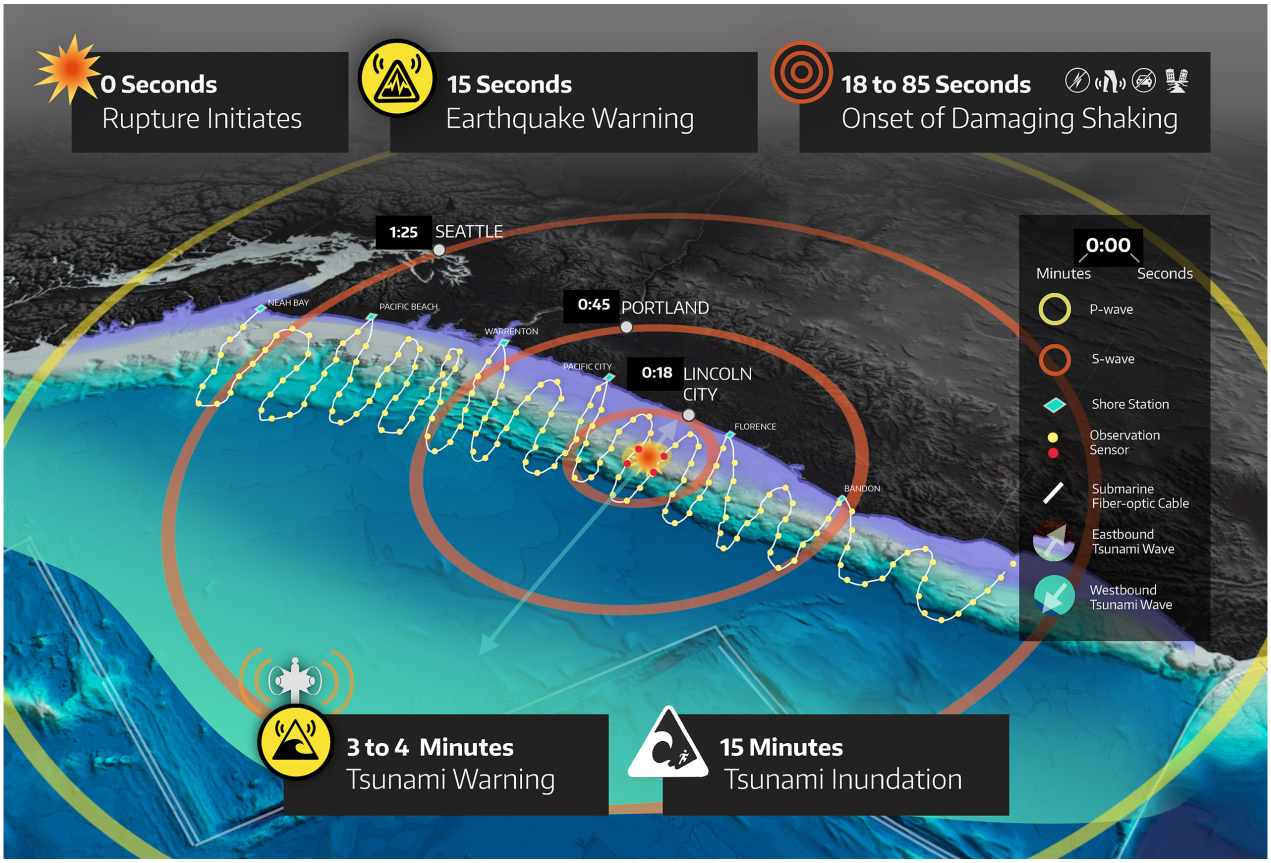


Figure 2. A timeline for earthquake and tsunami early warning that would be enabled by an offshore instrument network. The timeline will vary for different locations depending on the epicenter of the earthquake (center star burst), here depicted offshore Oregon.

estimates. Direct observations of seafloor movement and sea surface height change would provide immediate constraints on calculations to pinpoint a tsunami source, and help to forecast the coastal wave height within the first 5–10 minutes after the earthquake, prior to tsunami wave inundation along the closest coastline. The potential benefit of these early warning systems is a significant reduction in deaths, injuries, and damage through preemptive and automated mitigation actions.

Continuous, real time observations from an offshore instrument network would also provide important seismological and geodetic data for the research community. Lacking sustained observations, scientists are not certain what constitutes normal seismic behavior on the Cascadia subduction zone; a long time series that includes normal seismic activity is required to interpret precursory phenomena. Following the 2011 Tohoku Japan and 2014 Iquique Chile subduction zone earthquakes, post-event analysis revealed that undetected transient fault slip was ongoing in the months prior to the earthquakes (Ruiz et al., 2014; Kato et al., 2012). Had fault slip been detected, the data would have provided an indication of unusual behavior along the faults prior to the large events. A similar strategy to monitor precursory events is used now to predict volcanic eruptions well in advance. Real time instrument networks located near the threat are key to the strategy. More research is needed to evaluate whether precursory behavior near subduction zone faults is common, and whether it may help indicate periods of heightened risk (Obara and Kato, 2016), but an earthquake and tsunami monitoring network deployed offshore that was developed for early warning purposes would also facilitate important research toward this goal.

Offshore Early Warning: Motivations and Benefits

The Threat of Subduction Zone Earthquakes and Tsunamis

Several recent events from around the globe have demonstrated the destructive power of subduction zone earthquakes and tsunamis, and motivate the need to better equip the population of the Pacific Northwest with an early warning system. Since 1960, more than 254,000 tsunami deaths have occurred as a result of five large earthquakes with magnitudes greater than 8.8 (Table 1). An additional 7,441 fatalities since 1960 were due to eleven magnitude 8–8.7 events. The 2004 Indian Ocean Sumatra–Andaman magnitude 9.1 earthquake and tsunami collectively killed more than 225,000 people, and the 2011 Tohoku Japan magnitude 9.1 earthquake and tsunami killed more than 20,000 people. Economic damage associated with this scale of a compound natural disaster is often difficult to quantify, but incorporates costs from extensive relief efforts, damage to infrastructure, and severe impacts to important industries (e.g., fishing and tourism for Indonesia in 2004 and the nuclear energy, automobile, and manufacturing industries for Japan in 2011). For both of

Table 1. Earthquakes of magnitude ≥ 8.8 and their societal impacts since 1960

YEAR	MAGNITUDE (M_w)	LOCATION	TSUNAMI		EARTHQUAKE DEATHS	INJURIES*	DAMAGES (Uninflated)
			Deaths	Max Run Up (ft)			
2011	9.1	Tohoku	16,959	128	1,475	6,152	$220 billion
2010	8.8	Chile	156	95	402	12,000	$30 billion
2004	9.1	Sumatra	226,898	166	1,001	-	$10 billion
1964	9.2	Alaska	124	170	15	-	$0.4 billion
1960	9.5	Chile	2,226**	82	2,226**	3,000	$1 billion

Data from National Centers for Environmental Information (NCEI) / World Data Service (WDS), Global Historical Tsunami Database, NOAA, doi:10.7289/V5PN93H7 and NCEI/WDS, Significant Earthquake Database, NOAA. doi:10.7289/V5TD9V7K (both accessed April 8, 2019).
*Injury numbers are not divided between earthquakes and tsunamis.
**The databases do not distinguish deaths from the tsunami and earthquake. The NCEI has an information sheet on the 1960 Chile earthquake noting that deaths in Chile were estimated between 490 and 5,700 for the combined earthquake and tsunami and that over 200 people died in Japan, Hawaii, and the Philippines due to the tsunami (May 22, 1960 Southern Chile Earthquake and Tsunami, NGDC Information Sheet, Updated March 2015, NOAA, www.ngdc.noaa.gov/hazard/data/publications/1960_0522.pdf).

the great earthquakes, damage estimates exceed many billions of dollars, and communities are still recovering many years later.

The primary goal of a tsunami early warning system would be to save lives by giving residents the maximum window of time to seek higher ground. For Cascadia, the resulting tsunami will primarily affect residents who live along the outer coast, where the at-risk population is estimated to be more than 43,000, swelling substantially during the summer months, with an additional 21,000 in Northern California (Oregon Seismic Safety Policy Advisory Commission, 2013). The number of fatalities is expected to be about 8,440 in Washington (Washington Emergency Management Division, 2015), 1,300–10,000 in Oregon (Oregon Seismic Safety Policy Advisory Commission, 2013), and 1,000 in Northern California (FEMA, 2013). Communities along the inland Salish Sea are also at risk from a tsunami. But of greatest concern are communities located on peninsulas facing the Pacific Ocean, such as Ocean Shores, WA, where the time needed to evacuate by foot will exceed the time it takes for the tsunami to reach the shore. In these circumstances, strategic siting of vertical evacuation structures can reduce fatalities, but every second is critical to ensure life safety.

Tsunami forecasting is a more complex exercise than earthquake magnitude or location calculations. Most tsunami warnings issued immediately after an earthquake are provisional, because coastal impacts may depend heavily on spatial details of the coseismic deformation and few near-source observations are available immediately. Examples of this challenge are the 2011 Tohoku Japan and 2004 Indian Ocean Sumatra–Andaman earthquakes, which produced tsunamis that were surprisingly large compared with initial forecasts. Furthermore, many offshore earthquakes, including those as strong as magnitude 8.0, do not produce a tsunami, particularly if the earthquake is located deep in Earth's crust. In contrast, the magnitude 7.5 2018 Sulawesi earthquake produced a large tsunami with a maximum run-up of 35 feet above the regular sea level, killing an estimated 4340 (Marshall, 2019). This may be an example of a relatively small earthquake triggering a submarine landslide on the continental slope where the sediments are unstable, thereby resulting in a displacement of water and the formation of a tsunami (Heinrich et al., 2000). The Sulawesi event may also be an example of a compound event (Heidarzadeh et al., 2019), which complicates the correlation between felt ground motions and tsunami sources, potentially making tsunamis more dangerous for unsuspecting coastal residents. Tsunamis can also strike a coast with little or no strong ground shaking, as has been observed for some slow earthquakes (Kanamori, 1972). Direct observations of seafloor or sea surface movement from an offshore instrument network would provide the best information about tsunami generation potential, and reduce the ambiguity when predicting the size of an incoming tsunami.

Early Warning Systems

An early warning system is one that identifies disturbances in the natural world that are likely to have a significant impact on society and provides useful alerts in anticipation of the impacts, which can then lead to a response to mitigate the effects (Basher, 2006). These alerts are triggered following the onset of an event, unlike a forecast that provides an estimate or prediction of an event's occurrence. For example, NOAA issues a tornado watch to indicate when tornadoes are possible, whereas a tornado warning is issued when a tornado has been sighted or detected on local radar. All warning systems share basic components:

- Instruments to record a physical signal
- Low-latency data transmission pathways
- Algorithms to detect an event, to estimate the size and location, and to generate alerts
- Pathways to distribute alerts rapidly to end-users
- An educated and informed set of users who know the proper response to a warning, or automated systems that respond appropriately

Earthquake Early Warning

Earthquake early warning (EEW) systems rely on observing the characteristics of an earthquake as close to the source (the rupturing fault) and as far from the asset (populated area) to be alerted as possible. Most seismic systems rely on very brief measurements (a few seconds at most) of the fast but weak early primary wave (P-wave) arrivals to determine the size and location of a source. The P-wave information is used to forecast the arrival of strong shaking from the more slowly propagating and more energetic secondary S-waves and surface waves (Figure 3). Such systems usually use networks of instruments to detect and locate the initiation of the event prior to the arrival of seismic waves at population centers. The USGS ShakeAlert system is based on this detection strategy (Given et al., 2018). Other seismic methods (e.g., Kuyuk et al., 2015; Kodera, 2018) use the pattern of strong shaking observed closer to the source to forecast strong shaking arrivals at more distant sites; this strategy is slower. Network methods may process data in real time at the instrument location, and convert the observations to EEW parameters (amplitudes and/

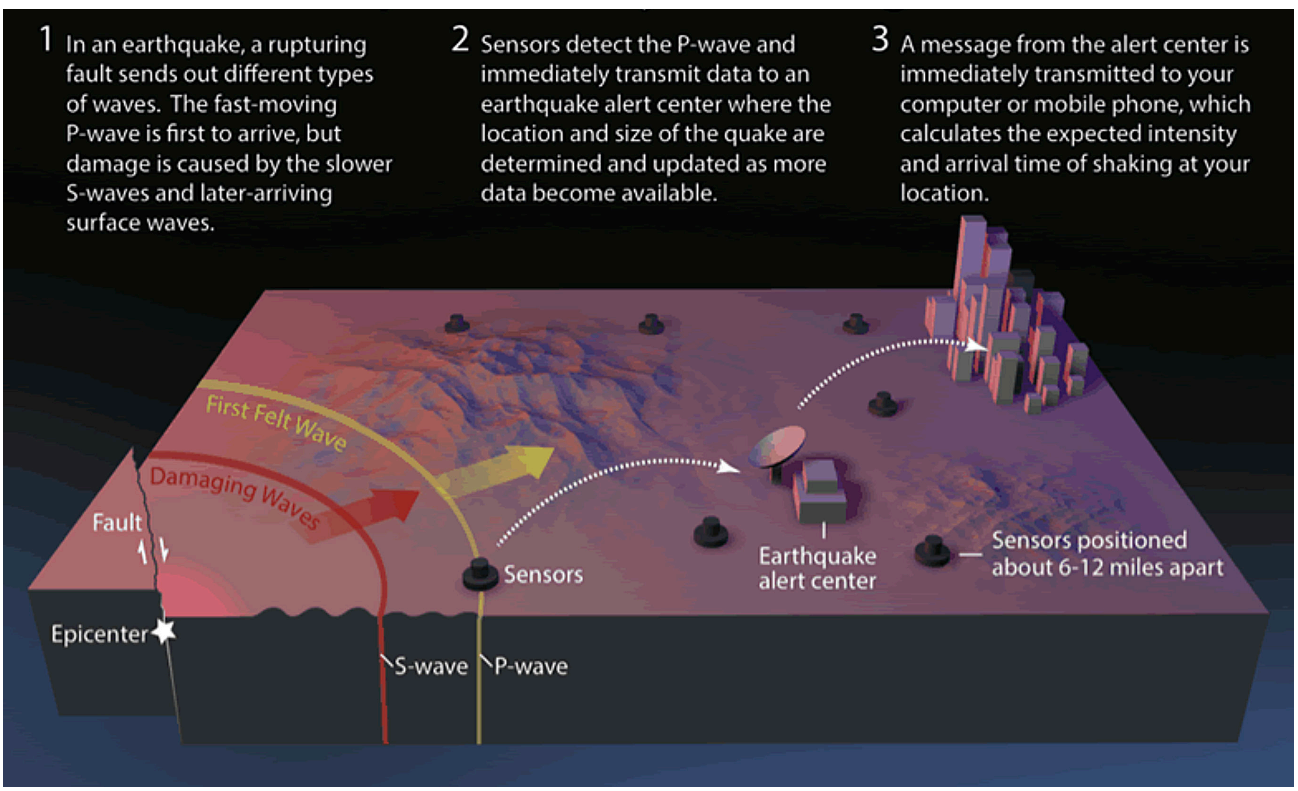


Figure 3. The principles of earthquake early warning. (Image by Erin Burkett, USGS, and Jeff Goertzen, *Orange County Register*.)

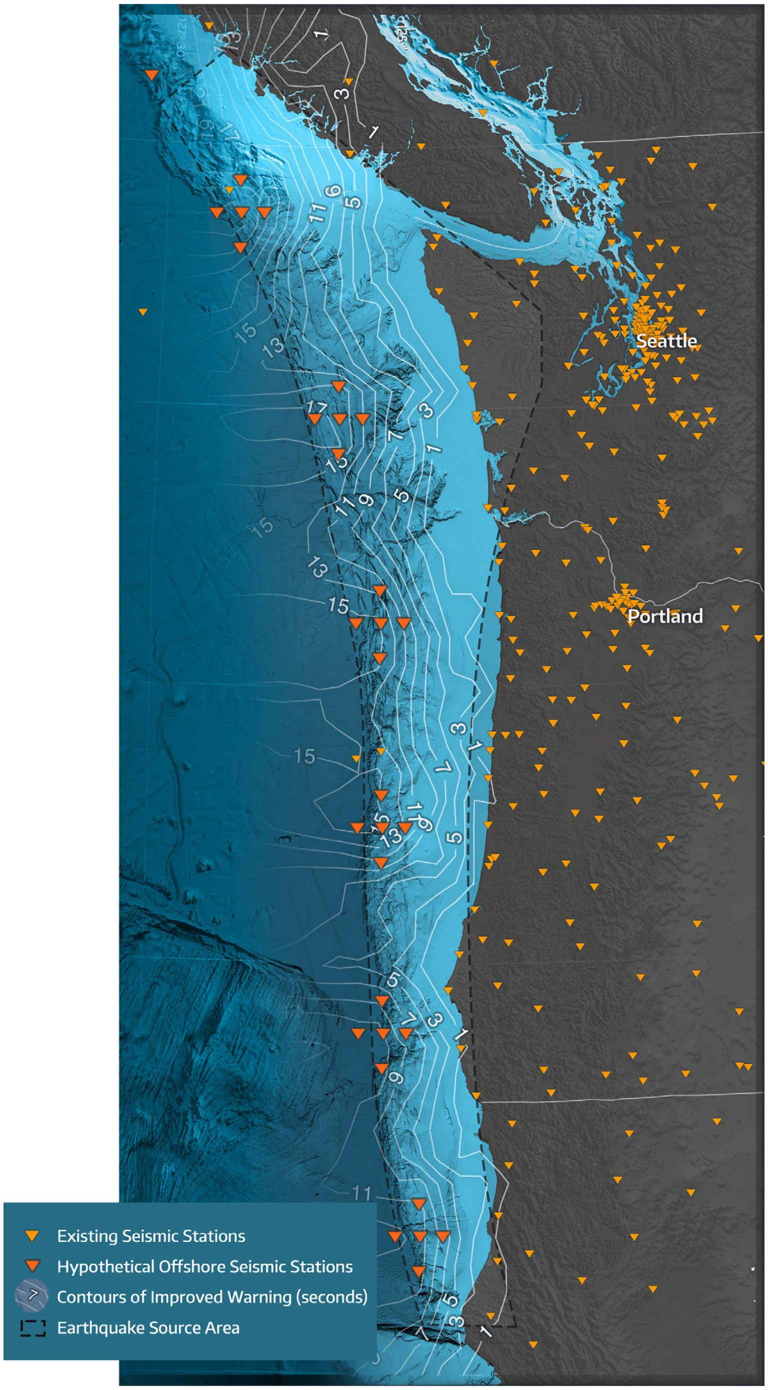


Figure 4. Simulation of improved earthquake warning times resulting from the addition of offshore sensors. The white contours indicate the additional seconds of warning from an offshore earthquake, when compared to a detection system using only land-based instruments. The time between the onset of an earthquake and the time to detect P-waves on four stations was first calculated as a function of location using just the land-based stations (smaller orange triangles). The calculation was then repeated after the addition of six clusters of offshore stations (larger red triangles) and the reduction in detection time contoured (white contours labelled in seconds). Earthquake warning times for a subduction zone earthquake (the locked region is outlined by a dashed black line) improve by up to 10–15 seconds for an earthquake nucleating near the western updip limit of the subduction zone.

or frequency content) or they may stream the complete data package to a center where data processing and alert production happen in near-real time.

Geodetic data — direct observations of the deformation associated with the fault rupturing process (the ground distortion) — are also used to identify the size and location of an emerging earthquake in near-real time. Geodetic EEW is most effective for large earthquakes observed close to the source. Geodetic methods include monitoring of monument positions using Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS). While geodetic methods are generally slower than seismic methods, they are the most certain to capture the full scale and slip distribution when an earthquake's magnitude exceeds a magnitude 7.5 threshold. The slight delay of geodetic estimates compared to seismic methods is largely a consequence of the observed phenomenon itself — it can take minutes for a very large earthquake to grow to its full size. In this way, seismic and geodetic data are complementary and independent inputs for a robust warning of very large earthquakes. Real time geodetic methods are in the early stages of being integrated into the ShakeAlert system (Murray et al., 2018).

EEW is used to notify people so that they may take mitigating actions — drop, cover, and hold on, and be aware of nearby falling hazards — and to initiate automatic actions for machine-controlled processes — slow trains, close or open valves, open elevator and fire station doors. Mitigation actions depend on the intensity of shaking expected and the warning time afforded. For a given earthquake, locations closer to the source will be shaken with higher intensities than more distant sites, yet will receive shorter warnings.

The alerts produced by an EEW system may be delivered by a host of technologies. Generally, an alert center generates and sends an electronic message, which is then provided to users through a low-latency delivery system. The messages themselves may be brief electronic files that contain the location and size of the earthquake and its expected shaking distribution. Receivers of these alerts can be technology enablers that use the alerts automatically to take actions to prepare for, and protect from, incipient shaking. Public alerts may be distributed by PA systems and/or sirens, by TV and radio broadcast interrupts, and by cell phones or other personal communications devices, among others.

The ShakeAlert system will provide a warning for subduction zone earthquakes. The timeliness and, perhaps, the reliability of the warning, however, would be improved with offshore instrumentation. Instruments near the offshore epicenter would detect a subduction zone earthquake earlier than coastal stations and are the only means to provide a warning to coastal communities near the earthquake (Figure 4). Earthquake early warning is most reliable for events that occur within the instrument network and thus, offshore instruments may reduce the possibility of false alarms caused by detections of more distant offshore earthquakes.

A Pacific Northwest Seismic Network Station

Tsunami Early Warning

Tsunamis are generated by the displacement of water. If the water surface is disturbed due to seafloor motion, then gravity acts to redistribute the water to a new equilibrium. This is accomplished by the initiation of a wave that propagates outward from the disturbance. As the wave approaches a coastline, the wave is compressed and the height increases. Local topographic features can also focus the wave, increasing inundation in some coastal regions. Because of its long wavelength, a tsunami appears onshore as a flood that flows inland for a great distance before receding. Earthquakes initiate this process by raising or lowering the seafloor, and subduction zone megathrust earthquakes have created the largest tsunamis in recorded history (Figure 5). Landslides can also produce tsunamis.

For tsunamis caused by earthquakes, tsunami early warning (TEW) systems typically depend on an initial estimate of an earthquake source (location and size). Computer models can then be used to estimate the deformation of the seafloor and the resulting perturbation of the sea surface, predicting the inundation time and wave height along the coastlines. The timeframe for TEW is different than EEW because the tsunami evolves and propagates over minutes-to-hours before impacts are realized, whereas earthquake shaking is experienced in seconds-to-minutes from the onset of the event. While TEW is a more complex operation compared to EEW, there is more time to perform calculations and issue the alert.

Currently, most tsunami warnings in the U.S. and other countries use DART systems, which were developed by the NOAA Pacific Marine Environmental Laboratory specifically for real-time detection and transmission of tsunami measurements to NOAA Tsunami Warning Centers in Alaska and Hawaii. The research and development effort was initiated in 1996, and by 2003 operational responsibility was transferred to the NOAA Data Buoy Center for the initial network of six DART systems off Alaska (three), Oregon (two), and near the equator (one). The success and value of the network became evident when six potential false alarms were avoided during 2000–2003 (González et al., 2005). Following the 2004 Indian Ocean Sumatra–Andaman tsunami the network grew to 64 DART stations in the Atlantic, Pacific, and Indian oceans, of which 39 are operated by the U.S. and 25 by partner countries.

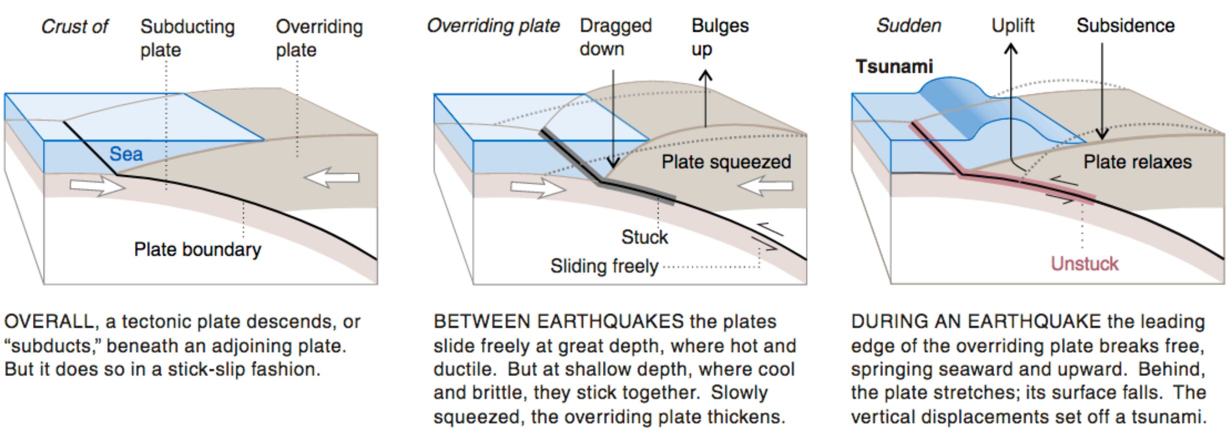


Figure 5. The physical processes that generate a tsunami during a subduction zone earthquake. (Image from Atwater et al., 2005.)

Ocean bottom pressure instruments at sites distant from the tsunami source measure changes in the hydrostatic pressure of the water column due to the increased surface elevation as a long-wavelength tsunami passes; they are also affected by S-waves. These data are used in real time to perform source inversion calculations and estimate the tsunami accurately enough that more distant coastal regions can be warned. The source inversion is accomplished by matching the DART observations to a linear combination of tsunami wave forms that have been precomputed from numerical models (Gica et al., 2008; Percival et al., 2011). This system provides tsunami warnings well in the Pacific Northwest for far-field tsunamis originating in, for example, Japan, Alaska, or Chile (Figure 6).

For nearfield warning in Cascadia, data from the existing DART buoy network has limited value. For example, a numerical model predicting the tsunami from a simulated magnitude ~9 earthquake that originates off the Oregon coast (Figure 7) shows that 15 minutes after the earthquake, the tsunami is already striking some coastal regions, but has not yet reached any of the three DART buoys in the Northeast Pacific. To provide nearfield warning, NOAA is now considering the future installation of DART buoys directly west of the trench, and thus closer to the source zone. One hour after the earthquake, the leading depression (blue) wave caused by co-seismic subsidence is entering Puget Sound while the much larger positive (red) tsunami wave is still traversing the Strait of Juan de Fuca, with an amplitude of

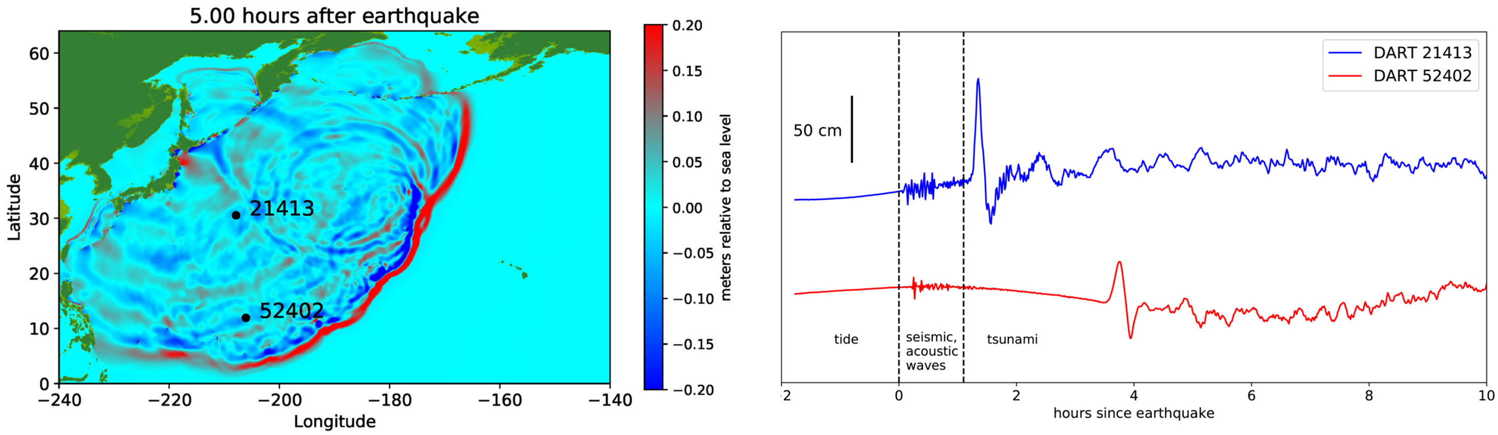


Figure 6. (left) A tsunami simulation of the 2011 Tohoku Japan tsunami 5 hours after the earthquake with color bar indicating displacement of the sea surface, which is relatively small while the waves propagate in deep water. (right) Seafloor pressure time series recorded by DART instruments at sites 21413 and 52402 for 10 hours after the earthquake. Tsunami seismic and hydroacoustic waves arrive at these instruments within the first hour after the earthquake, while the tsunami takes roughly 1.5 and 3.5 hours to reach these locations. The tsunami does not reach Hawaii or California until roughly 8 and 10 hours post-quake, respectively, giving ample time to issue warnings based on DART observations.

about 3 m (10 ft) in this simulation. At 2 hours post-quake, the tsunami is striking Whidbey Island, the San Juan Islands, and the community of Port Townsend, WA. At 3 hours, a diminished, but still potentially deadly, wave is apparent throughout Puget Sound, with particularly large wave heights in Bellingham Bay and farther north in the Salish Sea (not shown).

The simulation also shows that along the outer Pacific Coast there are large edge waves with complex structure that propagate up and down the continental shelf for many hours, with positive amplitude striking the vulnerable communities near Grays Harbor and Willapa Bay at 3 hours post-quake (Figure 7). This hypothetical earthquake was chosen from a set of 1300 simulations (Melgar et al., 2016). These simulated quakes and tsunamis yield different wave patterns for events with the same magnitude, and different amplitudes and arrival times (particularly for secondary waves) at each location. This variability is due largely to differences in the deformation patterns of the ocean bottom and coastal regions for different earthquake models and accentuates the need for better methodologies to assess the detailed nature and potential impact of an actual earthquake in real time.

For nearfield warnings, the U.S. system now relies primarily on rapid point source seismic inversion estimates of earthquake parameters including location, magnitude, and faulting style. The median response time for the warning is around 8 minutes and it does not include a forecast of the expected tsunami wave heights. Because the current system relies mostly on regional seismic data, the seismic estimate is prone to magnitude saturation, in which the system cannot distinguish between large and very large earthquakes. Thus, even if a tsunami forecast were to be made it would likely underestimate the hazard. This was the case during the 2011 Tohoku Japan earthquake, in which the initial warning severely underestimated the hazard and was not updated until many hours after the earthquake.

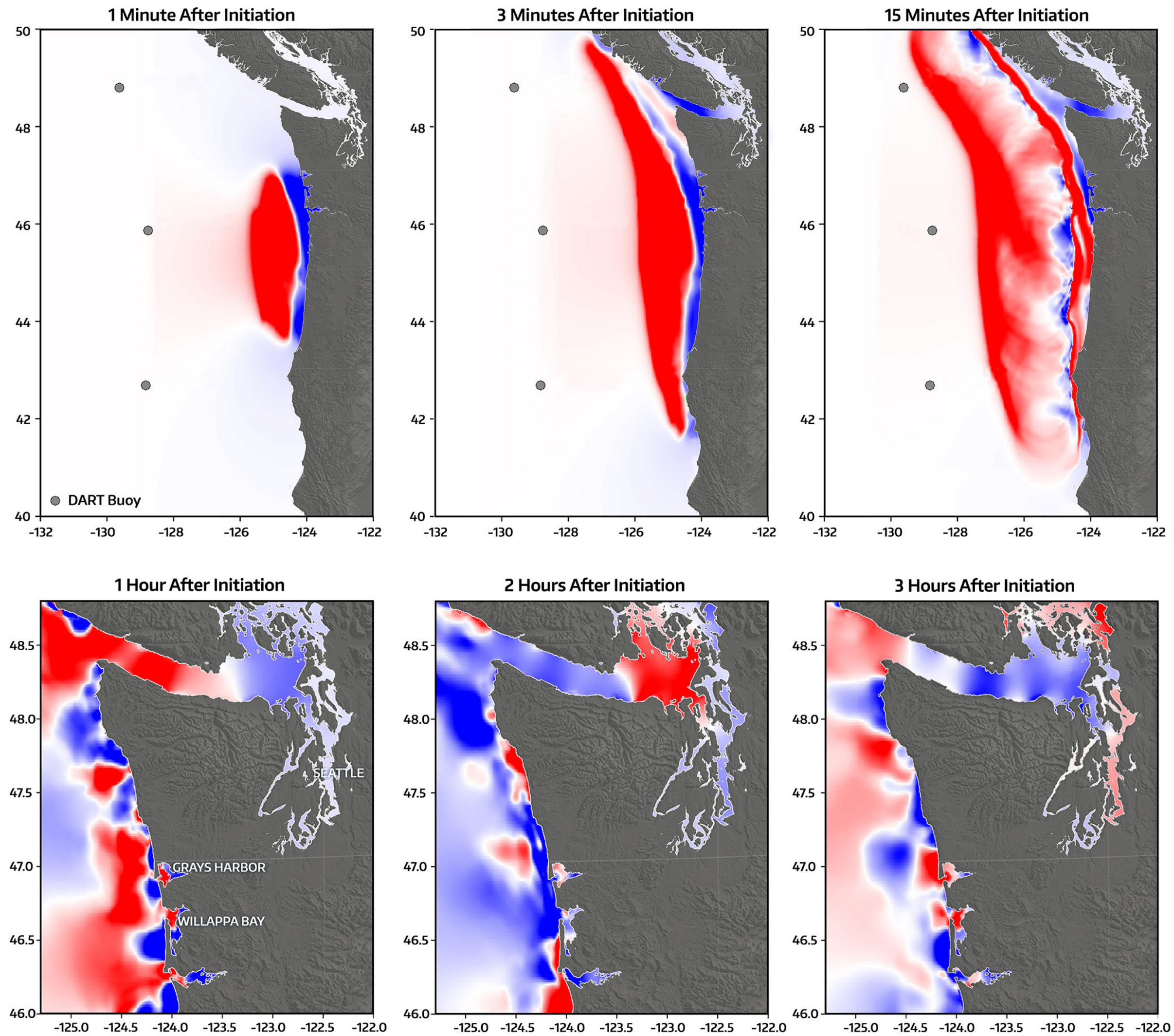


Figure 7. The tsunami predicted by a numerical model for a hypothetical magnitude ~9 earthquake that originates off the Oregon coast and ruptures bilaterally to the north and south over about 5 minutes. The initial seafloor deformation is –2.7 to +8.6 m. The red-blue color indicates elevation of the tsunami waves above or below sea level, respectively, and the colors saturate at ±1-m elevation for clarity of the plots, although the tsunami generated is more than 10 m (33 ft) high when striking parts of the coast. The top three frames show the tsunami 1, 3, and 15 minutes after the earthquake starts with the location of three DART buoys in the region shown (dots in top row). The bottom three frames show a zoomed view of the Washington coast, the Strait of Juan de Fuca, and Puget Sound at 1, 2, and 3 hours after the earthquake.

Efforts are now underway to incorporate geodetic observations from onshore GNSS stations into the rapid source inversion process (Crowell et al., 2018a, b; Biffard et al., 2017). A recent study reports that geodesy circumvents the magnitude saturation problem and produces reliable estimates of earthquake source characteristics in the first 1–2 minutes and a near-source tsunami warning within ~10 minutes (Melgar et al., 2016). Incorporating this technology into the warning centers could lead to immediate improvements in nearfield tsunami amplitude forecasting. Additional improvements in forecast ability for nearfield hazards could be made by incorporating offshore observations. These efforts are already underway in Japan, using data from the Seafloor Observation Network for Earthquakes and Tsunamis (S-Net; p. 44–45) and Dense Ocean Floor Network for Earthquakes and Tsunamis (DONET; p. 44–45) cabled networks.

Early Warning Systems Using Offshore Observations

An effective earthquake and tsunami early warning system must answer the following questions:

- Has an event happened?
- How large is the event?
- Where is the event?
- How long until ground shaking/tsunami waves reach populated areas?
- How intense will ground shaking/tsunami waves be?
- When is it safe to return to coastal regions?

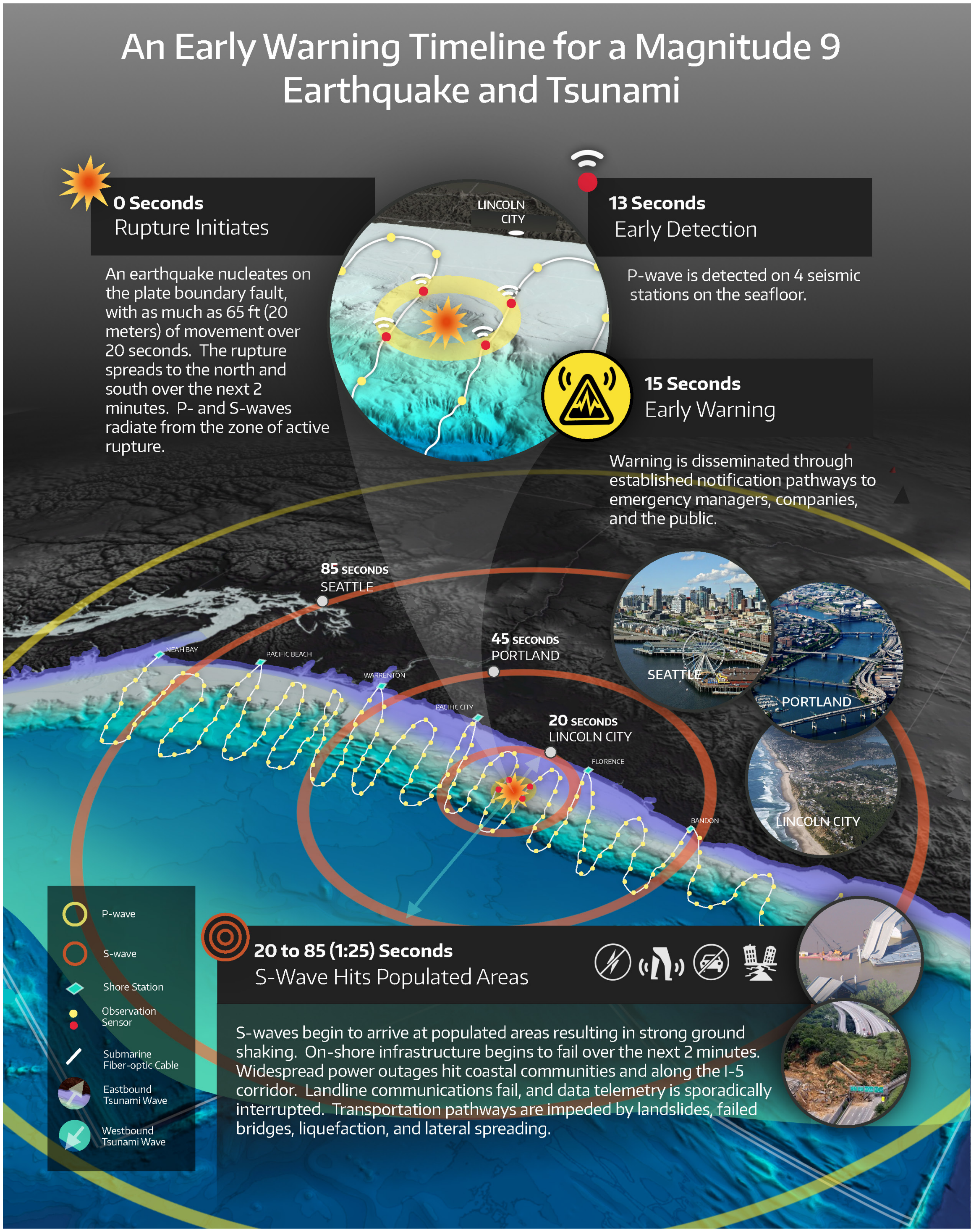
Developing a framework for answering these questions, and designing warning and response activities is the focus of existing earthquake and tsunami early warning protocols (Given et al., 2018); research and development efforts are underway to design observation-based algorithms to provide warnings. There are specific observations needed for EEW, TEW, and rapid modeling of events (Table 2). Some of these observations are similar for onshore and offshore environments, but some cannot be made without offshore instruments. For either case, offshore observations would make warnings faster and more accurate.

If a magnitude 9 earthquake on the Cascadia subduction zone occurred, how would an EEW and TEW system work? Paleoseismic studies (Goldfinger et al., 2012; Witter et al., 2013) report that large megathrust earthquakes, many extending along the entire Cascadia margin, have occurred repeatedly, most recently in 1700 (Atwater et al., 2015; Satake et al., 2003). Such an event is a reasonable and even likely scenario of a future Pacific Northwest great earthquake. Considering an earthquake and tsunami scenario based on a magnitude 9, full-margin rupture, key parameters such as the north–south (along-strike) and east–west (down-dip) rupture extent, the amount of seafloor uplift, and maximum amount of slip along the fault have important effects on the size of resulting tsunami waves, on the amount of strong ground shaking experienced along the West Coast, and on the propagation time of surface waves and tsunami waves that are expected to impact the region.

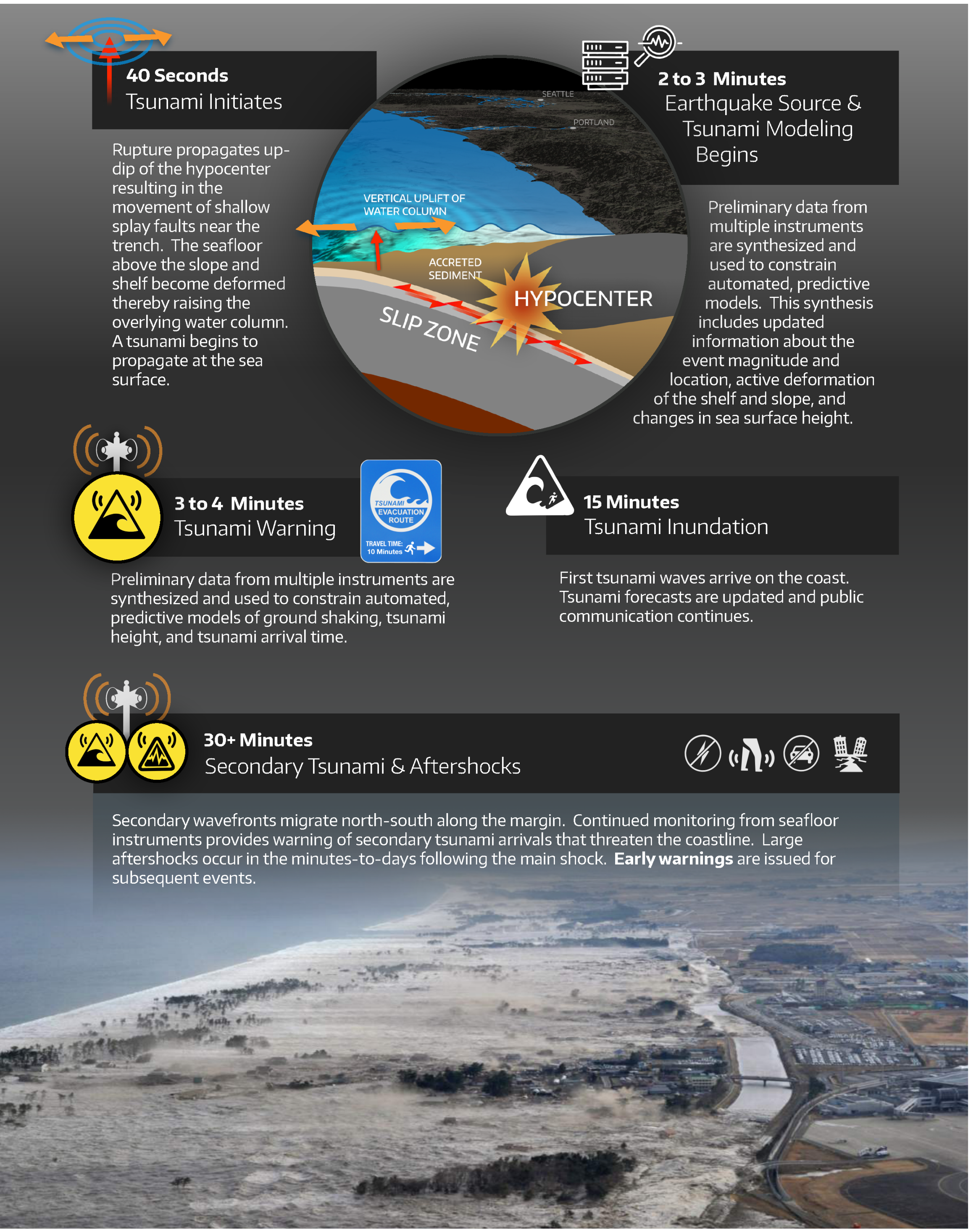
Table 2. Observations required for early warning

PURPOSE	OBSERVATIONAL REQUIREMENT
Earthquake detection and location	P-wave detection at multiple stations
Evaluate magnitude estimate	Scaled recordings of peak ground motion amplitude
Earthquake location estimate	High-rate static and dynamic deformation monitoring
Tsunami forecast	Earthquake source estimate (moment tensor solution)
Tsunami model	Seafloor and sea surface displacement
Tsunami model refinement	Sea surface wave amplitude in deep and shallow water environments

The scenario illustrated here (p. 20–21) uses a hypothetical source hypocenter (the initiation point of the earthquake rupture) approximately 40 miles offshore Lincoln City, Oregon; the location of the hypocenter influences the time by which communities begin to experience earthquake effects and tsunami waves. The scenario also specifies the amount of seafloor deformation, based on recent research of possible earthquake events (Witter et al., 2011, 2013).



The key milestones of the hypothetical scenario are the initiation of the earthquake, the measurement of shaking by an instrument network, the detection of the incipient event and the generation of a warning (application of well-developed early warning algorithms), the transmission of the warning to population centers, and the onset of local impacts in the form of strong ground shaking and water inundation along the coastline. Rupture along the fault during a magnitude 9 earthquake would develop over 3–5 minutes, perhaps longer.



Offshore observations would make earthquake and tsunami warnings faster and more accurate.

Promptly after rupture initiation, warning system elements would start reacting: ~10–15 seconds after the initiation of an event of any size, seismic stations would have observed the fastest P-waves, and an alarm would be issued. Soon thereafter, and well before the earthquake process has completed, strong ground motions would be felt at the closest communities such as Lincoln City (~20 s after initiation), Salem (~40 s), Portland (~45 s), and Seattle (~85 s). The destructive impacts to infrastructure begin as soon as these ground motions begin. The EEW would also trigger the tsunami modeling algorithms and seed initial modeling parameters.

As the event continues to grow in magnitude, the seafloor displacement would begin generating tsunami waves, the largest of which would be sourced near the region of the largest shallow fault slip, again offshore Lincoln City, and potentially extending in a north–south extent along most of the margin. As soon as seafloor displacement occurs, seafloor geodetic instrumentation would be used to characterize the source of the tsunami, refine the ongoing modeling, and produce a detailed tsunami forecast. Models and inundation maps driven and generated by data from offshore instruments should be capable of producing a detailed warning well before tsunami waves reach the Oregon coastline, about 10–15 minutes after the initiation of fault slip. Refinement of warnings, earthquake source estimates, and tsunami source models would continue as more data were collected from onshore and offshore instruments, and as the rupture continues to evolve. Tsunami forecasts would continue to be updated for several hours after the earthquake to determine when it is safe to return to coastal areas.

Coastal residents expect that any local large tsunami will be preceded by strong ground shaking, but this is not always the case. Subduction zones like Cascadia, such as the Chile, Central America, Sumatra, and Alaska margins have generated tsunamis that were not accompanied by the ground shaking associated with a magnitude 8–9 earthquake. These present a special challenge to existing tsunami warning systems. 'Tsunami earthquakes' have been documented at subduction zones globally (Ammon et al., 2006; Kanamori, 1972; Kanamori and Kikuchi, 1993; Lay et al., 2007) and are usually characterized as an earthquake that occurs near the updip extent of a plate boundary fault, usually far offshore and with a slow rupture relative to that of a typical earthquake. These events generate a large tsunami relative to the magnitude of the earthquake. One recent example is the magnitude 7.8 2010 Mentawai earthquake, which ruptured the shallow portion of the subduction zone off Sumatra and generated a run-up that was much larger than anticipated by locals who felt the earthquake; 431 lives were lost (Lay et al., 2011). A relatively small earthquake can also trigger a large slope instability (Heinrich et al., 2000), or a slope instability can occur with no earthquake at all (Schiermeier, 2017). Here, displacement of material along the seafloor creates a large tsunami wave without any ground shaking felt at the coastline. These scenarios, in which there is little or no earthquake shaking experienced on land, would make seafloor instrumentation essential for sensing the initiation of a large tsunami. For a slow earthquake rupture or submarine landslide source, the initial EEW sequence may be less important than the integration of direct seafloor displacement and sea surface height measurements into an offshore tsunami warning system. Because little or no ground shaking would be felt by people on land, they would have even less awareness that a tsunami is imminent in these scenarios (p. 24–25).

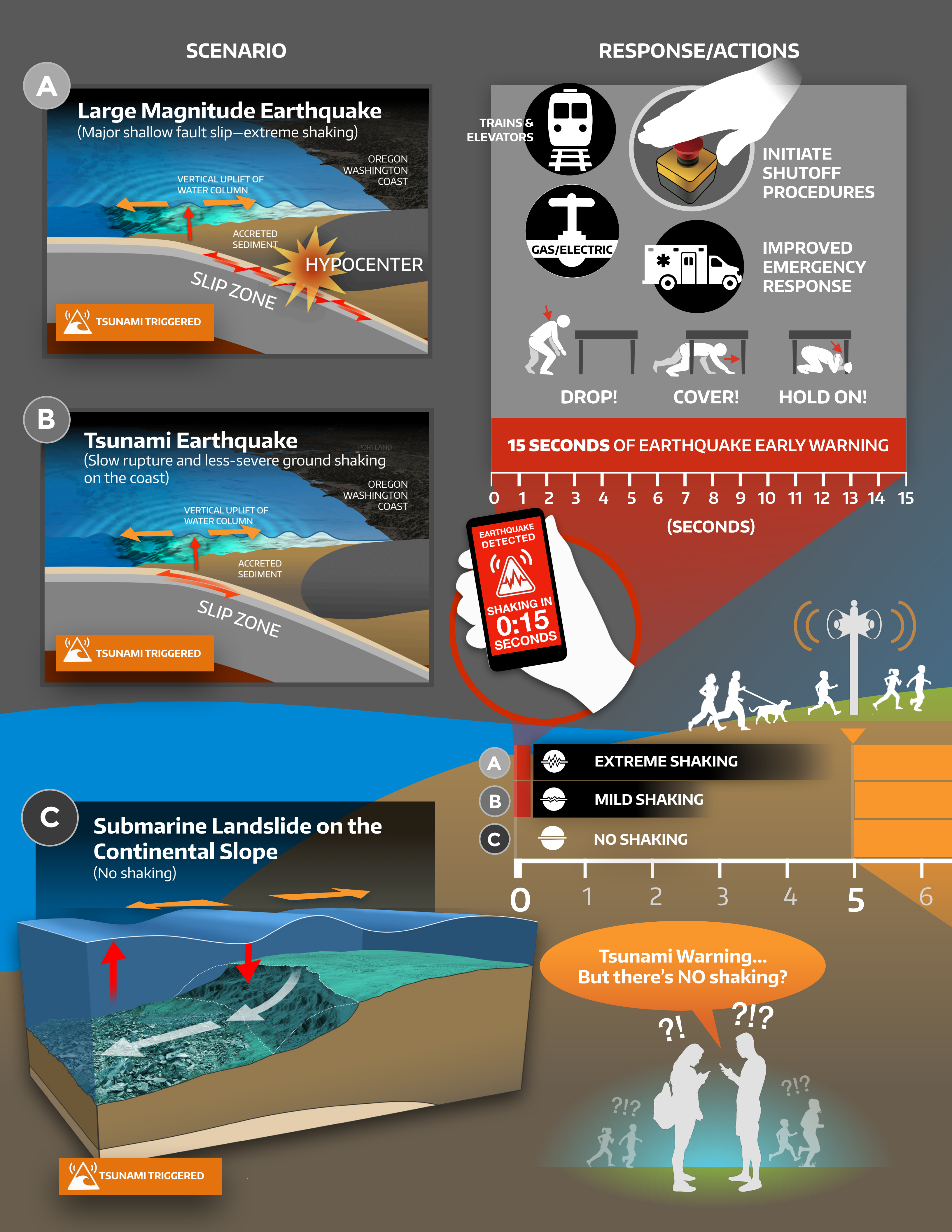
The scenarios described here and other models provide a tool to evaluate the relative timelines of the source process, seafloor and land-based observational goals, analysis goals, and impacts. They also can be used to prioritize specific system elements. Extending a seismic monitoring network offshore reduces the time needed to detect the arrival of initial P-waves by several seconds, adding this amount of time to the total earthquake warning time for both the closest and more distant communities. The capability to quantify the seafloor deformation patterns in real time using a seafloor instrument network could identify the onset of a tsunami, reduce the time needed to conduct accurate tsunami modeling, and provide several additional minutes of accurate tsunami impact estimates to guide warnings and emergency responses (LeVeque et al., 2018). Currently, without geodetic information offshore, tsunami modeling begins when an earthquake source is determined from far-field seismic stations, after the earthquake rupture process has completed (~5 minutes). Tsunami models driven by the far-field seismic stations produce less accurate forecasts of anticipated impacts such as run-up heights, which are critical to the nearfield coastal communities.

Early Warning Saves Lives and Reduces Damage

It is widely accepted that early warning systems save lives (UNISDR, 2010). A relatively well-established example of successful warning systems are cyclone warning systems, which provide longer warning times (days as compared to minutes), but also require much greater evacuation distances. The Hong Kong Tropical Cyclone Warning System has dramatically reduced the number of deaths and missing persons since 1960 (Rogers and Tsirkunov, 2010). Cyclone deaths in Bangladesh have also decreased dramatically since 1970, due in part to the Bangladesh early warning system (Haque et al., 2012).

Motivated by the clear benefits, EEW systems have already been implemented in several countries worldwide, including Mexico, Japan, Turkey, Romania, China, Italy, and Taiwan. Both Mexico and Japan operate systems that disseminate widespread warnings to the public and the lessons learned from these systems (Allen et al., 2012) are helping to guide similar implementations in several other countries, including the U.S., where the ShakeAlert system is being developed for the West Coast. The best demonstration of the effectiveness of an EEW system is the 2011 Tohoku Japan earthquake. Here, the Japanese EEW system provided several million people with 15–20 s of warning prior to the most severe shaking, with 90% reporting that they took actions to protect themselves or their family from injury (Fujinawa and Noda, 2013). Studies of the casualties from the Tohoku Japan tsunami show that an earlier evacuation start time was an important predictor of survival (Yun and Hamada, 2015). Japan is now in the process of developing the world's first nearshore tsunami warning system using local offshore observations to improve the quality and timeliness of warnings.

The benefits of early warning in the Pacific Northwest are reduced damage to infrastructure and its impacts, and fewer fatalities and injuries. The economic benefits of early warning are likely substantial, although they are difficult to estimate and more detailed studies are needed. Direct and indirect economic losses for a subduction zone earthquake have been predicted to be approximately $49 billion in Washington, $32 billion in Oregon (Cascadia Region Earthquake Workgroup, 2013), and CAN$75 billion for British Columbia (AIR Worldwide, 2013). For comparison, estimates of the actual losses for the 2011 Tohoku

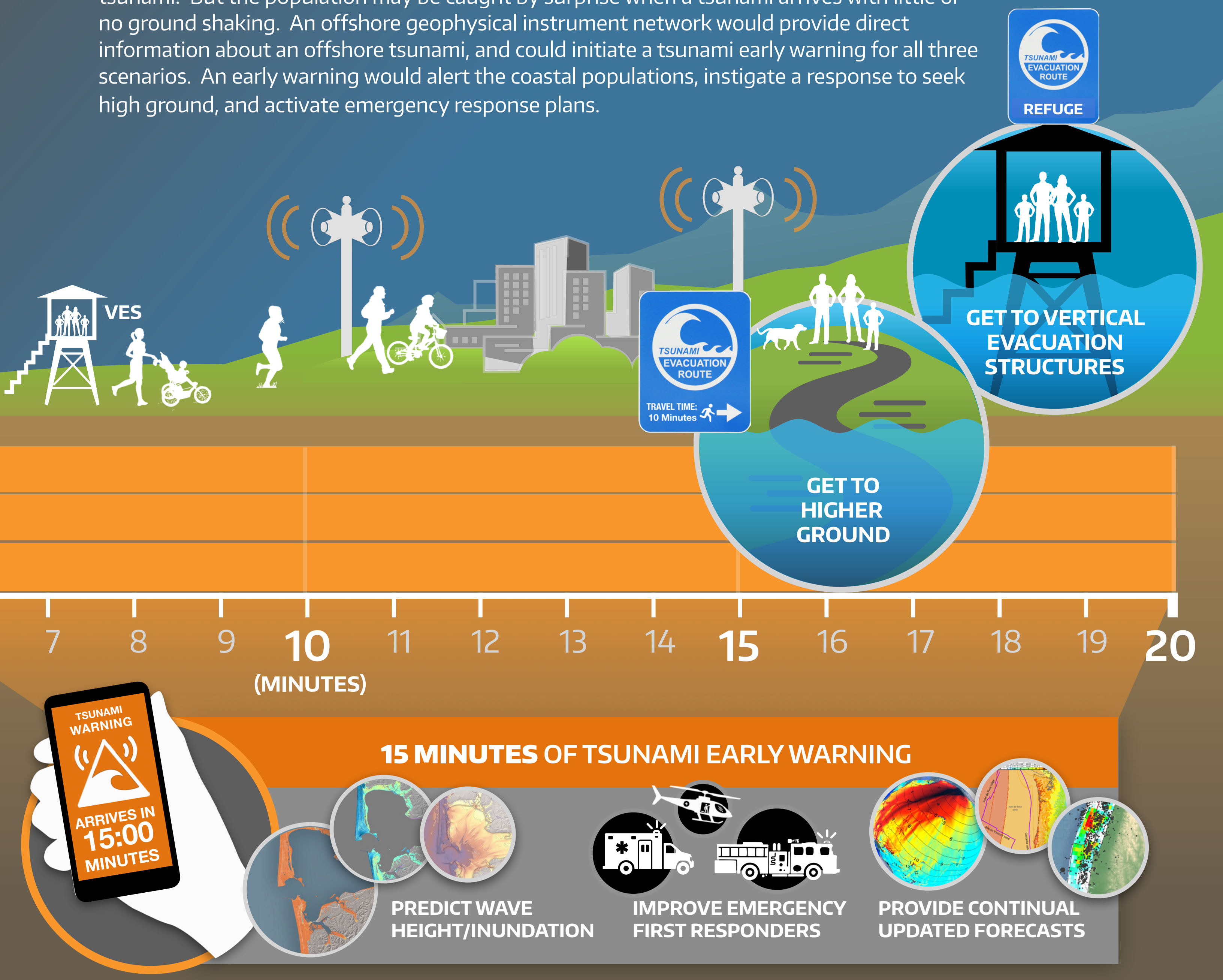


SCENARIO
RESPONSE/ACTIONS
A
Large Magnitude Earthquake
(Major shallow fault slip—extreme shaking)
OREGON WASHINGTON COAST
VERTICAL UPLIFT OF WATER COLUMN
ACCRETED SEDIMENT
HYPOCENTER
SLIP ZONE
TSUNAMI TRIGGERED
B
Tsunami Earthquake
(Slow rupture and less-severe ground shaking on the coast)
PORTLAND
OREGON WASHINGTON COAST
VERTICAL UPLIFT OF WATER COLUMN
ACCRETED SEDIMENT
SLIP ZONE
TSUNAMI TRIGGERED
TRAINS & ELEVATORS
GAS/ELECTRIC
INITIATE SHUTOFF PROCEDURES
IMPROVED EMERGENCY RESPONSE
DROP!
COVER!
HOLD ON!
15 SECONDS OF EARTHQUAKE EARLY WARNING
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
(SECONDS)
EARTHQUAKE DETECTED
SHAKING IN 0:15 SECONDS
A EXTREME SHAKING
B MILD SHAKING
C NO SHAKING
0 1 2 3 4 5 6
C
Submarine Landslide on the Continental Slope
(No shaking)
TSUNAMI TRIGGERED
Tsunami Warning...
But there's NO shaking?
?!
?!?
?!?
?!?

TSUNAMI EARTHQUAKE & SUBMARINE LANDSLIDE EVENT

There are three possible scenarios that can lead to a tsunami: (A) a large magnitude earthquake that distorts the seafloor (see page 18 for the magnitude 9 scenario), (B) a tsunami earthquake (or sometimes called a slow earthquake) that distorts the seafloor, and produces a tsunami that is larger than expected relative to the magnitude of the earthquake, or (C) a submarine landslide that displaces seawater and initiates a tsunami. For these three scenarios, residents on the coast would experience dramatically different levels of ground shaking prior to the arrival of the tsunami, ranging from intense shaking from a large earthquake, to mild shaking from a tsunami earthquake, to no shaking for the submarine landslide.

The violent shaking of a large offshore earthquake would forewarn the coastal population of a possible tsunami. But the population may be caught by surprise when a tsunami arrives with little or no ground shaking. An offshore geophysical instrument network would provide direct information about an offshore tsunami, and could initiate a tsunami early warning for all three scenarios. An early warning would alert the coastal populations, instigate a response to seek high ground, and activate emergency response plans.



RESPONSE/ACTIONS

earthquake range from $220 billion (Table 1) to over $300 billion (Daniell et al., 2011). Much of the direct damage from an earthquake and tsunami cannot be avoided by early warning but there are some significant exceptions. For example, EEW can be used to shut down gas lines to minimize fires, secure delicate manufacturing and data systems, and protect transportation infrastructure by slowing down trains and securing airports (Strauss and Allen, 2016). The indirect economic benefits from early warning are likely to be more widespread because if society is more resilient, economic activity can resume more quickly. The Multihazard Mitigation Council has found that, on average, every $1 spent on mitigation of natural disasters provides $4–$6 in cost reduction (Multihazard Mitigation Council, 2017).

The benefits of fewer casualties gained with early warning are easier to estimate. For example, based on the nature of casualties following the magnitude 6.9 1989 Loma Prieta and magnitude 6.7 1994 Northridge California earthquakes (Shoaf et al., 1998), EEW might be expected to reduce injuries by over 50% for a population that is well trained about effective responses. For the Northridge earthquake the estimated cost of injuries was $1.8–2.9 billion (Porter et al., 2006), so EEW might have translated into savings of $1–1.5 billion (Strauss and Allen, 2016). A TEW system would save lives by giving individuals the maximum amount of time to evacuate the inundation zone. Given FEMA's value of $6.3 million per life and anticipated fatalities of 16,000 along the coast, the potential human cost from a Cascadia subduction zone tsunami is near $100 billion. Even with only a small reduction in injuries and fatalities, an earthquake and tsunami early warning system would pay for itself and other preparedness planning.

Without a warning system in place, strong shaking along the coast would likely be the only advanced warning that a large tsunami is expected. Planning and education is essential to ensure that people know to move as quickly as possible to high ground, as far above sea level as possible. However, there are several reasons why it is also desirable to develop more effective methods for providing nearfield earthquake and tsunami warnings. Improved earthquake warnings that allow people along the coast time to drop, cover, and hold on before the worst shaking starts, or potentially leave an unsafe building or stop dangerous activities, would reduce injuries, and increase the number of people who would then be able to move quickly out of the inundation zone or access vertical evacuation structures once the shaking stops. Moreover, although the first wave will arrive at coastal locations near the earthquake source region very quickly, tsunami wave inundation often continues for many hours after the first wave has arrived. An improved TEW system would provide more detailed information about the wave heights, expected arrival times, and later arriving waves than is available from the current warning system. Along with more timely warnings to the public, this would aid first responders and provide better data to guide decision making by emergency managers.

Although the correlation between earthquake ground shaking and a potential imminent tsunami is becoming more recognized by the general public, this type of warning will not exist for all scenarios, as some events and locations will not necessarily be associated with strong shaking. The advantages of creating a TEW system are especially clear for coastal communities in the Salish Sea (including Puget Sound). These communities will experience the first wave more than two hours after the earthquake due to the relatively slow propagation through the Strait of Juan de Fuca. In scenarios where tsunamis are triggered by an earthquake concentrated on the southern edge of the Cascadia subduction zone from a 'tsunami earthquake' that has relatively little shaking, or by a submarine landslide event that is aseismic, a better nearfield tsunami warning system could provide the only warning for these communities that a tsunami is imminent, as well as valuable information regarding the time, size, and severity of a coming event.

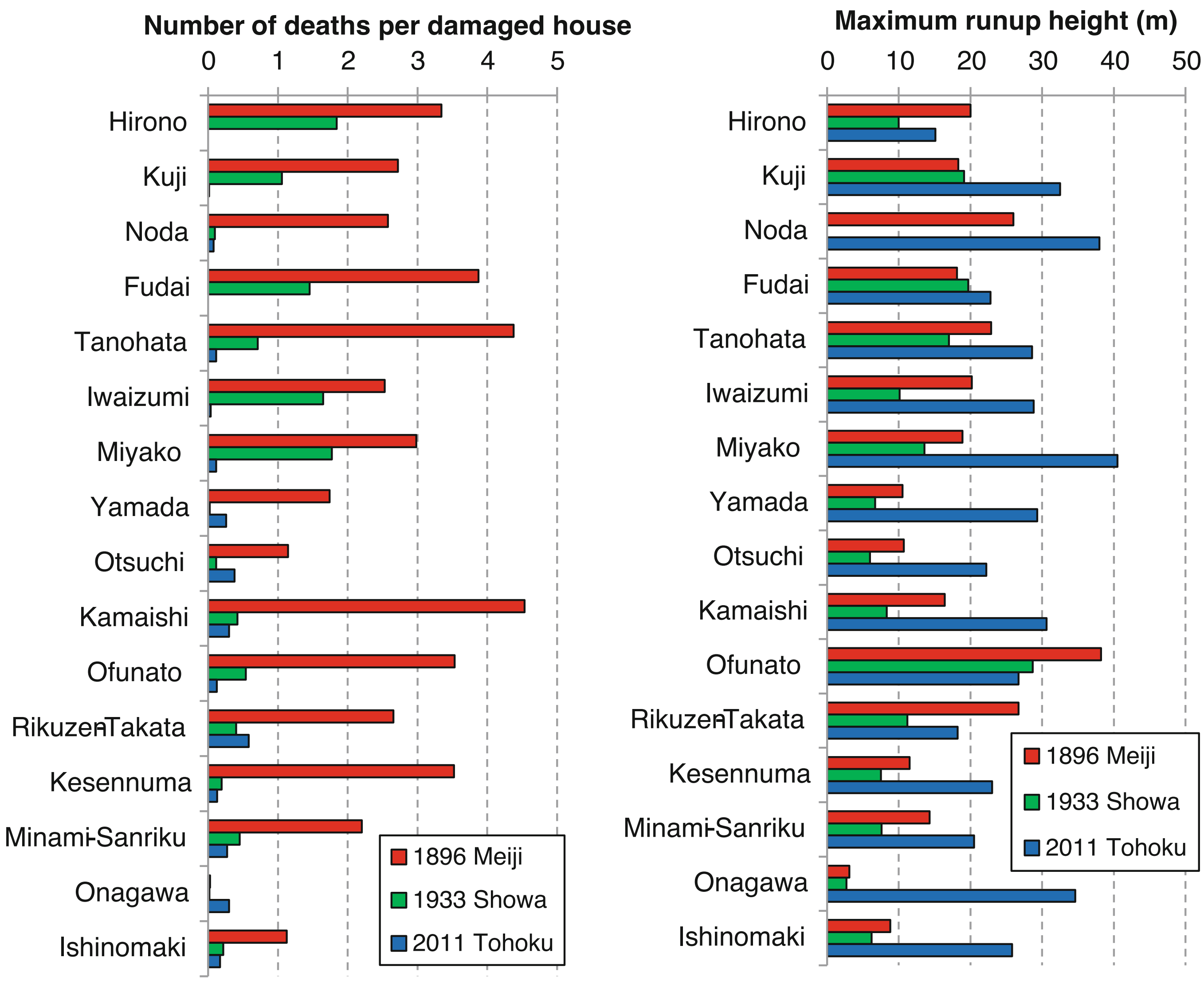


Figure 8. A comparison of fatalities associated with three tsunami events on the Japanese coast: the 1896 Meiji, 1933 Showa, and 2011 Tohoku events. Fatalities were reduced over time (left) due to integrated mitigation and early warning efforts, despite similar tsunami run-up heights for the three events (right). Adapted from Suppasri et al. (2013).

Early Warning as Part of a Holistic Loss Reduction Plan

An early warning system is but one component of an effective strategy to reduce the loss of life and property from earthquakes and tsunamis. A complete loss reduction system can be framed in pre-, co-, and post-event terms as preparedness, warning and response, and recovery. All parts of this system are interdependent and all are necessary for effective reduction of the loss of life and material community assets. A recent study of historical earthquake and tsunami events in Japan reports that integrated mitigation and early warning efforts have been responsible for a dramatic reduction in fatalities (Suppasri et al., 2013; Figure 8).

Pre-event preparedness. The value of early warnings is limited by the preparedness of the users to take protective action and the effectiveness of the system to distribute the warnings. Given the relatively short warning times for EEW, human actions to offset otherwise damaging impacts such as stopping dangerous activities, getting under tables, and moving away from falling hazards, rely on effective education and training. Automated responses such as shutting off valves, slowing trains, and stopping delicate manufacturing processes must be carefully preplanned and implemented. Both the human and automated components must be developed with the local and state emergency managers and disaster mitigation planners. In addition, it is essential to distribute effective warnings widely and extremely rapidly, and all of these capabilities must be developed through pre-event preparedness. The details of warning distribution modalities are beyond the scope of this report, but are in use in other countries and being developed for terrestrial-based EEW on the U.S. West Coast. They include sirens, broadcast radio and tv messages, and cell phone apps.

Ocosta Elementary School, Westport, WA

Preparation also includes the task of hardening infrastructure at particular risk from earthquakes such as unreinforced masonry buildings, structures on ground prone to liquefaction, old high-rise buildings, transportation corridors including bridges, and utility systems. On the coast, vertical evacuation structures are absolutely critical to provide refuge from a tsunami in areas where people cannot reach high ground within the warning time frame. Japanese communities embraced the concept after the 2004 Sumatra tsunami and a significant number of lives were saved in the 2011 Tohoku Japan tsunami, as residents evacuated to the rooftops of existing multi-story buildings and specially designed towers, berms, and other structures (Fraser et al., 2012). Washington State's Project Safe Haven has identified 75 coastal sites where vertical evacuation structures are needed (Wood et al., 2014). These structures must survive both the earthquake and the tsunamis. While efforts to design and construct vertical evacuation structures are community-driven, the involvement of emergency managers, social scientists, and other scientific, engineering, and technical professionals is essential. In 2016, a new Ocosta Elementary School building in Westport, WA, was completed, featuring a gym with a rooftop tsunami safe haven that was added for about 10% of the total cost; this was the first tsunami vertical evacuation structure in the country, with financial support provided by the passage of a local bond issue. Various funding sources, including FEMA grants, can support vertical evacuation structure design and construction. Several communities in Washington are now engaged in developing proposals and/or designing structures, including the Shoalwater Bay Tribe, the Aberdeen School District, and the Pacific County Fire District. Another vital need in tsunami prone areas are resilient transportation corridors to enable people on foot to exit tsunami inundation zones or reach vertical evacuation structures after an earthquake.

Co-event warning is needed to reduce the deaths, injuries, and damage that can be avoided by a direct action in the seconds-to-minutes before the arrival of strong ground shaking and the tsunami wave. Most injuries during an earthquake originate from falling debris when the shaking begins. Even minor injuries can impede an individual from quickly evacuating a tsunami inundation zone. Situational awareness and the well-informed anticipation of imminent shaking that follows an EEW will allow people to take the necessary actions to better protect themselves. Most deaths from the 2011 Tohoku Japan and 2004 Sumatra earthquakes were a result of the tsunami. A TEW increases the amount of time for people to evacuate inland and/or to high ground, and, importantly, also provides warning for unheralded tsunamis originating from a slow earthquake or submarine landslide.

Co-event response depends on the education and training of a population and the development of automatic systems to take life-saving action, and a reliable early warning system to provide enough time for the execution of these actions.

Post-event recovery depends on pre-event planning to increase the probability of population survival and enable the continued existence of a viable community by mitigating the disastrous impacts of earthquakes and tsunamis. Preparedness plans are needed at all levels to expedite recovery at community, city, county, state, and federal levels. The tragedy of a natural disaster extends beyond the immediate impacts of the natural event itself, and includes cascading impacts on the economic, social, and cultural foundations of the community. Resilience is a component of preparedness that seeks to ensure the recovery and long-term existence, sustainability, and vitality of a community by focusing on strategies to improve the post-disaster outcome. Community resilience is a somewhat amorphous concept but it has been defined in terms of nine key components: local knowledge, community networks and relationships, communication, health, governance and leadership, resources, economic investment, preparedness, and mental outlook (Patel et al., 2017).

Northern California, Oregon, Washington, and British Columbia will suffer the greatest impact of a Cascadia subduction zone earthquake and tsunami. California promotes resilience in each of its state-level natural hazard plans (State of California Emergency Plan, 2017), while Oregon, Washington, and British Columbia have developed comprehensive emergency management systems encompassing preparedness, warning, and recovery plans focused on the concept of resilience (Oregon Seismic Safety Policy Advisory Commission, 2013; Washington State Emergency Management Division, 2012; British Columbia Emergency Management System, 2016).

An Opportunity for New Scientific Insights

In addition to its application for EEW and TEW, a real time and continuous offshore instrument network would intrinsically incorporate unprecedented scientific observational capabilities, which, in the long term, may provide the earthquake research community an opportunity to better understand the physical processes at work within the subduction zone system. In this way, infrastructure for early warning could lead to critical research breakthroughs in the areas of early warning protocols or even earthquake and tsunami prediction. Most research on subduction zone earthquakes has been conducted using land-based observations far from the source, or short-term deployments of sensors offshore, generating snapshots of earth processes that are limited in time and space. The availability of continuous data containing information on small earthquakes, tectonic deformation patterns, or other, as yet poorly sampled earth processes (e.g., submarine landslides and turbidites, tectonic tremor, transient slow slip) across the primary fault zone offshore Cascadia, could lead to the development of new monitoring strategies that would provide improved forecasts.

In the last 10 years, several great earthquakes have occurred worldwide along margins including Sumatra, Japan, and Chile. With evolving onshore and offshore observational capabilities, precursory activity has been identified with some of these events such as the 2011 Tohoku Japan (Ruiz et al., 2014; Kato et al., 2012) and 2014 Iquique, Chile earthquakes (Ruiz et al., 2014). Phenomena like these have the potential to provide new insights into the precursory processes of large slip events on subduction plate boundary faults. Observations do not yet exist on most subduction zone margins to distinguish potential precursory activity like foreshocks (smaller earthquakes preceding larger earthquakes), changes in microseismicity patterns (very small earthquakes that may change in temporal occurrence rate or spatial location), or sub-seismic processes like slow slip or transient locking (plate motion that is too slow to generate seismic waves, in locations accompanied by tectonic tremor). Developing a continuous, real time, offshore instrument network for early warning would have the benefit of simultaneously providing information on the state of the subduction fault environment that could be used for basic earthquake research (Table 3).

Earth science insights enabled by an offshore instrument network include:

- The stress state of the plate boundary — important for monitoring the earthquake cycle and the general mechanical behavior of the fault
- The location of strong or weak asperities — relevant to anticipating where strong, high-frequency ground shaking is likely to originate
- The geometry of the system and existence of branching or splay faults that extend above or below the primary plate boundary — important for modeling large slip and seafloor deformation leading to tsunamis
- How deformation is accommodated above and around the locked portion of the plate boundary at Cascadia

Table 3. Offshore instrument network observations for long-term monitoring and scientific research

RESEARCH PURPOSE	OBSERVATIONAL REQUIREMENT
Characterize background seismicity or tectonic tremor	Seismic station distribution at uniform density for detection and depth determination
Evaluate plate boundary slip (locking) behavior	Continuous seafloor geodetic monitoring, horizontal and vertical motion
Characterize multiscale deformation	Alternative tools to monitor diffusional and dislocation processes, fluid flow, heat flow, and temporal evolution of gravity field, and repeat multibeam bathymetry or seafloor interferometry

Instruments to Detect and Monitor Offshore Events

The core components of any offshore earthquake or tsunami detection system are the geophysical instruments that make fundamental observations of earth or ocean movements before, during, and after an earthquake and tsunami. There are many existing and evolving technologies that would enable EEW and TEW, which can be grouped into three categories:

1. Instruments intended primarily for early warning of earthquakes
2. Instruments to detect and monitor tsunamis as they approach shore
3. Instruments needed to fulfill long-term research objectives (e.g., geodetic and formation strain research) to improve our ability to assess the likelihood and potential impact of future earthquakes and tsunamis

Several technologies that may fulfill a primary role in one of these categories may also provide synergistic or secondary support to another area. In some cases, technologies initially developed for unrelated applications show promise for EEW and TEW. In yet other instances, new technologies are under development that may enhance our ability to detect or characterize offshore earthquake or tsunami events (Table 4).

Detecting Earthquakes

Seismometers record ground movement by making fine measurements of the motion of an internal mass with respect to the instrument frame. This technology was first introduced over 2000 years ago, with accelerated development since the end of the 19th century. Ground motion is experienced over a wide range of frequencies, with low-frequency waves responsible for a gentle rolling motion during an earthquake and high-frequency waves associated with rapid shaking. Modern seismometers can measure and digitally report 3-axis motion (east/north/vertical) over a broad range of these frequencies (hundredths to hundreds of hertz).

Seismometers can be subdivided into different instrument types based on their sensitivity to different wave frequencies. For example, strong motion sensors, or accelerometers, are a class of seismometers most sensitive to high-frequency energy (10–50 Hz), and are able to register large magnitude signals that might be off-scale for seismometers measuring lower frequencies.

Table 4. Instruments for EEW, TEW, and long-term research and monitoring applications, with indications of whether the sensing technology is of primary or secondary use, represents a mature technology with developing application, or is an emerging technology.

INSTRUMENT	EARTHQUAKE DETECTION	TSUNAMI DETECTION & CHARACTERIZATION	RESEARCH AND MONITORING
Seismometer	P	S	P
Strong Motion/ Accelerometer	P		P
Seafloor Tilt	AD		P
Gravimeter	AD		P
Bottom Pressure	S	P	P
GNSS Buoy		P	
GNSS displacements (land-based)	S	AD	P
GNSS Ionosphere (land-based)		AD	
GNSS-Acoustic			P/AD
HF Radar		AD	
Sonar Survey (bathymetry)			AD
Satellite Laser		E	
Fiber Optic Strain/ Distributed Acoustic Sensing (DAS)	E	E	E
Self-Calibrating Pressure	S	S	E
6-component Seismometer	E		

P = Developed and in use as primary means of detection

S = Developed and in use as a secondary means of detection

AD = Application under development (underlying technology already proven)

E = Emerging technology

Seismometer technology is mature and robust. When provided continuous power and built from appropriate material, underwater seismometers are capable of long-term ocean deployments for many years without maintenance. In successful installations, ocean bottom seismometers (OBS) are well-coupled to the seabed, sometimes installed by a remotely operated vehicle (ROV), and efforts are made to dampen noise induced by water flow (Figure 9).

While seismometers are the primary instrument for earthquake detection, other motion-sensitive measurement technologies may be used to detect seismic waves. Sometimes referred to as inclinometers, tilt instruments can detect fine changes in the local slope of the seafloor to tenths of microradians.

Several emerging technologies hold potential for sensing motions of the seafloor. One effect of earthquake-induced seafloor motion is the change in seafloor strain (elongation

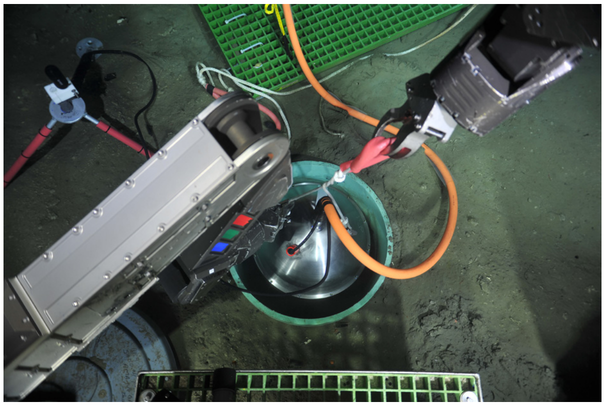
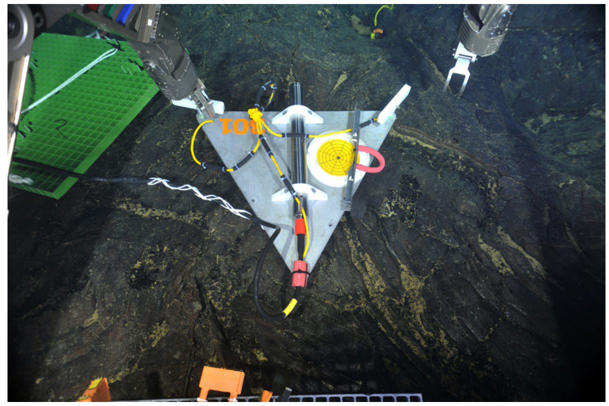



Figure 9. (left) A broadband OBS installed in a caisson that will be filled with silica beads to dampen noise yet provide good coupling to seabed ground motion. (right) A short-period OBS installed at ASHES vent field on Axial Seamount. The sensing unit is housed in titanium to resist corrosion. (Photos from NSF-OOI/UW/CSSF.)

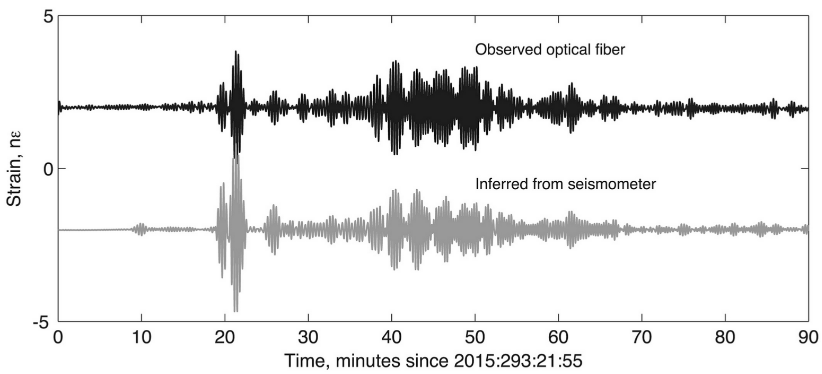


Figure 10. Comparison of seismic event detection by an optical fiber strain meter and a traditional seismometer. Figure from Zumberge et al. (2018).

or compression). Long- and short-term changes in strain are detectable by an emerging measurement technology that uses changes in backscatter of pulsed light signals transmitted through an optical fiber. The technology known as Distributed Acoustic Sensing (DAS) measures disturbances at acoustic frequencies (Parker et al., 2014). A single DAS system may be able to detect events along a 40–50-km length of cable and localize the activity to within a few meters (resolution determined by optical pulse length). Further, DAS has the potential to use dark fibers, that is, unused optical fibers, in existing transoceanic fiber optic cables for seismic monitoring.

Optical fiber strain measurements show promise when the fiber optic cables can be well-coupled to the seabed. The strain signal detected through an optical fiber stretched between two seafloor anchors compares well with inferred seismometer data of the same event (Figure 10; Zumberge et al., 2018).

Changes in gravity signals can indicate corresponding changes associated with movement of the earth (Vallée et al., 2017). The momentary density changes in the earth's rock structures that occur during an earthquake can account for small changes in gravity that travel at the speed of light, much faster than the P-waves measured by seismometers. Although the gravity signal is weak, there is ongoing research on the use of gravimeters to detect large earthquakes.

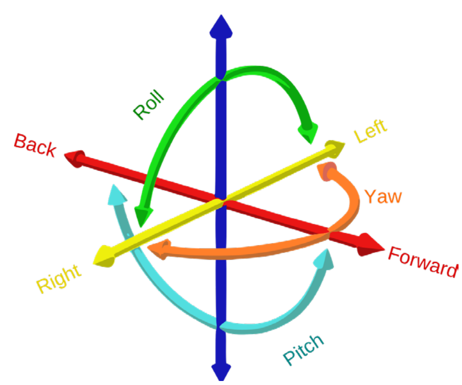


Figure 11. Six-axis motion. From GregorDS, CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0.

Another emerging technique for earthquake detection adds rotational sensing to standard three-axis accelerometers (Nigbor, 1994; Schreiber et al., 2009). When measured in conjunction with three-axis linear motion, rotation improves our understanding of the complex six degrees-of-freedom motion (Figure 11) that can occur at the source of earthquake events by adding roll, pitch, and yaw observations to lateral and vertical translation. High-precision and low-noise measurements of rotation are typically made using ring laser gyroscopes, but smaller, less costly alternatives may be viable to integrate with accelerometers for seismic applications.

Detecting Tsunamis

In the far field, out of the seafloor co-seismic displacement region, tsunami waves are most effectively measured by ocean bottom pressure sensors. Pressure measured at the seafloor is an indicator of the height of the water column above the instrument. Therefore, changes in pressure can be correlated with changes in the water height above the sensor at any given time. Modern sensors, installed on the seafloor, can measure depth with sub-millimeter resolution. The NOAA DART buoy network began with six research buoys in 2001 and now consists of more than 60 operational buoys designed for multi-year operation (Figure 12) that deliver real time tsunami and tide data to Tsunami Warning Centers.

However, in the nearfield region where seafloor co-seismic displacement occurs, it is difficult to determine the absolute amplitude of the tsunami wave using a pressure sensor alone because the water column initially moves synchronously with the seabed. The addition of a co-located surface GNSS receiver enables a more direct and accurate measurement of sea surface elevation; GNSS buoy technology has evolved to achieve a measurement precision of centimeters to decimeters, which is adequate for measuring maximum tsunami amplitudes on the order of meters in the near field (Nagai et al., 2007; Akoh et al., 2017).

In addition to the point measurements of pressure and the water surface height, direct measurements of seafloor motion provide critical information to determine earthquake location and magnitude, and provide initial constraints for models of tsunami propagation. Therefore, several of the earthquake sensors described in the previous section, including seismometers, tiltmeters, DAS systems, or six-component seismometers, may have a role in TEW.

As tsunamis near the coastline, coastal-mounted high-frequency (HF) radar networks, typically used to measure ocean surface currents in near-real time (Paduan and Washburn, 2013), may prove useful for tsunami detection and forecasting (Toguchi et al., 2018; Roarty et al., 2019). HF radar systems perform hourly current averaging as part of the NOAA Integrated Ocean Observing System program (Appendix C), and are capable of measuring surface currents out to 200 km with kilometer-scale resolution.

Several other remote sensing approaches for detecting a tsunami hold potential but are still in development. Satellite laser and land-based GNSS observations can be used to measure and detect the elevated sea surface during a tsunami. GNSS observations are sensitive to changes in the ionosphere, which become distorted by the propagating tsunami (Savastano et al., 2017; Kamogawa et al., 2016). Additionally, laser ranging from orbiting satellites (Hamlington et al., 2012) or GNSS observations from passing ships (Inazu et al., 2018) can be used to observe the tsunami directly. While these approaches are promising, it has not yet been demonstrated if any of them can transfer data in near-real time to provide timely alerts, or have the necessary coverage or reliability. Direct onshore observations of surface displacements from GNSS is the closest to an operational state and could provide near-real time warning (Melgar and Bock, 2013). This approach of using only onshore data still has

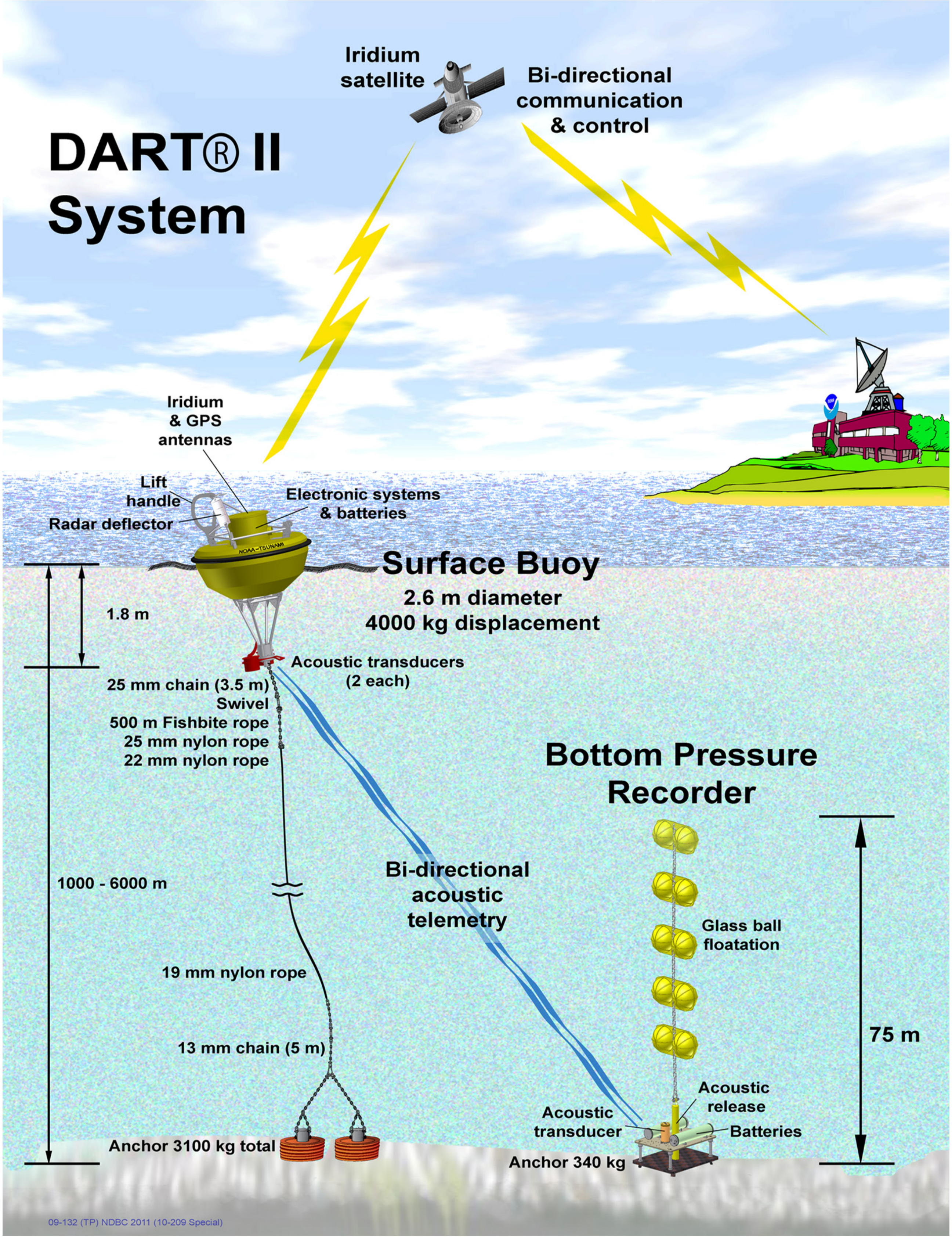


Figure 12. DART II tsunami detection system uses a seafloor pressure sensor to measure changes in the height of the water column and a sea surface platform with a GNSS antenna to measure position and keep accurate time. The buoy also provides a communication link between the sensors and a data analysis center. Image from https://www.ndbc.noaa.gov/dart/dart.shtml.

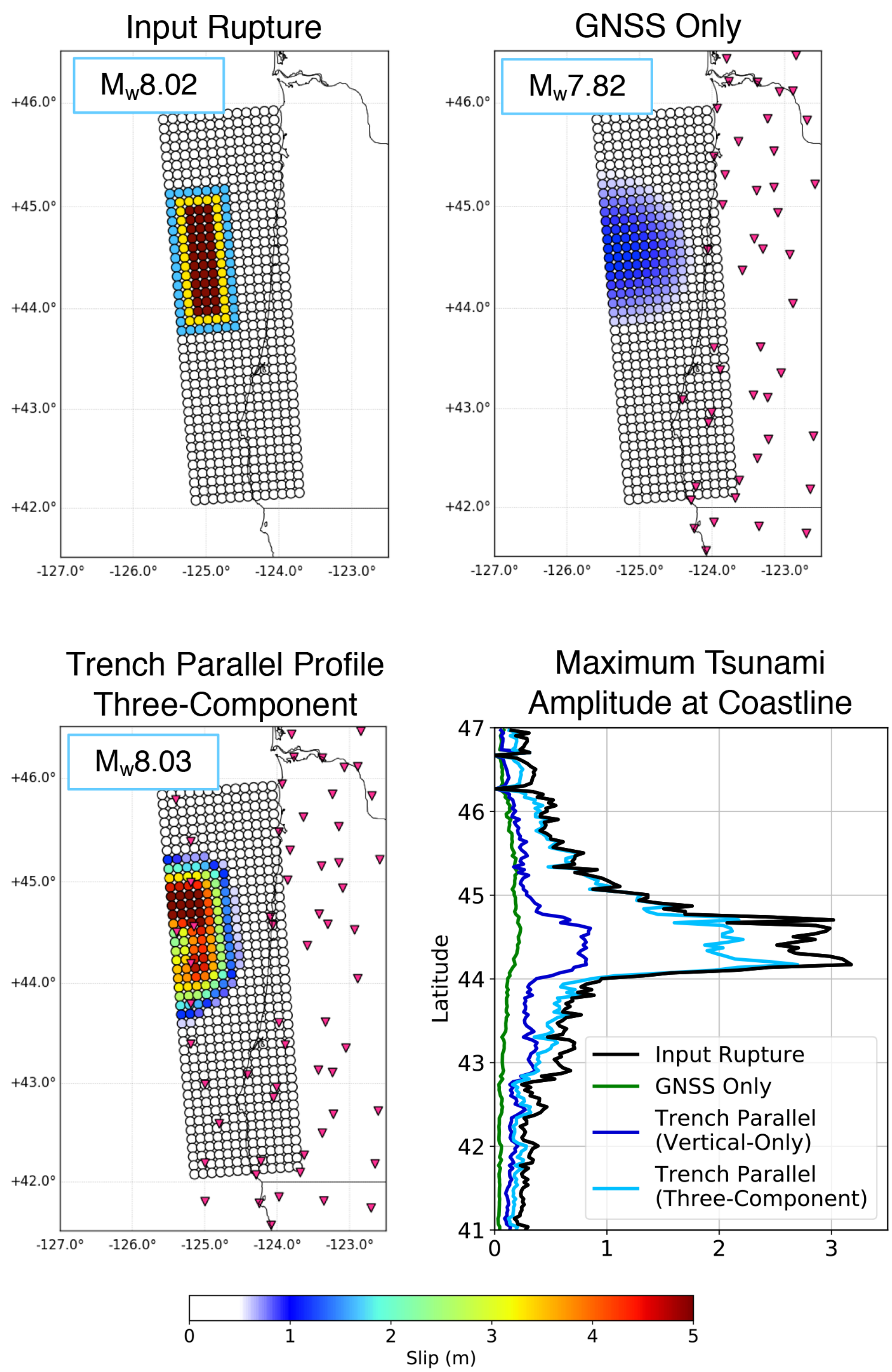


Figure 13. Predicted tsunami wave height at the coastline (lower right) given different offshore instrument arrangements that measure surface deformation for an offshore earthquake. The input fault slip model (colored circles in upper left plot) define the amount of fault slip on the fault during a hypothetical earthquake. 'GNSS only' uses the onshore GNSS data to constrain the earthquake source (colored circles in upper right) and to predict the tsunami height at the coastline. The 'Trench Parallel Profile' includes a line of deformation measurements on the seafloor in addition to the onshore instruments to estimate the fault slip (lower left) and to predict the tsunami height at the coastline. An ideal instrument network would reproduce tsunami height indicated by the black line (lower right). Seafloor observations significantly improve the prediction of the tsunami height (light blue line in lower right) compared to a network of only onshore instruments (green line). Adapted from Saunders and Haase (2018).

limited offshore resolution, particularly for events that rupture the trench (Williamson and Newman, 2018). Thus, the forecasted tsunami wave heights may be underpredicted using only onshore data (Figure 13).

Measuring Deformation

In addition to detecting sudden seismic events and the resulting tsunamis, EEW and TEW instruments will provide critical observations to aid hazard assessments and scientific study. The instruments would enhance insight into plate movements and crustal strain, improving our understanding of the precursors to imminent seismic activity. The sensors can also measure the slow and gradual motion of tectonic plates that lead to the build-up of strain along the subduction zone prior to the next earthquake. By quantifying this strain, scientists can gain insight into where strain is accumulating and where the risk is elevated.

Continental GNSS stations measure plate movements well, but because satellite signals do not penetrate through the ocean, alternative means of tracking geodetic movements on the seafloor are needed. Acoustic-GNSS, developed to make geodetic measurements of the seafloor (Fujita et al., 2006; Spiess et al., 1998), involves seafloor mounted beacons that communicate acoustically with a surface vessel carrying a GNSS antenna. In a time-intensive procedure, the surface vessel is able to use repeated acoustic ranging data over days to years to compute the absolute position of the beacons. Repeated acoustic-GNSS observations provide an indication of seafloor motion attributable to locking or slip on faults. Recently, autonomous vehicles, such as the Liquid Robotics Wave Glider, have been developed as a low-cost platform (relative to ships) to collect acoustic-GNSS data. It has not yet been explored whether acoustic-GNSS can be operated in the near-real time mode appropriate for early warning.

Observations of strain, tilt, and pressure made in seafloor boreholes provide measurements of accumulated formation strain within the seabed. These measurements are key components of the International Ocean Discovery Program, which sponsors scientific seabed drilling. Boreholes offer further opportunities for additional sensing in an environment that is well-coupled to the seabed, hence able to provide reliable measurements of movement of the underlying rock. When it comes to measuring slowly-moving tectonic plates, a deficiency of many seafloor instruments is measurement drift that is similar in magnitude to the plate motion that is being measured. Emerging in situ calibration methodologies can be applied to pressure and accelerometer sensors to eliminate major measurement drift modes, and make these measurements viable for geodetic observation.

Active tectonic deformation results in changes in seafloor bathymetry, and seafloor mapping technologies can be used to measure these changes. Sonar systems, including multibeam, sidescan, and sub-bottom echosounders are used to survey the seafloor to measure bathymetry, surface morphology, and the layering of substrates below the seafloor. Bathymetric resolution is typically a function of the sonar's range from the seafloor. Consequently, autonomous underwater vehicles (AUVs), which are decoupled from the sea surface waves and are able to survey at constant altitude above the seabed, are able to generate much higher quality and resolution bathymetric data than vessel-borne sonars. Repeated AUV mapping over time is a valuable means of measuring changes in the seafloor.

System Requirements

An early warning system based on offshore instruments must be designed with the scientific and technical capabilities required to meet its high-level objectives. These system requirements are organized into three hierarchical levels, with each level providing greater specificity (Figure 14). The first level (L1) describes the top level goal of the system, the second level (L2) describes the individual sub-goals, and the third level (L3) describes the detailed requirements for each sub-goal. Additional documentation for the hierarchical requirements is available in online supplemental materials.

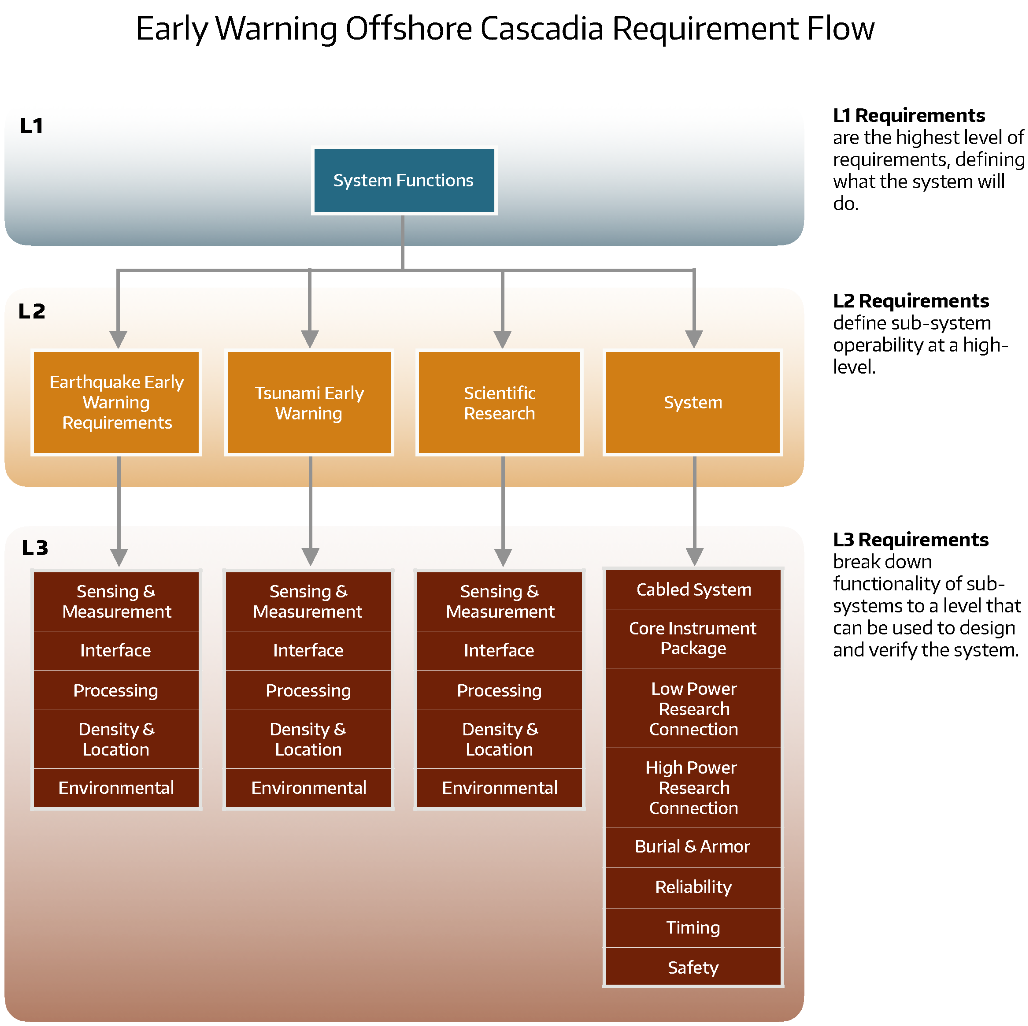


Figure 14. Cascadia EEW and TEW offshore instrument network requirements

Offshore instrument network requirements:

- Detect and provide timely information about potentially catastrophic offshore earthquake activity along the Cascadia subduction zone
- Detect and provide timely information about potentially catastrophic tsunamis originating along the Cascadia subduction zone
- Make and provide continuous time series observations of the Cascadia subduction zone
- Share raw and processed data with warning systems in real time

Note that this discussion of the requirements does not cover capabilities associated with the dissemination of the alert, which is the responsibility of federal and state agencies (USGS, NOAA, state emergency managers). Nor does this study address the public education campaign that is required for a successful public response. The focus of this study is the offshore components that provide observables to an EEW and TEW system. Any final system will need to consider the dissemination pathways and messaging of alerts to the public.

Earthquake Early Warning Requirements

The core activity for a network-based EEW system is to trigger on the P-wave from multiple stations, quickly estimate the location and magnitude, and issue an alert. Many of the technical requirements for such a task have already been defined as part of the ShakeAlert system (Given et al., 2018). The requirements relevant to an offshore system include:

- The detection, classification, and location of all earthquakes likely to be 'strongly felt' (Modified Mercalli Intensity ≥ V) from locations onshore
- An initial event detection within 10 seconds of nucleation, requiring a nominal station spacing of 50 km
- A delay in data transmission (latency) of less than 2 seconds from the instruments to the analysis center
- Continuous observations as the earthquake evolves so that the source parameters (magnitude and rupture extent) can be updated
- System resilience such that at least part of the system remains operational after the mainshock, and can issue alerts for the aftershocks
- A geographic distribution of stations that is widespread along the coast and offshore, both to 'surround' an epicenter and to facilitate tracking of a propagating large rupture

A critical driving factor on network design and costs is the station spacing required to achieve the desired warning time. The requirements here are not strict, but rather reflect realistic trade-offs between the expense and complexity of a denser monitoring network and the seconds of warning that the additional stations afford. Because the assets we wish to warn are generally onshore and not directly above the rupturing offshore faults, the need for ultra-rapid alert generation is relaxed relative to terrestrial monitoring. The station spacing of the terrestrial seismic network used for EEW in the Pacific Northwest is 10–40 km, depending on the proximity of the locale to be alerted to likely earthquake sources and the level of risk there. While a similar spacing offshore would provide uniform coverage across the shoreline, such an offshore density may be cost prohibitive. Fifty-km spacing should be sufficient. In general, stations do not need to be evenly spaced, such as in a regular grid. Denser spacing over the continental slope and trench would provide greater benefit than for stations closest to the shoreline (Araki et al., 2009; Kawaguchi et al., 2014). Nearshore stations would also be exposed to greater risks (i.e., trawling) and would have high levels of seismic noise in shallow water.

Tsunami Early Warning Requirements

A Cascadia subduction zone earthquake places the entire outer Pacific, Strait of Juan de Fuca, and Salish Sea coastlines at risk of tsunami-related fatalities and injuries, as well as infrastructure damage. For illustrative purposes, a scenario can be used to consider the needs and requirements for an effective TEW system. As the rupture of the fault evolves and deforms the seabed, the water column is also distorted and a tsunami wave begins to propagate. As the tsunami waves encounter shallow water, the wavelength is shortened and the amplitude increases. In 10–30 minutes following the earthquake, the first tsunami wave impacts the coast. The wave height and arrival time will vary along the Northern California, Oregon, Washington, and British Columbia coast depending on the epicenter of the earthquake.

In one possible simulation (Figure 7), the tsunami spreads inland through the estuaries, penetrating 2 km or more in some low lying areas, sweeping over the peninsulas at the entrances to Grays Harbor and Willipa Bay, and destroying everything in its path there and at other locations along the entire U.S. West Coast. Over the next 1–3 hours, several large secondary waves follow. These later arrivals are potentially very destructive because residents may be caught unaware and these waves carry debris created by previous waves. Waves entering the Strait of Juan de Fuca also take several hours to reach some locations in the Salish Sea. Throughout this period, slow-moving but dangerous edge waves traveling for large distances parallel to the coast may also impact nearshore sites. To warn against the initial and secondary waves, an effective TEW system must:

- Provide accurate and timely earthquake source parameters, largely provided by the EEW system, to seed the initial tsunami models used to predict coastal wave heights and arrival times
- In 5 minutes or less, provide coastal impact predictions on a length scale of tens of kilometers
- Provide coastal impact predictions every 10–30 minutes at decreasing length scales, down to 10-m resolution, focused on population centers and critical infrastructure sites, until the end of the tsunami threat

In comparison with EEW, the station spacing and distribution required for TEW is less well determined. Tsunami warning for a megathrust earthquake requires that the earthquake source parameters are well constrained by geophysical observations. Given the wavelengths and coast-parallel continuity of the first tsunami wave (Figure 7), it can be reasonably inferred that the 50-km station spacing required for EEW is also sufficient to observe the initial tsunami. However, if the goal is solely tsunami warning, more studies will be required to determine whether a sparser distribution of sensors would be adequate and if the optimal distribution of stations is uniform. For example, just a few stations may be adequate west of the rupture zone to characterize the first tsunami wave, with a higher density network necessary close to the shore to observe the edge waves that propagate near the coast for many hours after the earthquake (Figure 7). The design of the tsunami instrument network must also consider the likely source zones and characteristics of tsunamis caused by submarine landslides. There has been some effort to develop the methodologies necessary to optimize the placement of stations in a tsunami network (e.g., Mulia et al., 2017; Saunders and Haase, 2018), but much more work will be required before an optimized near-source tsunami instrument network can be proposed for the Cascadia subduction zone.

Monitoring and Scientific Research Requirements

The primary societal benefit of an offshore instrument network will be its ability to provide an early warning for earthquakes and tsunamis and, secondarily, the data collected on the network will enable monitoring of seismic activity in areas not already spanned by existing terrestrial instrument networks. Offshore observations are imperative for understanding the tsunamigenic potential of the trench, identifying active splay faults in the accretionary prism, and characterizing anomalous seismic activity. An offshore network could also be enhanced with additional instruments to capture oceanographic data for monitoring deep ocean currents and upwellings, and low-oxygen environments, as well as track fish and whale migrations. The requirements for aiding scientific study and hazard assessments of the subduction zone include:

- Continuous, sustained recordings of seafloor seismicity and deformation, with days-to-weeks latency in data telemetry
- A diverse mix of instrument types (e.g., seismometers, seafloor pressure gauges, geodetic instruments, hydrological instruments)

Real time latency is not a critical requirement for monitoring and scientific study, as the analysis of the data typically occurs over weeks to months. Even so, the research community is developing an expectation for near-real time data given the real time nature of terrestrial seismic and geodetic networks. A diverse mix of instrument types are necessary for scientific studies. Geophysical models are typically non-unique, and multiple, independent observational constraints are critical to resolve active faults, their geometry, and sense of motion. Finally, seafloor instruments are more susceptible to noise sources than terrestrial instruments. Surface winds, deep ocean currents, and tides are some of the noise sources that can dominate the observations. The best way to isolate and remove these noise sources is to have multiple observations on a mix of instrument types. More hardened instrument designs can also help shield sensors from noise sources.

Instrument Platforms and Network Design

The instruments on an offshore network capture measurements of surface motion, deformation, strain, or pressure. For these data to be useful for early warning, they must be transmitted back to an onshore analysis center. The network must include support structures (platforms) that maintain power and communications. Instruments can be deployed on the seabed, in the water column, or at the sea surface. Therefore, there are a variety of platforms that house these instruments and interconnect them. Here we discuss seafloor cabled systems and non-cabled options appropriate for EEW and TEW applications. A more technical discussion of the instruments and platforms is documented in an accompanying report (online supplemental materials). Additional components of an early warning system that are not discussed here include the alert generation, dissemination, and response. It is expected that an offshore instrument network would contribute data to the ShakeAlert and the U.S. Tsunami Warning systems that actually issue the alerts, and coordinate messaging and education.

Cabled Systems

Cabled systems are seafloor networks based on telecom industry technology that has been augmented to support oceanographic instruments and other equipment. These systems rely on shore stations to provide power and communications to undersea equipment through cables that incorporate copper conductors and optical fibers.

Cabled systems are used by navies, the offshore oil and gas industry, and cabled undersea observatories for multi-year/multi-site instrument deployments that require very low data latency. Of the three, cabled undersea observatories are the most applicable to an early warning system. The Japanese DONET and S-Net systems are relevant examples, being designed explicitly for offshore detection of earthquakes and tsunamis. Also relevant are general-purpose cabled ocean observatories such as the Ocean Observatories Initiative Cabled Array and the Ocean Networks Canada NEPTUNE and VENUS arrays (Appendix C).

A key benefit of cabled systems is that instruments are interconnected and hardwired to the shore station, and thus data availability to users is in real time, which is of great value for an early warning system. The cable from shore provides generous power, so these systems tend to have low average maintenance costs over time relative to standalone seafloor instruments, which require frequent servicing to replace batteries. Depending on configuration, cabled systems can also support additional instrumentation, including devices with high power and/or high bandwidth needs.

Cabled systems exist in two principle formats. The first is a continuous, linear string of instruments separated by lengths of cable and deployed in a single operation by a cable ship (e.g., the Japanese S-Net). The absence of underwater connectors has the potential to yield a very reliable system with few points of failure, but limits the instrument suite to relatively small and robust devices. For this format, a ROV is only needed for deployment when the cable is buried, typically in the nearshore environment to protect it from accidental damage by commercial fishing activities. Repairs would require a section of the cable to be recovered to the deck of a ship to allow the damaged elements to be cut out and replaced.

The second type of cabled system format is a modular array, relying on ROV wet-mate connectors to attach instruments and cables to dedicated seafloor junction boxes in a star or ring architecture. DONET, the OOI-CA, and ONC NEPTUNE are examples of this type of system. Although the more capital intensive of the two cabled array forms, it does allow relatively rapid servicing and the ability to add or change instruments with a ROV. A cabled system could also adopt a hybrid approach with linear instrument suites used to cover a large area and junction boxes at sites of particular interest.

Power

The two main options for powering a subsea cabled network are constant voltage and constant current. A constant voltage system uses a single conductor with –10 kV DC supplied by the shore station, and uses seawater to close the circuit as the electrical return path. Specialized nodes in the system convert the –10 kV down to lower voltages used by the instrument packages. The advantage of the constant voltage system is that it can provide high power (>10 kW) to devices that are hundreds of kilometers offshore. The OOI-CA and ONC NEPTUNE systems are based on this power configuration.

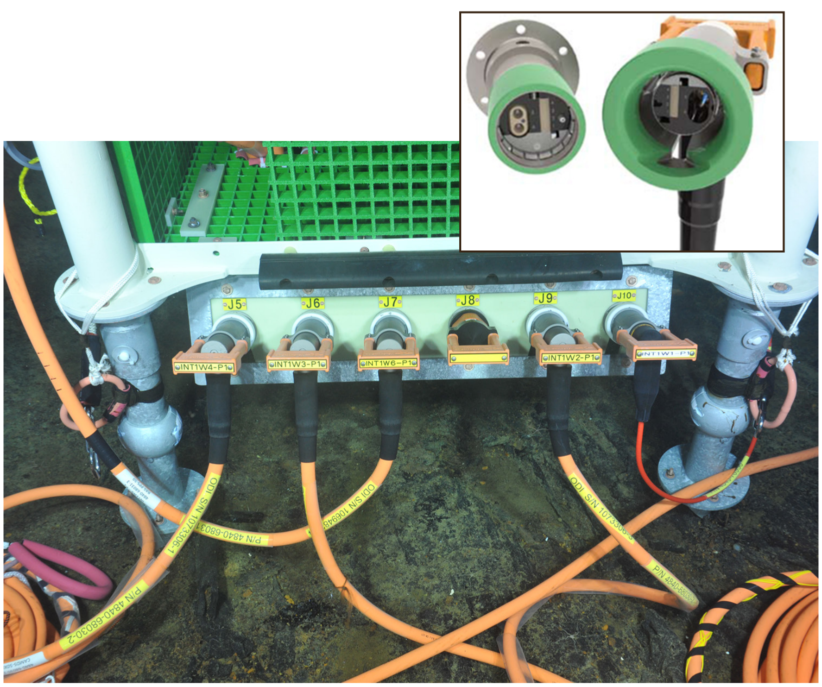
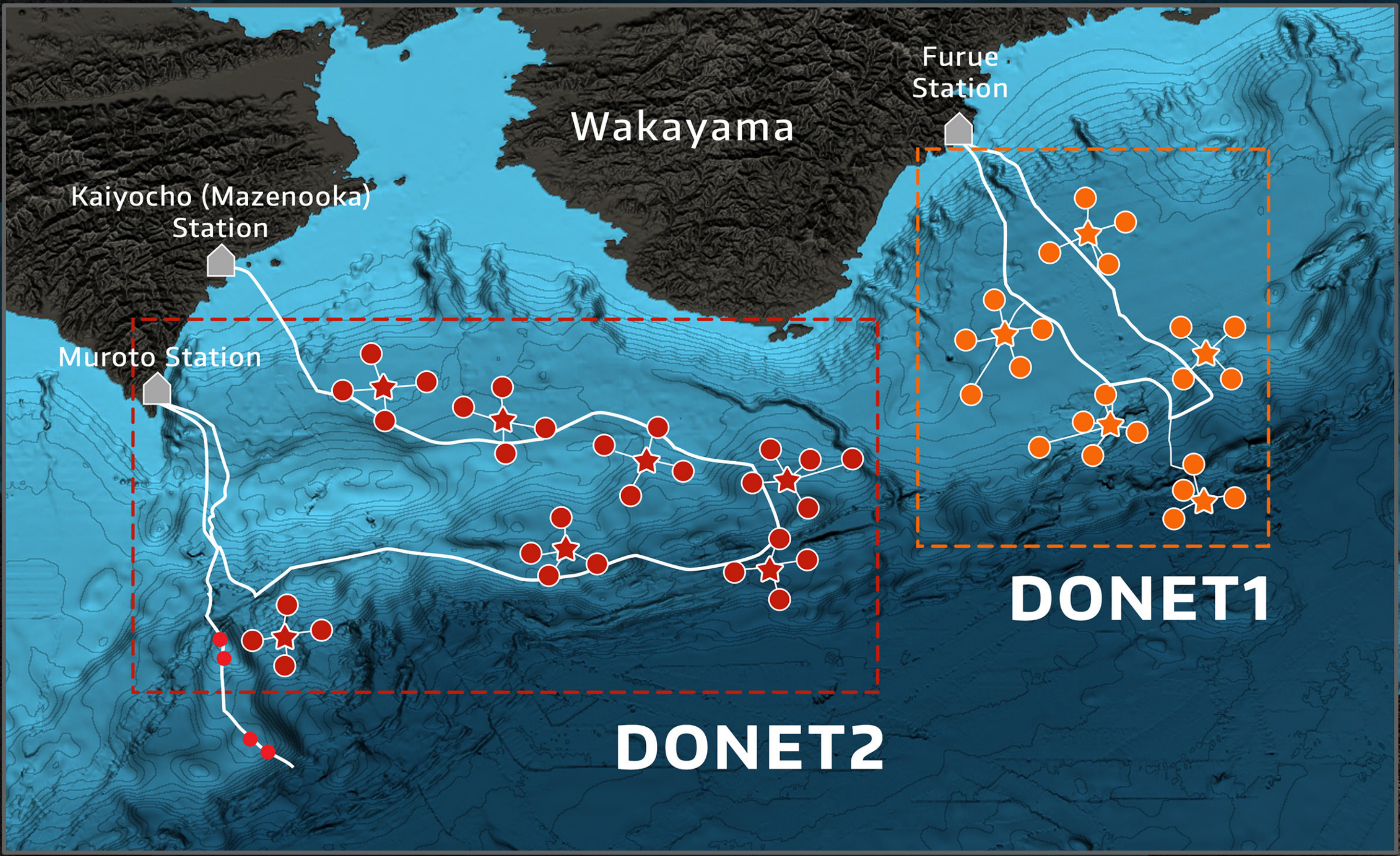
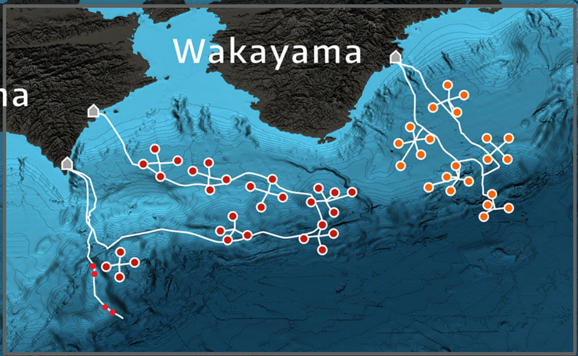


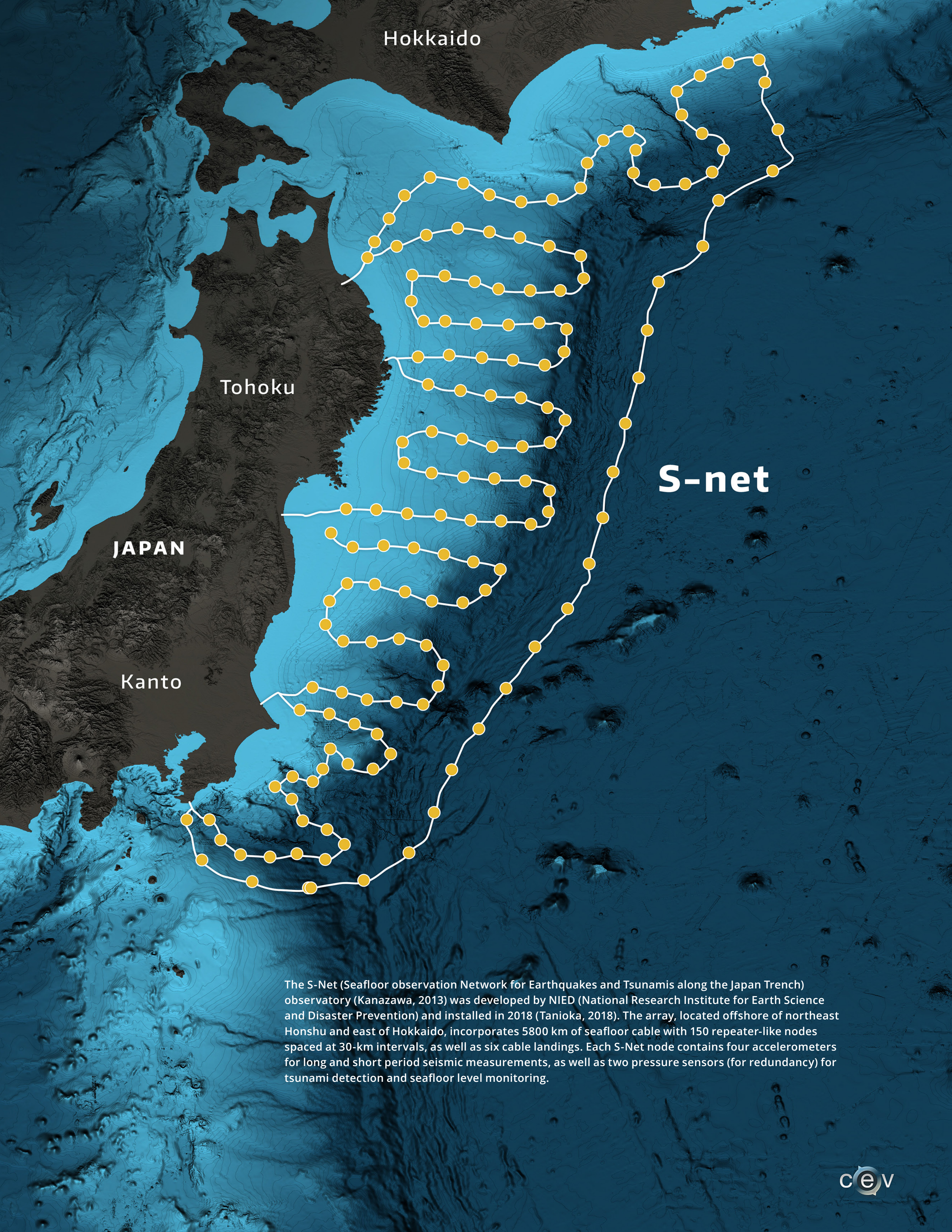
Figure 15. Wet-mate connectors on an OOI-CA junction box.

DONET 1, DONET 2, and S-net





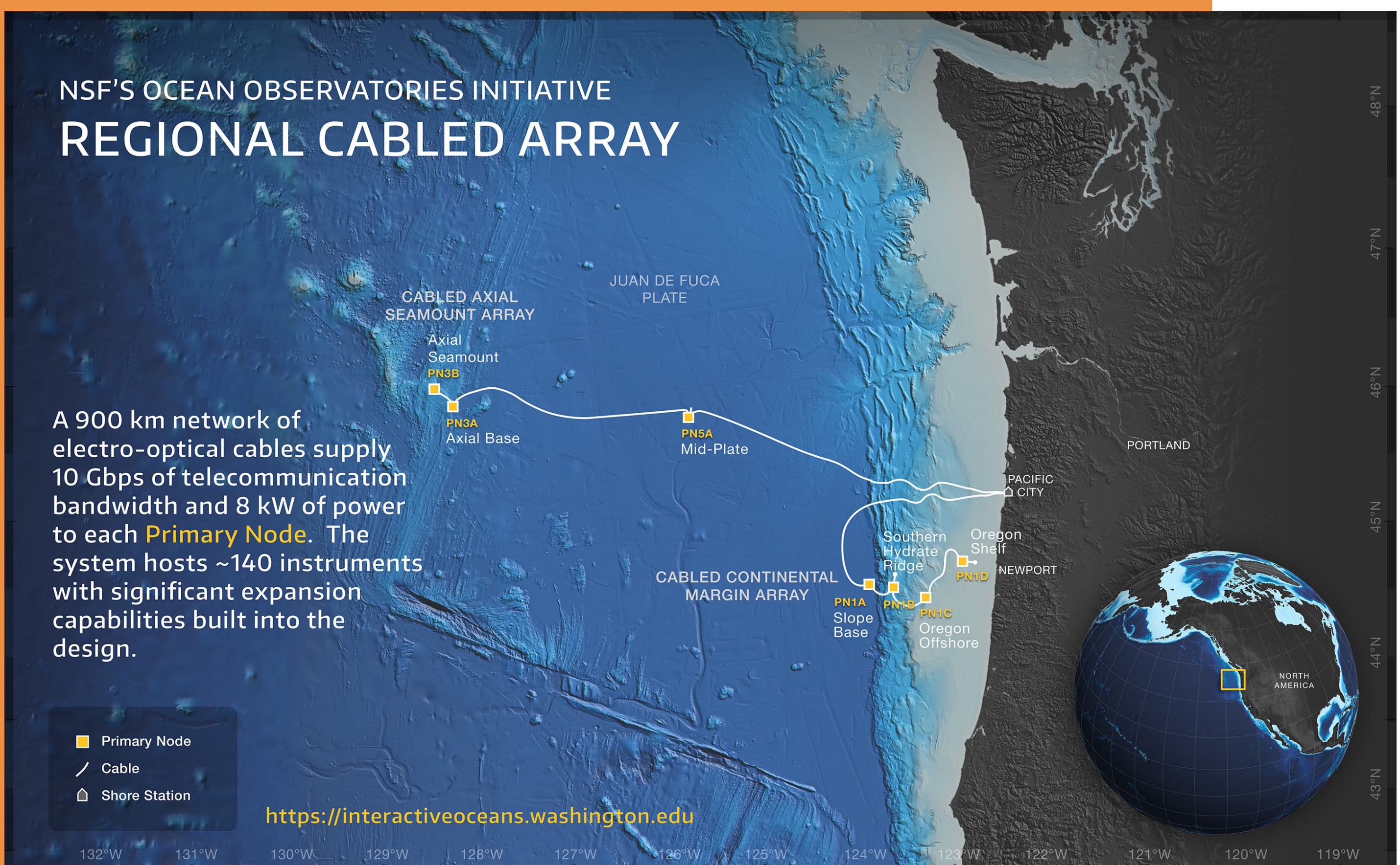
The DONET (Dense Oceanfloor Network System for Earthquakes and Tsunamis) observatory was developed by JAMSTEC (Japan Agency for Marine-Earth Science and Technology). Having a 300-km primary cable, it was installed in 2011 in the Nankai Trough off the south coast of Honshu, Japan. Unlike the OOI and the ONC observatories, DONET is focused exclusively on earthquake, geodetic, and tsunami observations. DONET2 is an extended version of DONET with a 450-km long primary cable, installed in 2015 to the southwest of the original observatory. Both observatories feature modular construction similar to the OOI and ONC observatories, and have multiple clusters of four or five instruments (circles; generally standalone seismometers and bottom pressure sensors) distributed around nodes (stars).



The S-Net (Seafloor observation Network for Earthquakes and Tsunamis along the Japan Trench) observatory (Kanazawa, 2013) was developed by NIED (National Research Institute for Earth Science and Disaster Prevention) and installed in 2018 (Tanioka, 2018). The array, located offshore of northeast Honshu and east of Hokkaido, incorporates 5800 km of seafloor cable with 150 repeater-like nodes spaced at 30-km intervals, as well as six cable landings. Each S-Net node contains four accelerometers for long and short period seismic measurements, as well as two pressure sensors (for redundancy) for tsunami detection and seafloor level monitoring.

A constant current system is standard for subsea telecom repeaters and is a mature and reliable technology. This approach relies on the same single-conductor, telecom-grade cable used in the constant voltage system and uses an inline Zener diode configuration in each repeater to provide a small amount of power (~ 20 W) to the internal optical repeater electronics. The challenge with this technology for EEW and TEW is that the internal electronics are at a very high voltage relative to the surrounding seawater, which makes electrical isolation more onerous for instruments that must be in contact with the seawater (i.e., pressure sensors). The DONET system in Japan uses a novel technology to convert the constant current power such that the voltage is referenced to seawater at each node, thereby eliminating the isolation issue but at the cost of increased system complexity.

Ocean Observatories Initiative Cabled Array



The OOI-CA was installed in 2014 and is operated by the University of Washington. It has a star topology with two primary cables and seven primary nodes and currently supports 18 junction boxes and approximately 140 scientific instruments, as well as profilers at three sites. The array uses a constant voltage power system.

Instrument Connections

There are two distinct strategies for connecting individual instruments to an undersea cable. For general purpose cabled observatories and some EEW systems, ROV wet-mate connectors allow the instrumentation to be replaced, repaired, and upgraded over the life of the system without having to replace or recover the expensive backbone cables (Figure 15). While this is a very powerful and reliable technology, it adds some complexity and expense for installation. The other option would be to hardwire all instruments directly to the backbone cable. This approach eliminates many potential failure points, reduces risk, and reduces installation cost. The main drawback for this option is that repairs become very expensive, requiring mobilization of a cable ship to recover and replace the backbone cable.

Ocean Networks Canada NEPTUNE

The ONC NEPTUNE cabled observatory was installed in 2009 and is operated by the University of Victoria, Canada. It is configured with a ring topology with six primary nodes and is generally comparable in size and functionality to the OOI-CA. Like the cabled array, ONC NEPTUNE uses a constant voltage power system.

Any systemic performance issues or instrument failures become cost-prohibitive to replace or repair. Also, it would not be practical to upgrade the system to take advantage of future improvements in sensor technologies.

Topology

The layout of a cabled system determines the instrument spacing and coverage, as well as the types of undersea risks to which the system is exposed. There are three main topologies that describe the layout and define how cable segments interconnect for an EEW and TEW system (Figure 16). In all cases, segments of undersea cable are connected to terrestrial power and communication systems at a shore station.

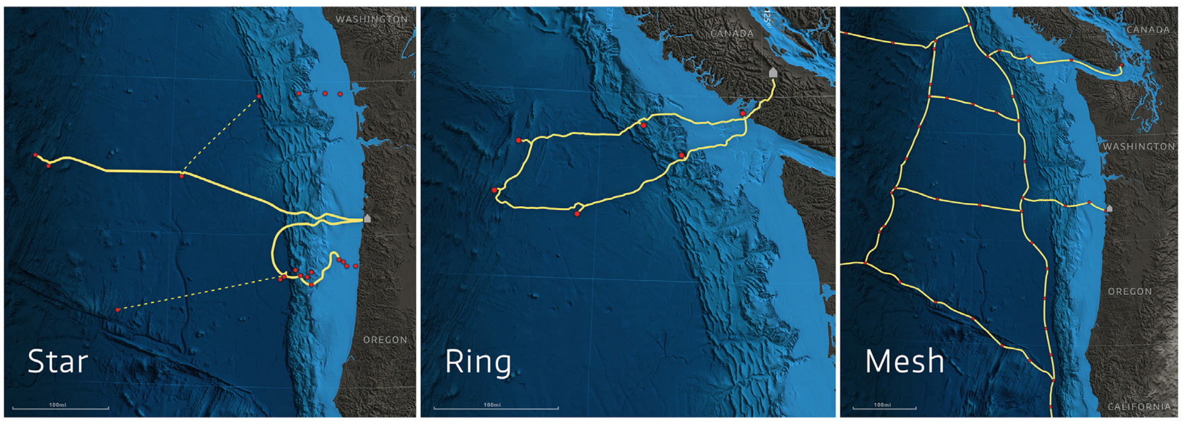


Figure 16. Cabled observatory topology options. The cable (yellow) connects nodes (red) where instruments are attached. The dotted yellow line in the star topology indicates possible extensions.

In a star configuration, a shore station provides power to a tree of offshore nodes. The OOI-CA is an example of a star configuration. While this approach can minimize the number of shore stations and total cable length, it has many single points of failure that reduce the overall reliability following an earthquake due to vulnerability to underwater landslides.

A ring configuration follows a loop design with the central stem landing at a shore station. The ONC NEPTUNE array is an example of a ring configuration. A variant of a ring configuration involves one or more loops that can be connected to multiple shore stations following an S- or U-shaped geometry; this approach allows the instrumentation to be powered from either shore station, which is an important feature that allows the system to continue to operate during and after an event in which the cable is cut by underwater landslides.

A mesh configuration has several cable segments interconnected at multiple points. Here, the power and switching systems at each intersection would be sophisticated enough to reconfigure dynamically in the event of cable breaks in the system, thereby bolstering reliability. This type of system is complex and difficult to implement given the technologies available and the need for the system to switch high voltages quickly without an interruption in service.

Example: Implementing a Ring Cabled System

A cabled offshore instrument network in a ring configuration is one of several that may meet the needs and scope of the project at the time of implementation. While there is an added expense to install multiple shore stations, a significant fraction of the instrument network would be expected to continue to operate in the event of severed cables. Given a ring configuration with multiple shore stations, we can explore the cost, reliability, and flexibility of two specific cable designs: the hardwired and connectorized systems.

A hardwired system would use constant current for power, have a ring topology, and instruments would be integrated into a repeater housing (Figure 17). This configuration minimizes the installation cost because there is no extra step of deploying instruments after the backbone cable is deployed with a cable ship. It also minimizes operation and maintenance costs. An added advantage is the ability to bury instrumentation fully in commercial fishing areas. The downside of this configuration is that it is not feasible to add new instrumentation as technology evolves. Furthermore, repairs are costly for such a system.

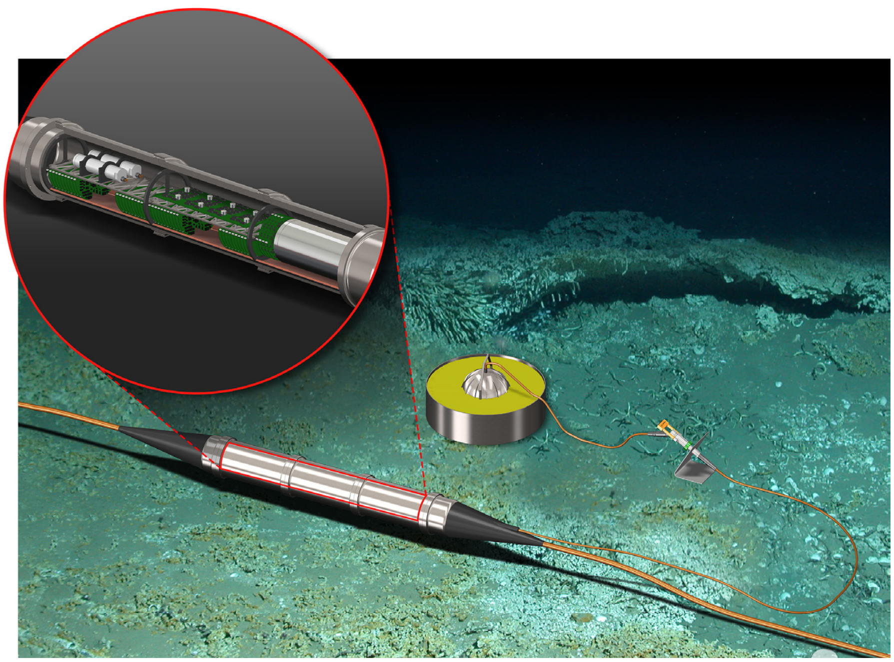


Figure 17. A cable design with instruments integrated into a repeater housing, similar to the design of the S-Net system. A repeater is an electronic device used to amplify a communications signal along a fiber optic cable. The repeater housing contains the internal electronics for communications, but could also include a pressure sensor and seismometer (see inset figure for cutaway). Once deployed, the repeater and instrument package are intended to be maintenance-free, but not adaptable. An optional external extension cable would allow additional instruments to be attached.

A connectorized system would use a cable ship to deploy the backbone cable and junction boxes, and another ship with an ROV to connect secondary cables and instruments to the junction box. This configuration is similar to the Japanese DONET system, using constant current for power, ROV wet-mate connectors to attach the instruments to the cable, and a ring topology to the junction boxes. An advantage is that repairs and upgrades to the instruments could be performed without recovering the main backbone cable to the surface with a cable ship. Such a system could be designed to allow additional instruments to be connected beyond the original specifications. The main downside of this system is that it is much more complex than the hardwired option and has more potential failure points. Because it is not possible to bury the instrument nodes and secondary cables, these components are more susceptible to damage from fishing activities in shallow water.

Cost Comparison

A hardwired system would have lower installation and maintenance costs than a corresponding modular system. For a hardwired system, instruments would be contained in housings and would be installed and buried (where necessary) directly by a cable ship. For hardwired components that are designed to last the life of the system, maintenance costs are expected to be mainly limited to repair of cable breaks from external aggression (e.g., fishing activities, anchors).

A connectorized system would be more expensive to install and perhaps to maintain. Regarding maintenance, the lower cost of servicing cruises (requiring a small ship and ROV instead of a cable ship) could be offset by the inherently lower reliability of a more complex system. The key assumption in this comparison is that hardwired system components are able to last the 25-year lifetime and behave as expected. If instruments fail prematurely at a high rate, or if there is a systemic sensor or electronics issue, the cost of repair would be significant. For example, if every component had to be serviced due to a systematic problem that was not discovered during testing, the cost of fixing the issue could be many times the initial cost of installing the system.

Installation costs for a representative hardwired and connectorized EEW/TEW system can be estimated by assuming the topology and number of shore stations. We consider two cable designs that extend from Northern California to the U.S.–Canada border, spanning a straight-line distance of nearly 520 miles / 830 km. The designs assume multiple shore stations with cable loops that extend down the continental slope and across the trench where the two geological plates meet (Figure 18). This layout ensures that basic instrument packages, in this case limited to ocean bottom seismometers and bottom pressure recorders, surround the likely source zone for the earthquake and tsunami.

The first design assumes a hardwired system (Figure 18a) while the second design features a connectorized system (Figure 18b). The total installation cost is estimated to be approximately $300 million for a hardwired system and $500 million for a connectorized system. These estimates were reviewed by Ocean Specialists, Inc. in February 2019 using industry rates, and included such categories as equipment, project management, research and development, engineering design, permitting, and ship time, among other considerations. These costs could vary significantly depending on a number of factors, including node and instrument quantities, areal extent, system configuration and requirements, telecom industry activity, competitiveness of potential bidders, implementation delays, and permitting constraints. A rough order of magnitude of the operation and maintenance costs of the infrastructure would be $5–10 million per year for the hardwired system and $20 million per year for the connectorized system. The operations and maintenance costs will be highly dependent on the ultimate configuration, but would include the annual maintenance of instruments, shore station maintenance and leasing, terrestrial networking charges, management, and utilities. The operations and maintenance costs are estimated based on similar costs for the OOI-CA.

Reliability

Relative to a connectorized EEW system, a hardwired system would have significantly fewer total components that are susceptible to damage or failure. It would also have simpler power and control systems, further reducing the possible failure points. Finally, because it would be fully buried (both the backbone cable and instruments) by a cable ship plow in the

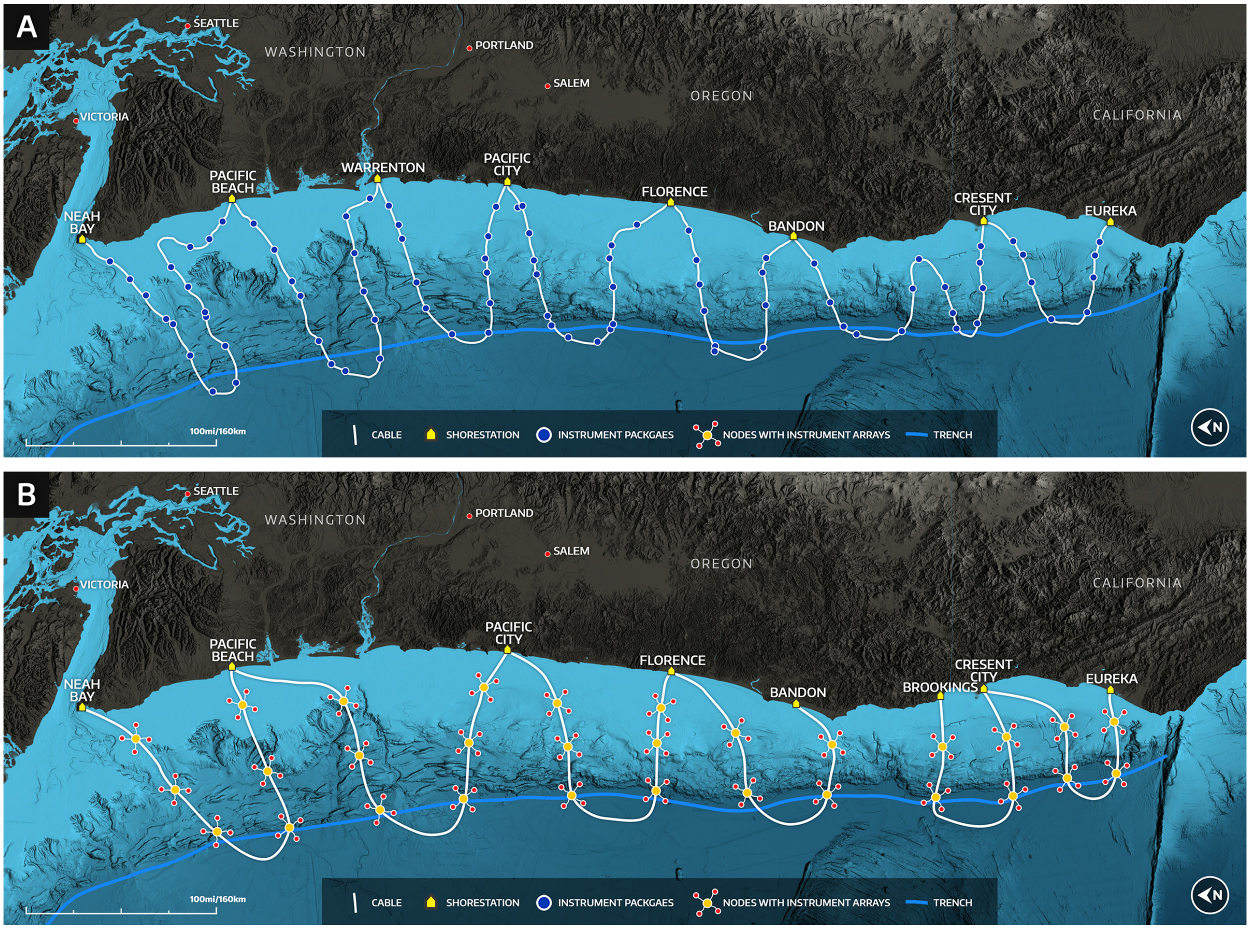


Figure 18. Idealized cable designs for an earthquake and tsunami early warning system along the Cascadia subduction zone. Shore stations identify where the seafloor cables connect to onshore stations that provide power and communications. The boundary between the two geological plates is represented by the trench (blue line). The likely source of the earthquake and tsunami would be located beneath the continental shelf and slope. (A) A hardwired design with 84 instrument packages (blue dots) installed in-line with the primary cable. This design is more efficient to install, but cannot be adapted after installation. (B) A connectorized design with 30 nodes (yellow dots), each node hosting multiple instrument arrays for a total of 120 (red dots). This design allows the system to be adapted over time and allows a wide variety of instrument types, but at greater cost.

shallow water depths of the continental shelf, it would avoid damage by fishing activities in the area. However, it would still be susceptible to cable breaks on the continental slope and abyssal plain from submarine landslides or turbidity currents.

The connectorized system would have many more points of failure. Wet-mate connectors can be made individually reliable, but, in aggregate, are still a weak point in the system when considering the number needed to cover the entire area. The extension cables between the backbone cable and the instruments will not be armored or buried as deeply as the hardwired system because they must be deployed by an ROV, which limits options for the types of cable used. Furthermore, the ROV wet-mate connection points and likely the junction boxes and instruments will not be buried, making them vulnerable to damage by fishing activities.

Maintenance and Flexibility

The main advantage of the connectorized system is that individual pieces can be configured, repaired, upgraded, and modified without recovering the backbone cable to the surface for splicing. Repairs by cable ship cost millions of dollars for each incident. With wet-mate connectors, a smaller and less expensive ship and ROV can perform operations quickly, with less risk and downtime for the entire system. This allows individual instruments to be swapped or repaired. New cables may be added or replaced and new instrumentation may be added over the life of the system to support new understandings of the geological processes or as new monitoring techniques are discovered.

A hardwired system would essentially be a fixed configuration for its lifetime, with no realistic opportunities to upgrade or modify the system. Significant engineering will be required to ensure a 25-year operable life for the instruments embedded in the repeater housing.

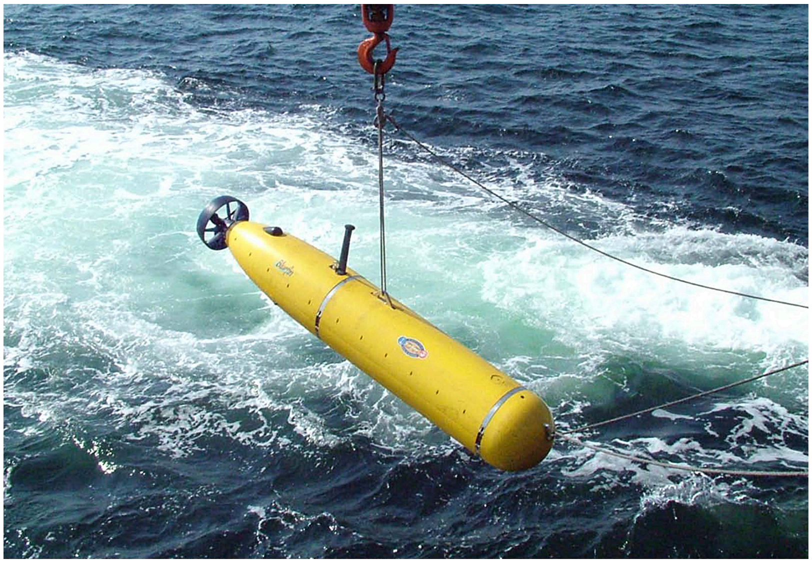
Moored Buoys

There are non-cabled options for transmitting data from seafloor instruments. Moored buoys have been used extensively as navigational aids and oceanographic research platforms, and for tsunami detection. An array of buoys could be configured to transmit data from the seafloor to an onshore analysis center via a satellite link. The best-known version for tsunami detection is the NOAA DART buoy, now in its fourth generation and in widespread use around the world (Meinig et al., 2005). Principally due to the acoustic data link between the seafloor instrument(s) and the buoy, DART buoys have an inherent lag of approximately two minutes from seafloor signal detection to receipt onshore. Therefore, a buoy system is best applied to TEW where high latency and low data sampling are acceptable.

As an alternative or complimentary technology to cabled systems, moored buoys are less susceptible to damage from turbidity currents and earthquakes, and are consequently more likely to remain operational after an earthquake, although the seafloor instruments are still at risk. Installation costs are lower for buoys than for cabled systems, depending on the quantity of buoys to be deployed. The cost of a commercial DART buoy is $500 thousand per unit (Bernard and Titov, 2015). Ship time is then required to deploy the buoys. The advantage of lower installation cost is offset by the need for significant regular maintenance, which requires frequent visits by a ship as well as replacement components. DART buoys are a good example of the current state of the art, and require servicing every two years on average to replace damaged and/or failed components such as moorings, electronics, and batteries. Buoy vandalism by humans and damage by marine mammals such as sea lions are recognized hazards. Reliability is also problematic due to occasional mooring failures. In 2010, the NOAA annual budget to maintain and operate a global array of 39 DART buoys was $12M per year (GAO, 2010). This likely represents an upper bound if considering a similarly scaled regional early warning network, because maintenance costs would likely be less if all the buoys were deployed within the same geographic area.

Mobile Platforms

Although a less-mature technology for EEW/TEW, mobile platforms such as AUVs could be developed to collect data from EEW/TEW seafloor instruments. AUVs are less likely to be affected by earthquakes and tsunamis than cabled systems, and their overall operational reliability is improving.



Each mobile platform could roam over areas of hundreds of square kilometers, collecting data by acoustic link from an array of seafloor instruments. The data latency (likely minutes to hours depending on the proximity of the AUV to the seafloor instruments) would preclude use in an EEW system, but may contribute towards a TEW system. If mobile platforms were stationed semi-permanently above each acoustically-connected instrument site, the capabilities would be similar to a network of acoustically connected buoys, but with the added capability to conduct custom missions throughout the water column or in the far field in response to sensed events. The use of mobile platforms may work well if part of a hybrid system, relying on low-latency cable transmissions for early warning and high-latency acoustic transmissions for scientific research via AUV. Subsea docking systems, still under development, would enable AUVs to be based at the seafloor below depths where biofouling is a known hazard. In these cases, docking station power and long-haul communications to shore would be provided by the cable or buoy.

Wireless Seafloor Networks

Seafloor cables, buoys, and AUVs in an early warning system transmit data over long distances, from the seafloor to terrestrial processing centers. Alternative communication pathways are under active development, and may provide new options in the near future. Wireless communications, excluding satellite or cell phone communications, might eventually enable a flexible node infrastructure. In an acoustic mesh network, each node communicates with its nearest neighbors, transmitting data (such as seismic and seafloor pressure data) and gathering accurate horizontal range information that measures horizontal deformation (Figure 19). Depending on battery capacity and duty cycle, acoustic mesh networks could eventually transmit detection parameters or reduced data products from individual sensors back to shore. Because such systems have not previously been demonstrated over large spatial areas, it is difficult to provide a reasonable cost estimate for such systems if deployed as a plate boundary early warning network.

Acoustic communication is the de facto standard for underwater wireless data transmissions and vehicle navigation, and is typically deployed as a point-to-point solution.

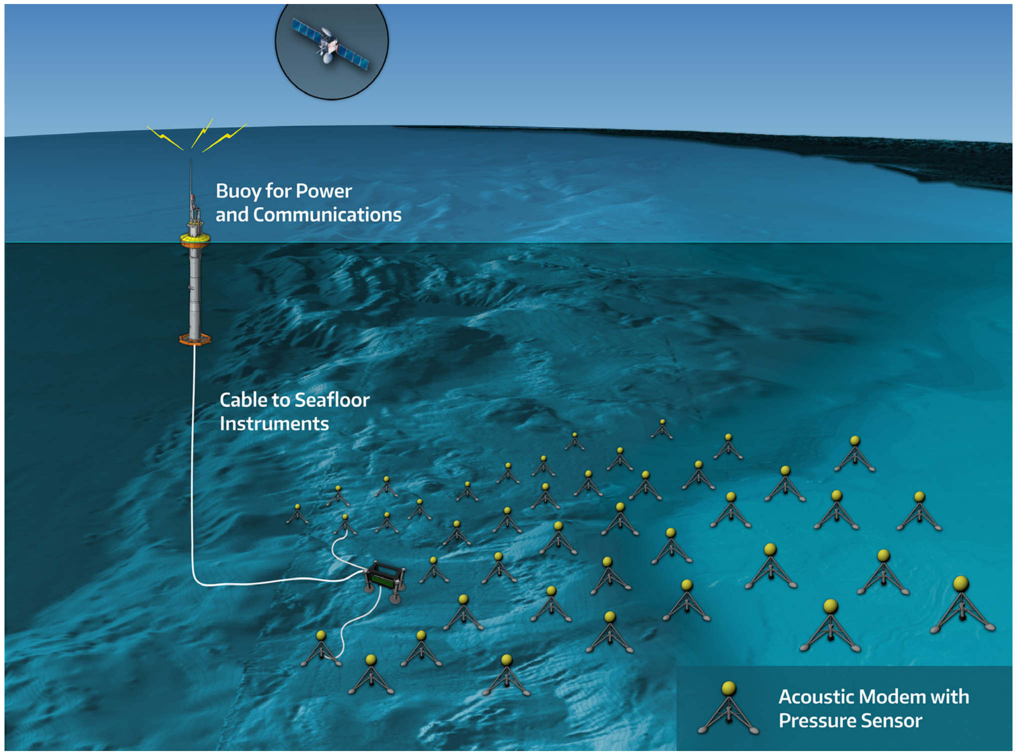


Figure 19. Scheme for a wireless acoustic mesh network.

For example, instrument data may be transmitted acoustically directly to a data collection node or buoy. At typical acoustic modem frequencies (~25 kHz), acoustic messaging can cover multiple kilometers, with data rates comparable to dial-up modems (< 9600 baud). Network protocols derived from terrestrial RF networks could transform a collection of seafloor mounted acoustic transponders into a multi-hopping data network, vehicle navigation array, and geodetic sensing platform (Figure 20). Given that acoustic methods transmit data at the speed of sound (1400–1500 m/s in seawater), data latencies would be ~2 minutes to cross the continental shelf (100–150 km) and arrive on land.

Emerging Platforms and Auxiliary

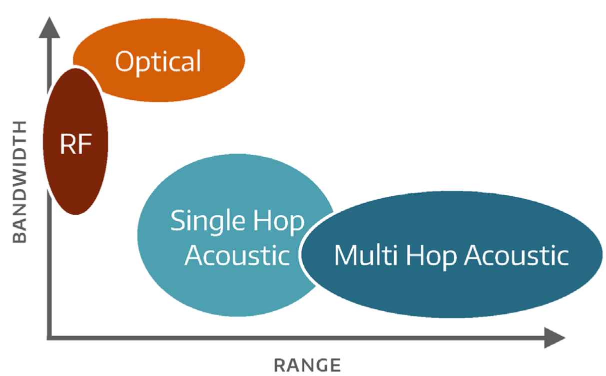


Figure 20. Relative range (distance spanned) vs. bandwidth (amount of data transferred) for subsea wireless options.

Technologies

Additional innovations may soon revolutionize short-range communications, eliminating the need for wet-mate connectors. Radio frequencies are rapidly attenuated underwater. But over short ranges (tens of centimeters), it is possible to maintain a Wi-Fi link. Commercially available subsea optical modems claim data rates of up to 500 Mbps, enough throughput for real time video signals, with range of up to 200 m. Optical communications, however, are susceptible to fouling and external light interference, so are best used in deeper installations, which tend to have clearer water and less biofouling.

If the cable is removed from design consideration, shore-based power is no longer available, but there are emerging technologies that may provide alternatives to the batteries used in autonomous instruments. These include advances in ongoing renewable energy harvesting (wind turbines, wave energy converters, tidal current systems) and wireless power transfer developments (i.e., inductive charging, adaptive resonant power transfer).

Further investigation of these emerging technologies as well as investment in innovation will enhance our future capabilities, not only of detecting offshore hazards, but also of understanding precursory activity of large seismic events that may one day lead to hazard forecasting. Therefore, it would be advantageous to maintain adaptability and flexibility in the deployed system to incorporate new technologies. As emerging technologies become more mature, the following areas should be considered when determining their use in an early warning and subduction zone monitoring system: data types and latency, reliability and risk exposure, capital cost, and operations and maintenance costs.

Risks

Any offshore detection and warning system will be exposed to known risks during the planning, implementation, and maintenance phases of the project. If the risks are realized, they can delay or even prevent implementation, increase construction and maintenance costs, and reduce the effectiveness of the system due to downtime or failures. The broad categories of risk are:

- **Delays in permitting and community support.** Here, the successful experiences of the OOI-CA in Oregon are invaluable and demonstrate the political importance of engagement with stakeholder communities, as well as meeting all statutory requirements for permitting.
- **System reliability.** The predicted reliability of new systems does not always match subsequent performance. It is therefore advantageous to use approaches that have been tested, and to investigate and exploit historical performance data to enhance reliability. Where less technologically mature approaches are deemed necessary, it is important to ensure that the system be serviceable to enable future repairs or replacements.
- **External aggression.** Both fishing activities and submarine landslides are a significant risk to seafloor infrastructure (Pope et al., 2017). Cabled system and seafloor installations are susceptible to turbidity currents and should be located carefully to minimize risk of damage. Shore infrastructure for cabled systems will be exposed to the same

earthquakes and tsunamis that are being detected, and should be hardened against these hazards. Buoys are susceptible to vandalism and damage from wildlife.

- **Weather and environment.** Infrastructure located at the sea surface (i.e., buoys) or on the coastline (i.e., shore stations) must be able to withstand wind, waves, and flooding imposed by severe storms.
- **Lack of sustained project funding.** It will be important to identify an adequate and stable source of funding for operation and maintenance because otherwise the system may be hard to sustain given that the catastrophic earthquakes that justify it are infrequent and provide few reminders to the public about the hazards.

Summary of Design Options

A variety of platforms and technologies are available to provide power and communications to a network of offshore instruments (Table 5), though different designs deliver varying capabilities for detection and warning of earthquakes and tsunamis. For EEW, an instrument network must provide low latency (less than a few seconds) and continuous data, and have sufficient areal coverage of the source zone to be effective. For TEW, sufficient coverage is also needed to detect and warn communities along the entire coastline; however, data latency, which can be on the order of minutes is acceptable, assuming an EEW is used to trigger the TEW system with initial parameters of the earthquake source.

Considering the list of mature technologies that are available to deliver power and communications, a seafloor cabled system is best situated to meet all of the stated system requirements for EEW and TEW, while also providing fundamental observations to assess the future hazards through scientific research. Fiber optic cable systems allow signals to move from instrument to shore in well under one second, including all internal latencies. This approach easily meets the overall system latency requirement. Further, this technology is readily available, mature, low maintenance and very reliable, and has been proven in many similar systems, including S-Net, DONET, OOI-CA, and ONC NEPTUNE. This approach has significant installation costs.

A moored buoy system, which transmits data acoustically from the seafloor to sea surface, and subsequently to land via satellite or cell phone system, is well demonstrated for TEW. However, it is unclear whether latencies could be made short enough to be useful for EEW. Comparing a buoy system to a cabled system with a comparable number of seafloor instruments, the operation and maintenance costs are of the same order of magnitude; but a buoy system has limited capabilities. It would not likely contribute to EEW, nor provide continuous high-bandwidth data streams. An alternative design would connect the buoy with an array of seafloor instruments using electromechanical stretch hoses that can withstand the effects of waves and wind. If such moorings prove sufficiently reliable, it might be possible to operate more extensive networks of near-real time underwater instruments from buoys rather than cabled networks. The tethered cable would provide a high-bandwidth data stream to the buoy for transmission via a dedicated satellite link, while the buoy could harvest wind/wave energy and send power to the seafloor instruments. Such a design could meet many of the requirements for an EEW/TEW network, and mirror the capabilities of a cabled system. But significant research and development would be needed to demonstrate the performance and reliability of such a system.

Table 5. The primary offshore platforms required for an EEW/TEW instrument network. High/Medium/Low provide a relative measure of how each platform compares for each category. Maturity describes the level of existing development and testing of the technology. Reliability describes the resilience and performance of the technology. Maintainability refers to the need to replace instruments and technology over the lifespan of the instrument network. Flexibility describes the ability to change or reconfigure the instruments after installation. O&M, operations and maintenance.

	HARDWIRED CABLE	CONNECTORIZED CABLE	BUOY ARRAY	MOBILE WIRELESS
EEW Capability	High	High	Low	Low
TEW Capability	High	High	High	Medium
Maturity*	High	High	High	Low
Installation Cost	Med-High	High	Low	Med-Low
O&M Cost	Low	Medium	High	High
Reliability	High	Med-High	Low	Low
Maintainability	Low	High	High	Low
Flexibility	Low	High	Low	Medium
Data Latency to Shore	< 1 second	< 1 second	10s of Seconds	10s of seconds

A hybrid approach would be to combine multiple technologies into an integrated system comprising limited cable segments for real-time transmission of ocean bottom seismographs located over the earthquake source region, buoys to detect outbound tsunami propagation, and HF radar for nearshore tsunami monitoring. The cabled instruments would provide the detection of the earthquake and constrain initial source parameters (event magnitude and extent). The cables might only extend to the edge of the continental shelf, but connect acoustically to an acoustic network that spans the trench. This would limit the risk of a cable break from a turbidity current or submarine landslide. Given that the tsunami propagates faster in deeper water, a limited array of bottom pressure sensors and buoys could be placed strategically just west of the trench to help constrain initial models of the tsunami. The models can then be tested against observations from coastal HF radar as the initial waves approach the shoreline, and the warnings updated accordingly. Such a system may not have the full spatial coverage or instrument density of a solely cabled system, but would provide greater system reliability and resilience. Given the numerous variables, a full cost comparison is beyond the scope of this analysis, but such a system could be constructed to maximize benefits of each technology, while minimizing risk and cost.

Certain technologies under development might support alternative designs. This may include a variety of autonomous wave, wind, and diesel powered surface vehicles that could replace a buoy, the development of robust electromechanical cables to facilitate high-bandwidth communications and power transfer between a buoy and the seafloor, new power systems that harvest wind, wave, or current energy from the environment, and technologies for wireless power and data transfer that eliminate the need to attach instruments to seafloor infrastructure with wet-mate connectors.

Extensive engagement with stakeholders will be critical to define the specifications of tsunami warning products, including delivery time, their method of dissemination, and how best to provide updates in a manner that is helpful rather than confusing.

Implementation Plan

Progress toward developing an offshore instrument network for EEW and TEW will require (1) expanding the scope of the planning efforts to engage government, industry, and community stakeholders to build consensus on the program's objectives and a coalition to seek implementation funding, and (2) conducting studies and prototyping experiments that will be necessary to optimize the system design.

Community Engagement

Early warning will only be effective if it is part of a comprehensive effort to prepare for a subduction zone earthquake so that the loss of life and infrastructure is minimized and communities are equipped to recover quickly. The planning for offshore early warning must be integrated into ongoing efforts to improve resiliency following a subduction zone earthquake, and this principle should guide the engagement efforts.

There are many stakeholders that must be engaged, namely government at various levels including those that represent coastal communities and tribes; federal agencies, including NOAA and the USGS that are respectively responsible for tsunami and earthquake warning/mitigation, FEMA, the U.S. Navy, and Coast Guard; state and county emergency managers and first responders; industry, including insurance/reinsurance, utilities, high tech, telecommunications, fishing, and maritime companies; non-government policy and philanthropic organizations; regional scientific experts, researchers, and various experts. While the focus of engagement efforts should be on the U.S., it will be important from the outset to include representation from Canada to ensure that the program leads to seamless monitoring that spans the border. Partnerships with Japan will be important so that the program can benefit from their experience implementing offshore monitoring systems, as will collaboration with countries considering offshore monitoring such as New Zealand and Chile.

Early engagement efforts should include:

- A kick-off workshop
- The formation of a program office
- A rigorous cost–benefit analysis
- Close collaboration with the federal agencies responsible for warning
- Engagement with coastal communities
- Consultation with researchers and technical experts

The kick-off workshop should include representatives of all the potential stakeholder groups, brief participants on this feasibility study, and seek input and consensus on the objectives and priorities for offshore monitoring, including how a program should be integrated with broader efforts to plan for the next great Cascadia earthquake. The key outcomes of early engagement activities should be agreement among the stakeholders on the mission and quantifiable benefits of the program, a consensus on how best to proceed, and a plan of action for engaging each stakeholder community.

The establishment and maintenance of a program office for offshore early warning will provide the organizational structure to coordinate interest at multiple institutions, support extensive follow-up stakeholder engagement, and develop an outreach program to the public. Program offices are commonly employed within academia to support large initiatives that require coordination among multiple communities (e.g., the National Office for the NSF Earthscope program that has underpinned an unprecedented geophysical study of the North American continent, and the University–National Oceanographic Laboratory System office that coordinates the U.S. academic fleet). This program office should have academic and community leadership, but will require a capable staff with expertise in academic–government–industry interactions and informal education. To build upon the kick-off workshop and avoid the risk of losing momentum, the staff would ideally be in place soon afterward, and if they were in place before, they could be a part of recruiting participants and conducting the workshop.

Because plans for public outreach should be centered around justifying the system through a clear articulation of the needs for and benefits of the program, it is important that the kick-off workshop lead to a rigorous cost–benefit analysis. The FEMA Hazus GIS-based disaster assessment tool (https://www.fema.gov/hazus) provides a standard methodology to assess potential casualties, damages, and economic losses from natural disasters and could be used as the basis of a comparative study to assess the impact of an offshore monitoring system. Broad stakeholder input will be important to support this effort. For example, the cooperation of industries and utilities will be required to understand how they might benefit and take advantage of early warning. Estimates of the life-saving potential of early warning must be informed by the plans of agencies and managers responsible for warning and disaster responses.

Strong collaborations must be formed with the two federal agencies responsible for warning to understand how early warning should be integrated into their operations. For EEW, the USGS, with a coalition of state and university partners, is in the process of implementing the ShakeAlert system along the west coast of the United States using data from land seismic and GNSS stations. With adequate funding, it would be relatively straightforward to incorporate offshore observations into this established system and thus take advantage of ShakeAlert's ongoing efforts to engage stakeholders, and develop systems to distribute useful warnings to government agencies, private organizations, and the public.

For tsunami early warning, much more work will be needed. The NOAA Tsunami Warning Centers now aim to deliver warnings for domestic events within five minutes (McLean et al., 2014), but these are derived only from the analysis of terrestrial seismic records. NOAA is exploring the use of GNSS data to reduce the time for accurate size estimates for large earthquakes (Melgar et al., 2016a), and is also considering the placement of DART buoys closer to the trench. Further consideration and analysis is needed to identify how best to enable a nearfield tsunami warning that is both accurate and timely. To ensure nearfield tsunami warnings, the data influx from an offshore sensor network must be integrated carefully into the operations at the Tsunami Warning Centers, and these centers must have the computational resources and algorithms to ensure robust automated warnings.

Aside from educating coastal populations in the nearfield to head immediately for higher ground after feeling or learning of an earthquake, the coastal evacuation plan is largely focused on timescales of hours for far-field tsunami warnings. Extensive engagement with stakeholders will be critical to define the specifications of tsunami warning products, including delivery time, their method of dissemination, and how best to provide updates in a manner that is helpful rather than confusing. It is also critical to determine how an offshore warning system fits with other essential mitigation and preparedness activities, including enhancing the resilience of infrastructure along the coast and coastal access routes, building vertical evacuation structures in tsunami inundation zones that are isolated from higher ground, and educating the public to ensure that populations respond appropriately to warnings.

A strong relationship must also be forged with FEMA, the federal agency tasked with helping people before, during, and after natural disasters. FEMA prepares people for natural disasters through education and provides federal assistance for short-term response and long-term recovery following a disaster. Because the benefit of earthquake and tsunami early warning derives primarily from its inclusion into a comprehensive plan to prepare, respond, and recover from disasters, the system must be developed in collaboration with FEMA.

From the outset, it will be critical to engage those directly impacted by the offshore infrastructure (instruments and platforms). The support of coastal communities will be needed to obtain permits for shore stations, which should be positioned far enough inland to be outside the tsunami inundation zone. Both commercial and tribal fishing communities must be engaged to minimize the impacts of offshore infrastructure on this industry and the risks of damage to the infrastructure by fishing. The positive interactions between the University of Washington OOI-CA team and the Oregon Fisherman's Cable Committee were extremely beneficial to that project and will serve as a useful template to move this effort forward.

Preparatory Scientific Studies

The occurrence of several very large destructive megathrust earthquakes in the past 15 years has led to a growing public awareness of the inevitability of a similar event in the Pacific Northwest (Schulz, 2015), and to increased scientific support for offshore studies that seek to understand the hazard posed by the Cascadia subduction zone. During 2011–2015, NSF supported a 4-year community deployment of ~70 ocean bottom seismometers along the full length of the Cascadia subduction zone and farther offshore on the Juan de Fuca plate (Toomey et al., 2014). This is by far the largest academic ocean bottom seismometer experiment ever conducted and it is transforming our understanding of offshore seismicity and of the deep structure of the subduction zone and Juan de Fuca plate.

Ongoing studies using these data are of particular relevance to offshore early warning; they are used to improve catalogs for offshore earthquakes occurring on and near the plate boundary (Stone et al., 2018; Morton et al., 2018), investigate earthquake amplitudes on the incoming plate and accretionary prism (Gomberg et al., 2018), and analyze noise sources on ocean bottom seismometers in the frequency band used to detect regional earthquakes

(Hilmo et al., 2017). Data from pressure sensors in the instruments are being used to model small tsunamis that propagated through the network (Gusman et al., 2016) and improve the design of future experiments to search for slow slip earthquakes offshore (Fredrickson et al., 2017).

NSF is supporting ongoing geodesy experiments using both GPS-acoustic (Chadwell, 2017) and calibrated bottom pressure measurements (Cook et al., 2017) that are likely to enhance our understanding of plate locking. NSF has supported the acquisition of a large, amphibious, magnetotelluric dataset (Parris, 2015) and recently funded an experiment that will acquire deep penetration seismic reflection data along the full length of the subduction zone (Carbotte, 2018).

For Cascadia, it is critical that we have a 'before' image of the continental slope and trench morphology so that we can identify what has changed after a megathrust event.

The USGS is collaborating with several universities and NOAA to initiate a program of seafloor mapping, shallow seismic imaging, and sediment core collection to understand the neotectonics of the accretionary prism (Brothers et al., 2019). Imaging using deep-penetration seismic reflection, seismic refraction, and electromagnetic techniques would provide improved constraints on the location of the plate boundary and the large-scale fault structure and style of deformation of the accretionary prism.

Cumulatively these studies are contributing to our understanding of the subduction zone offshore, but there are additional observational studies that could be used to prepare for the next megathrust event and optimize the design of an offshore warning system, including:

- High-resolution bathymetric mapping of the seafloor, particularly along the slope and trench
- Complete geophysical imaging of the subsurface structure to identify faults and potential slope failures
- Additional geodetic studies to constrain the locking state of the megathrust and identify possible source zones for megathrust rupture
- Ocean bottom seismic arrays to map active, low-level seismicity or tremor
- High-resolution DEMs of coastal estuaries, and an assessment of which low-lying regions require high-resolution inundation modeling for an incoming tsunami

Most of the continental slope has been mapped in a piecemeal fashion by ship-based multibeam systems, but the data and processing quality are variable and the horizontal resolution in most places is limited to ~100 m. There are ongoing efforts to integrate these existing data, but new efforts to map the margin, including the continental shelf, at higher resolution with the latest ship-based systems and autonomous vehicles would contribute substantially to geological studies of active processes and could help to optimize the instrument locations and cable routes for an offshore instrument network. These bathymetric datasets should be of high enough resolution and uniform quality so that they can be used for change detection. For the 2011 Tohoku Japan tsunami, differential bathymetry was instrumental in quantifying the seafloor deformation associated with the tsunami (Fujiwara et al., 2011). For Cascadia, it is critical that we have a 'before' image of the continental slope and trench morphology so that we can identify what has changed after a megathrust event.

There are extensive image datasets of the subduction zone built with multichannel seismic and electromagnetic techniques. The high-resolution seismic imaging of the shallow subsurface planned by the USGS will be an important addition because it will constrain the location of active shallow faults that might rupture during a large megathrust event and contribute to a tsunami. In conjunction with seafloor mapping and sediment core analysis, it will help identify areas of slope instability that could also contribute to tsunami generation and would be poor sites for seafloor instrumentation. It will thus be important for the academic community to work with the USGS and their Canadian counterparts to ensure that shallow imaging data are collected and analyzed along the entire subduction zone.

Offshore geodetic studies of the subduction zone are still in their infancy and limited to a small number of sites. A comprehensive effort to obtain dense geodetic observations along the entire subduction zone using established GNSS-acoustic and seafloor pressure monitoring techniques would contribute substantially to our understanding of the distribution of plate boundary locking and episodic slow slip, and thus improve our understanding of the tsunamigenic and ground shaking potential of the next megathrust earthquake. This could feed directly into the system design of a warning system by improving constraints on the required footprint for monitoring and identifying segments of the subduction zone where the hazard is likely the highest.

Although there have been substantial efforts to obtain ocean bottom seismometer data along the entire Cascadia subduction zone, the need for more studies remains. For example, while the studies to date confirm that earthquake rates are low along much of the plate boundary offshore (Stone et al., 2018), they detected some earthquakes and had limited sensitivity in many regions because of a relatively large instrument spacing and the failure of instruments to record good data at some sites. Good recordings of a smaller number of earthquakes on the plate boundary and accurate locations obtained with improved seismic velocity models from new seismic imaging could provide important constraints on the structure of the plate interface. If slow slip events occur in the offshore environment, then microearthquake activity may be episodic, which could justify future deployments.

Cumulatively, the offshore observations will lead to a better understanding of the structure of the margin and the styles of earthquakes, leading to an improved suite of earthquake simulations. These can, in turn, support the detailed simulations of early warning system performance for a full range of possible megathrust earthquakes.

Instrument Network Design Research

Extensive modeling studies will be required to optimize the distribution and spacing of instruments. Robust EEW requires that multiple seismic instruments are positioned near

While the next major event cannot be predicted, it is possible to generate hypothetical scenarios based on knowledge of the fault geometry, the geological evidence from past events, and the study of recent earthquakes on other subduction zones.

the epicenter of the earthquake and it is relatively straightforward to create contour maps of the predicted warning times for idealized system designs as a function of earthquake epicenter or warning location. However, more sophisticated modeling efforts will be required to develop a design that will minimize the impacts of localized system downtime due to point breaks in cables (Pope et al., 2017), junction box and instrument failures, and scheduled maintenance. Probabilistic modeling studies will be required to predict how well a hardened design might perform after a large megathrust earthquake, which could damage key components of the system and limit its performance for subsequent aftershocks.

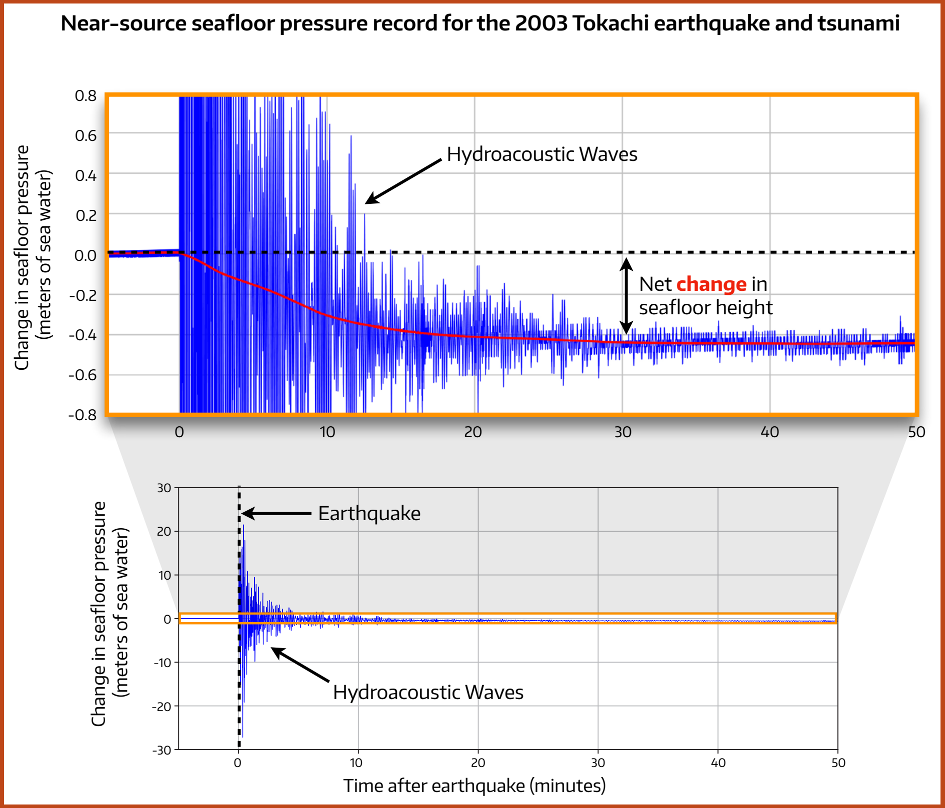
The lack of historical seismic and tsunami events in Cascadia makes the current hazard in the region more uncertain and potentially more dangerous, because the period of relative seismic quiescence throughout the past 300+ years has likely added to complacency in preparedness and inadequate building codes. Although this has no bearing on the probability of future events, it adds a degree of difficulty in anticipating key impacts of possible large earthquakes and tsunamis, or optimizing a warning system for a specific earthquake source. Past earthquakes have varied greatly in magnitude, extent, and duration of quiescent periods. While the next major event cannot be predicted, it is possible to generate hypothetical scenarios based on knowledge of the fault geometry, the geological evidence from past events, and the study of recent earthquakes on other subduction zones.

Alternative efforts at simulating the range of rupture properties and associated ground motions have used stochastic modeling of large earthquake rupture patterns, leading to a much larger suite of "random" but geophysically reasonable scenarios. One set of 1300 hypothetical events (Melgar et al., 2016a) have been coupled with ground motion modeling to provide a framework to anticipate the timing and amplitude of strong ground motion, and to test the response of the ShakeAlert EEW systems to large events. They can also be used for design optimization of an onshore or offshore instrument network built for earthquake and tsunami early warning, and to test statistical inversion techniques that may be necessary to generate warnings from such a network in real time. An early planning objective for such a network would be the further development of a more detailed set of scenarios to aid the specification of instrument type and spacing, uniformity of instrument types across the network, and real time data analysis or modeling tasks to optimize effectiveness.

Ongoing research into probabilistic approaches will provide formal confidence limits on the final impact prediction in the form of statistical inversion. In the process, we will enhance our understanding of the physical dynamics and enhance the value of the predictions to decision-makers. Future observational and computational power may

The Challenge of Real Time Tsunami Detection

It is not straightforward to use ocean bottom pressure to determine the sea surface motion in the immediate source region (LeVeque et al., 2018). If the ocean were incompressible (i.e., constant density), then the surface would nearly track the seafloor motion over the time scale of the earthquake, with no change in water depth and no change in hydrostatic pressure. Changes in water depth would only be detected over a longer time scale (several minutes) as the tsunami propagates away from the source region. Moreover, the hydroacoustic waves generated by the seafloor motion can have amplitudes that are orders of magnitude larger than the change in hydrostatic pressure that would be induced by the amplitude of the tsunami generated. Ocean bottom pressure records from several recent earthquakes have been discussed extensively in the scientific literature (see summary in LeVeque et al., 2018) and been analyzed with numerical model simulations.



The figure shows the signature of a tsunami as observed by a bottom pressure recorder (station PG1) deployed off the coast of Hokkaido, Japan within the source region of the magnitude 8.1 Tokachi Japan earthquake in 2003. This record illustrates the difficulty of interpreting data in real time, as rapid fluctuations in pressure in the first 10 minutes mask the subtle offset in pressure from the net upward movement of the seafloor. The change in pressure is plotted in units of "meters of sea water," and depicts changes in the height of the water column due to either changes in sea surface height or changes in seafloor height. The top panel shows a zoomed-in version of the bottom, with a moving average shown by the red line. The hydroacoustic waves generated during the earthquake have amplitudes roughly 50 times larger than the net change in hydrostatic pressure from the 0.4 m of coseismic uplift of the seafloor at this location. Unfortunately, the tsunami signal is almost completely masked by the acoustic waves during the critical first 10 minutes. Future research is required to explore whether the tsunami signal can be extracted from similar records in near-real time.

eventually increase to the point where real time data inversion, simulations of tsunami generation, propagation and inundation, and the application of probabilistic algorithms are feasible and cost-effective.

For tsunami warning the modeling is more complex because there are still unanswered questions regarding the interpretation of real time seafloor pressure records in the source region. It is unclear how pressure records are best complemented by other observations so as to yield unambiguous measurements of sea surface displacements in the earthquake source zone. Furthermore, tsunami early warning depends upon sustained observations throughout and following the ground shaking. From the outset of an event, modeling studies must be linked tightly to estimates of the chances that particular components of the system will fail, such as dropouts from individual or groups of instruments. Indeed, such modeling studies will likely play a critical role in determining the topology and design of the network, including the mixture of cabled and non-cabled instruments. Because observations that constrain the tsunami will continue to be obtained as it moves toward and then floods coastlines, algorithms will be required that continually assimilate new data into an updating forecast.

A better understanding of the relation between seafloor motion and wave generation in the ocean is essential to interpret the data that might be collected from sensors on the seafloor or from direct observation of the sea surface (e.g., by HF radar or GNSS buoys). This has been identified as a significant research challenge that must be addressed. The DART network is a critical component of the far-field warning system because changes in ocean bottom pressure reflect the amplitude of a long wavelength tsunami as it passes. In this situation, changes in hydrostatic pressure due to changes in water depth are the primary signal, and these are used to calculate the change in surface elevation.

A detailed desktop study will be necessary to support the final system design. A desktop study is a standard planning mechanism to identify potential complications or considerations such as permitting, layout, cable crossing, and other offshore risks. It is important to quantify and minimize the impacts of turbidity flows and landslides on the seafloor infrastructure following an earthquake, as well as those from both natural and anthropogenic sources during the system’s life. An initial desktop study was performed as part of the development for this report. However, a more extensive study will be needed once a final instrument network design is chosen.

Although the basic instrument suite for earthquake and tsunami monitoring could comprise two standard instruments, a seismometer/accelerometer and a pressure sensor, it will be important to conduct studies to test and evaluate new sensor technologies. Most importantly, any new technologies need to be fully developed and demonstrated before they can be deployed in large numbers on a large seafloor instrument network. For example, distributed acoustic sensing is a relatively new technique that utilizes Rayleigh scattering in a fiber optic cable to measure the linear strain associated with seismic waves with very high spatial resolution along the length of the cable. This technique should be tested on the seafloor using one of the existing cabled observatories or with a cable of opportunity. Six-component seismometers that measure both linear and rotational accelerations (e.g., Nigbor, 1994) may hold promise for measuring unambiguous seafloor displacements necessary for modeling tsunamis, but the performance of these instruments needs to be assessed on the seafloor and on laboratory shake tables.

To the extent that the warning system can support enhanced geodetic observations, it may be important to test new approaches to measure strain including self-calibrating pressure and tilt sensors (Sasagawa and Zumberge, 2013; Wilcock et al., 2018), fiber optic strain meters (Zumberge et al., 2018), and quantum gravimeters (Freier et al., 2016). Although the time requirements for EEW will likely require instruments that are cabled to shore, TEW could rely on autonomous sea-surface platforms that communicate with the seafloor either acoustically or via electromechanical cables, and then communicate with shore either via satellite or radio. If such systems are envisioned, it will be essential to test the performance of this communication pathway in the harsh winter environment of the Northeast Pacific Ocean.

There is ongoing international scientific interest in Scientific Monitoring and Reliable Telecommunications (SMART) cable systems, which take advantage of transoceanic telecommunications cables by incorporating a basic package of environmental sensors into the optical fiber repeaters. The conceptual designs demonstrating technical feasibility have been completed by a Joint Task Force established in 2012 by the International Telecommunications Union, the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization, and the World Meteorological Organization, but no SMART cables have been installed in the ocean. If a similar approach were adopted for Cascadia, it would require some development work but could lead to a highly reliable system that could be buried to avoid conflicts with commercial fishing.

Funding

As for most projects, funding will be the most challenging aspect and can be divided into the funding necessary for preparatory work and the funding necessary to design, install, and then operate the offshore infrastructure.

Project Planning

Stakeholder Engagement and Public Outreach. A kickoff workshop for stakeholders could be run inexpensively and funded from a variety of sources. However, because a successful workshop is likely to lead to a lot of ideas and action items that would keep a project office busy, funding would ideally be in place for the project office at the time of or soon after the workshop. Funds from a philanthropic organization could provide one route to fund a workshop and form the office. An alternative but likely slower one, would be to hold a workshop and then approach the federal and state agencies responsible for disaster warnings and response. In the long term, the project office should seek support from multiple sources (potentially both public and private) with core operational funds ideally embedded in efforts at academic institutions, and state and federal agencies that prepare for disasters.

Characterizing the Subduction Zone Offshore. There are extensive ongoing offshore studies of the Cascadia subduction zone supported by NSF and the USGS. These efforts may be expanded further as the planning for the NSF SZ4D (McGuire et al., 2017) and USGS Initiative for Advanced Subduction Zone Science (Gomberg et al., 2017) lead to new opportunities. It will be important to collaborate with these new programs. However, without additional funding, it is unlikely that all the required observational studies will come to fruition. The current USGS effort led by the Coastal and Marine Geology Program does not have monitoring objectives, while NSF experiments are driven by the need to test scientific hypotheses and not the desire for comprehensive monitoring. Without additional funds, it is unlikely that geodetic observations will be obtained at the optimal density to support the design of an offshore monitoring system. Similarly, there is no clear source of funding for ocean bottom seismometer experiments that seek to build upon the Cascadia initiative by monitoring offshore seismicity for longer durations or with denser networks. New funding may also be needed to support mapping efforts to obtain complete coverage of potential cable routes and instrument sites.

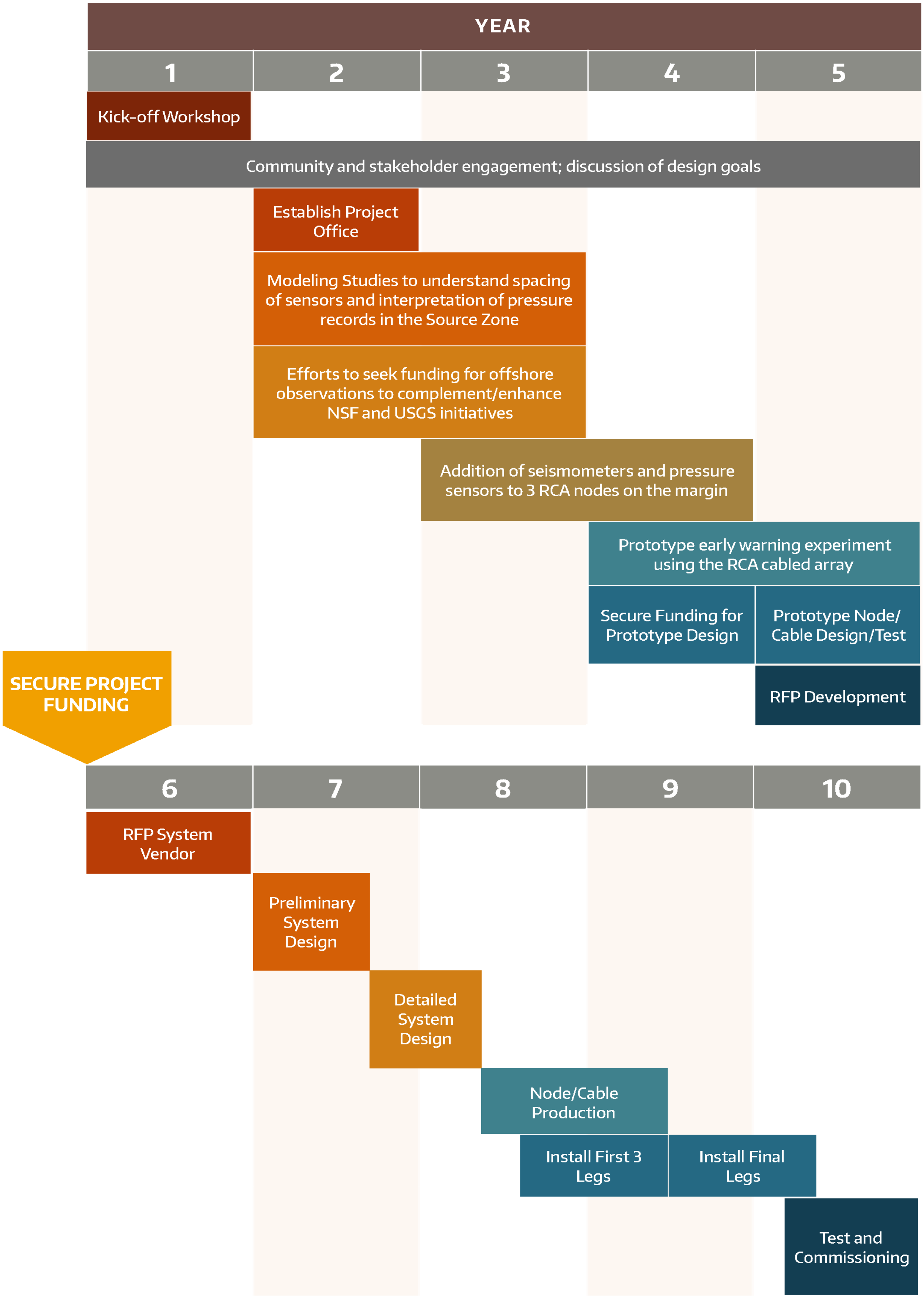
Utilizing the Ocean Observatories Initiative Cabled Array. The OOI-CA can advance monitoring science, provide testbeds for new instrumentation and observational platforms, and support prototype warning systems. Its sister observatory, the ONC NEPTUNE cabled observatory, is being incorporated into the Canadian systems for EEW and tsunami detection and modeling. As of 2019, the Cabled Array includes four primary nodes on the subduction zone, one at the slope base, two at depths of 1900 m and 600 m on the continental slope, and one at 150 m on the shelf as well as medium power junction boxes on Hydrate Ridge and at 80 m depth on the shelf. However, at present only the primary node at slope base and the medium power nodes on Hydrate Ridge support seafloor instrumentation.

Funds should be obtained for the medium powered instrument boxes at the three primary nodes on the central Oregon slope and shelf, and for the installation of seafloor instrumentation including seismometers, strong motion sensors, and pressure gauges. This instrumentation can address scientific questions related to understanding the high levels of seismicity off central Oregon, whether the subduction zone is only partially locked off central Oregon, and whether slip is accommodated by steady creep or slow slip events. The nodes would provide a test bed for new geodetic instruments, new technologies such as distributed acoustic sensing (DAS), and prototype cable systems into which seismic and pressure sensors are incorporated in-line with the cable. The expanded infrastructure could also enable a prototype demonstration warning system that can be used to test data delivery and analysis, and build awareness in coastal communities.

Modeling Studies. Funding will be required for modeling studies to optimize the distribution of instruments for earthquake and tsunami early warning and understand how pressure records in the source zone can be analyzed to isolate the effects of seafloor acceleration, acoustic reverberations, and static pressure changes. Funds for such studies could come from NSF, the USGS, NOAA, and philanthropic organizations.

Risk Communication and Education. The success and effectiveness of any early warning system will ultimately be measured by the outcomes (actions that reduce injuries, damage, and deaths). The effectiveness of any system will be hampered if the public and other end

The timetable for installation will depend on funding. With sustained funding, the full system could be completed in one decade.


YEAR
1
2
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5
Kick-off Workshop
Community and stakeholder engagement; discussion of design goals
Establish Project Office
Modeling Studies to understand spacing of sensors and interpretation of pressure records in the Source Zone
Efforts to seek funding for offshore observations to complement/enhance NSF and USGS initiatives
Addition of seismometers and pressure sensors to 3 RCA nodes on the margin
Prototype early warning experiment using the RCA cabled array
Secure Funding for Prototype Design
Prototype Node/ Cable Design/Test
RFP Development
SECURE PROJECT FUNDING
6
7
8
9
10
RFP System Vendor
Preliminary System Design
Detailed System Design
Node/Cable Production
Install First 3 Legs
Install Final Legs
Test and Commissioning

users are not fully educated on how best to respond to an early warning. It is important to understand how users are likely to assess and respond to imminent risks. Additional social science and preparedness research is needed to more fully explore how early warnings will be used, the best communication pathways, how best to educate the public in advance, and what messaging should be included in any early warning (i.e., Lindell and Prater, 2010).

Installation Timeline

There are two strategies for installing an offshore instrument network for early warning. An incremental approach requires less funding to initiate an operational warning system by focusing on a portion or portions of the coast where populations are most at risk. With this approach, lessons can be learned from early installations as the system is expanded to the full subduction zone, and the successful installation and operation of the early phases can be used to justify expanding the system. A one-step approach will optimize early warning for the full subduction zone from the onset, requires only one "heavy lift" to secure installation funds, and may achieve economies of scale that lower the total cost of a complete system. It may well be that detailed planning efforts will show that one approach is more optimal. For example, the engineers may recommend a phased approach to minimize the risk of implementing a new technology or the cost–benefit analysis may indicate that early warning infrastructure is particularly beneficial in a more limited region. Alternatively, the modeling studies may determine that adequate early warning requires complete coverage of the subduction zone.

Offshore monitoring can contribute substantially to the timeliness, reliability, and accuracy of earthquake and tsunami early warnings and has the potential to save many lives.

The decision between an incremental or one-step approach is likely to be driven by political considerations and the availability of funding. Planning needs to consider both options and recognize that the prospects for and path to funding is likely to be influenced in unpredictable ways by current events, including a destructive earthquake. Both strategies have been adopted for existing seafloor instrument networks. The ONC NEPTUNE cabled observatory and the OOI-CA followed a one-step approach although the latter was designed after the former was installed. In contrast, the DONET system illustrates an incremental approach, where JAMSTEC has expanded offshore coverage and instrumentation over time, allowing for updated designs and new observing technologies to be incorporated.

The timetable for installation will depend on funding. With sustained funding, the full system could be completed in one decade.

Summary

This report considers the value and feasibility of an offshore network of geophysical instrumentation extending along the length of the Cascadia subduction zone that would be designed to improve earthquake and tsunami early warning. The Cascadia subduction zone is a significant earthquake hazard with a history of destructive offshore megathrust earthquakes comparable to those recently experienced by Japan, Chile, and Sumatra. Such an earthquake will lead to several minutes of strong shaking that will extend inshore to the large population centers of the Pacific Northwest, and will be followed by a destructive tsunami that will reach the outer coast within ~15 minutes and inland waters within hours. Offshore monitoring can contribute substantially to the timeliness, reliability, and accuracy of earthquake and tsunami early warnings and has the potential to save many lives and improve the resilience of coastal communities if implemented as part of a comprehensive strategy to prepare for the next great earthquake.

Along the coast, the tsunami will kill the most people but earthquake early warning is important because it will help ensure that a well-trained population avoids injuries and entrapment that would prevent them from escaping the tsunami. While not the primary motivation, the sustained monitoring required for early warning will contribute substantially to scientific studies that will improve our understanding of the subduction zone hazard and investigate precursory signals that might be predictive of megathrust earthquakes.

The basic seafloor instrument system for early warning is a network of seismic and pressure sensors spaced approximately 50 km apart. The small latency required for EEW is most simply satisfied by a cabled system that could incorporate sensors hardwired in line with the telecommunications cable or connected through junction boxes and extension cables. Hybrid designs are also possible. A hardwired system is simpler, cheaper, and, if well designed, more reliable than a connectorized system, but lacks the flexibility to easily repair and upgrade instruments. For TEW, the time available to provide warnings is longer and non-cabled systems that communicate acoustically through the ocean and then via satellite or radio to shore are a feasible alternative. A system that combines cabled and non-cabled components might be the best approach to ensure that the system survives to monitor the tsunami after an earthquake.

An offshore early warning system that extends along the entire U.S. West Coast will cost several hundred million dollars and a variety of preparatory studies will be required to optimize the design. Extensive modeling with simulated earthquakes and tsunamis will help determine the maximum spacing and optimal positions to meet early warning objectives. A comprehensive effort to obtain observational data along the entire subduction zone to complement ongoing hypothesis driven scientific studies would help inform the design of a full-scale offshore monitoring system. Further investigation is required to understand how seafloor pressure observations in the earthquake source region can be supplemented by advanced processing or additional observations to measure the formation of the tsunami wave at the sea surface. There are several emerging technologies, including distributed acoustic sensing (seismic array observations with an optical fiber), improved methods of seafloor geodesy, and advances in autonomous vehicles and wireless data and power transfer that need to be evaluated for their potential contributions to a system. The existing Ocean Observatories Initiative and Ocean Networks Canada scientific cabled observatories off central Oregon and Vancouver Island should be used to test sensors, evaluate technology, and develop and test prototype early warning systems.

Many stakeholders must be engaged to build a coalition of academia, government, and the private sector to promote the value of early warning and raise funds. It is particularly important to develop a system that is responsive to the needs of the coastal communities that face the greatest hazard and that is coordinated with federal agencies responsible for warning and disaster response. A kickoff workshop would provide a mechanism to initiate the next phase and a rigorous cost–benefit analysis could help rally public support for the system. A project office with strong leadership can maintain continuity, grow consensus, engage society, and oversee fundraising.

It is particularly important to develop a system that is responsive to the needs of the coastal communities that face the greatest hazard.

If a Cascadia magnitude 9 megathrust earthquake occurred today, the resulting tsunami would kill thousands, and some coastal communities would likely never recover. While there is a tendency to assume a fatalistic attitude to such events and disregard the threat, the reality is that the impact on communities and the loss of life could be substantially reduced by a rational approach to invest in preparedness. An offshore early warning system is a necessary part of this investment and it is important to develop and execute a plan to implement it.

References

AIR Worldwide. *Study of Impact and the Insurance and Economic Cost of a Major Earthquake in British Columbia and Ontario/Québec.* Prepared for the Insurance Bureau of Canada (2013) 344 pp.

Akoh, R., T. Ishikawa, T. Kojima, M. Tomaru, and S. Maeno. High-resolution modeling of tsunami run-up flooding: A case study of flooding in Kamaishi city, Japan, induced by the 2011 Tohoku tsunami, *Nat. Hazards Earth Syst. Sci*., 17, 1871–1883, https://doi.org/10.5194/nhess-17-1871-2017, 2017.

Allen, R.M., E.S. Cochran, T. J. Huggins, S. Miles, and D. Otegui. Lessons from Mexico's earthquake early warning system, *Eos*, 99, doi:10.1029/2018EO105095, 2018.

Ammon, C. J., H. Kanamori, T. Lay, and A.A. Velasco. The 17 July 2006 Java tsunami earthquake. *Geophys. Res. Lett.*, 33, doi: 10.1029/2006GL028005, 2006.

Araki, E., K. Kawaguchi, S. Kaneko, and Y. Kaneda. Design of deep ocean submarine cable observation network for earthquakes and tsunamis. *Proc., MTS/IEEE OCEANS, 8-11 April, Kobe, Japan*, doi:10.1109/OCEANSKOBE.2008.4531071 (IEEE, 2008).

Atwater, B.F., S. Musumi-Rokkaku, K. Satake, Y. Tsuji, K. Ueda, and D.K. Yamaguchi. *The Orphan Tsunami of 1700—Japanese Clues to a Parent Earthquake in North America*, 2nd ed. (Seattle: University of Washington Press, U.S. Geological Survey Professional Paper 1707, 2015) 135 pp.

Basher, R. Global early warning systems for natural hazards: Systematic and people-centred. *Philos. Trans. R. Soc. London, Ser. A*, 364, 2167-2182, doi: 10.1098/rsta.2006.1819, 2006.

Bernard, E.N., and C. Meinig. History and future of deep-ocean tsunami measurements. *Proc., MTS/IEEE OCEANS'11, Waikoloa, HI, 19-22 September*, doi: 10.23919/OCEANS.2011.6106894 (IEEE, 2011).

Bernard, E., and V. Titov. Evolution of tsunami warning systems and products. *Philos. Trans. R. Soc. London, Ser. A*, 373, doi: 10.1098/rsta.2014.0371, 2015.

Biffard, B., A. Rosenberger, B. Pirenne, M. Valenzuela, and M. MacArthur. Real-time integration of positioning and accelerometer data for early earthquake warning on Canada's west coast. *Proc., American Geophysical Union Fall Meeting, 11-15 December, New Orleans*, Abstract IN31C-0086 (AGU, 2017).

British Columbia Emergency Management System Guide (BCEMS: 2016) 144 pp. Accessed August 2019: https://www2.gov.bc.ca/assets/gov/public-safety-and-emergency-services/emergency-preparedness-response-recovery/embc/bcems/bcems_guide_2016_final_fillable.pdf

Brothers, D., J. Conrad, P. Dartnell, A. East, P. Hart, J.C. Hill, S. Johnson, J. Lauesner, M. McGann, T. Parsons, R. Sliter, M. L. Walton, and J. Watt. *U. S. West Coast and Alaska Marine Hazards* (2019). Accessed August 2019: https://www.usgs.gov/centers/pcmsc/science/us-west-coast-and-alaska-marine-geohazards

Carbotte, S. *Collaborative Research: Illuminating the Cascadia plate boundary zone and accretionary wedge with a regional-scale ultra-long offset multi-channel seismic study*, National Science Foundation Award #1827452, 2018. Accessed August 2019: https://www.nsf.gov/awardsearch/showAward?AWD_ID=1827452

Cascadia Region Earthquake Workgroup (CREW). *Cascadia Subduction Zone Earthquakes: A Magnitude 9.0 Earthquake Scenario* (2013) 30 p. Access August 2019: http://www.crew.org/wp-content/uploads/2016/04/cascadia_subduction_scenario_2013.pdf

Chadwell, C.D. Update on GPS-acoustics measurements on the continental slope of the Cascadia Subduction Zone. *Proc., American Geophysical Union Fall Meeting, 11-15 December, New Orleans*, Abstract T51E-1288 (AGU, 2017).

Cook, M.J., G.S. Sasagawa, E.C. Roland, D.A. Schmidt, W.S.D. Wilcock, and M.A. Zumberge. Campaign-style measurements of vertical seafloor deformation in the Cascadia subduction zone using an absolute self-calibrating pressure recorder. *Proc., American Geophysical Union Fall Meeting, 11-15 December, New Orleans*, Abstract T51-0528, (AGU, 2017).

Crowell, B.W., D. Melgar, and J. Geng. Hypothetical real-time GNSS modeling of the 2016 Mw 7.8 Kaikoura Earthquake: Perspectives from ground motion and tsunami inundation prediction. *Bull. Seismol. Soc. Am.*, 108, 1736-1745, doi:10.1785/0120170247, 2018a.

Crowell, B.W., D.A. Schmidt, P. Bodin, J.E. Vidale, B. Baker, S. Barrientos, and J. Geng. G-FAST earthquake early warning potential for great earthquakes in Chile, *Seism. Res. Lett.*, 89, 542-556, doi:10.1785/0220170180, 2018b.

Daniell, J., B. Khazai, F. Wenzel, and V. Vervaeck. The CATDAT damaging earthquakes database. *Nat. Hazards Earth Syst. Sci.*, 11, 2235-2251, 2011.

Federal Emergency Management Agency Region IX and California Governor's Office of Emergency Services. *California Cascadia Subduction Zone Earthquake and Tsunami Response Plan* (FEMA and Cal OES: 2013) 144 pp. Accessed August 2019: https://www.caloes.ca.gov/PlanningPreparednessSite/Documents/CascadiaCatastrophicEQConops(Public)_2013.pdf

Fraser, S., G.S. Leonard, H. Murakami, and I. Matsuo. Tsunami vertical evacuation buildings—Lessons for international preparedness following the 2011 Great East Japan tsunami. *J. Disast. Res.*, 7, 446-457, 2012.

Fredrickson, E.F., W.S.D. Wilcock, P. MacCready, E.C. Roland, D.A. Schmidt, M.A. Zumberge, G. Sasagawa, and A.L. Kuparov.

Evaluating the use of seafloor pressure data for the study of slow slip earthquakes; insights from the 2011-2015 Cascadia Initiative deployment. *Proc., American Geophysical Union Fall Meeting, 11-15 December, New Orleans*, Abstract, T51E-0530 (AGU, 2017).

Freier, C., M. Hauth, V. Schkolnik, B. Leykauf, M. Schilling, H. Wziontek, H.G. Scherneck, J. Müller, and A. Peters. Mobile quantum gravity sensor with unprecedented stability. *J. Phys.: Conf. Ser.*, 723, doi: 10.1088/1742-6596/723/1/012050, 2016.

Fujinawa, Y., and Y. Noda. Japan's earthquake early warning system on 11 March 2011: Performance, shortcomings, and changes. *Earthquake Spectra*, 29, S341-S368, doi: 10.1193/1.4000127, 2013.

Fujita, M., T. Ishikawa, M. Mochizuki, M. Sato, S.I. Toyama, M. Katayama, K. Kawai, Y. Matsumoto, T. Yabuki, A. Asada, and O.L. Colombo. GPS/Acoustic seafloor geodetic observation: method of data analysis and its application. *Earth Planets Space*, 58, 265-275, doi: 10.1186/BF03351923, 2006.

Fujiwara, T., S. Kodaira, T. No, Y. Kaiho, N. Takahashi, and Y. Kaneda. The 2011 Tohoku-Oki Earthquake: Displacement reaching the trench axis. *Science*, 334, 1240, doi: 10.1126/science.1211554, 2011.

Gica, E., M.C. Spillane, V.V. Titov, C.D. Chamberlin, and J.C. Newman. *Development of the forecast propagation database for NOAA's Short-term Inundation Forecast for Tsunamis (SIFT)*. NOAA Technical Memorandum OAR PMEL–139, 2008, 89 pp. Accessed August 2019: https://www.pmel.noaa.gov/public/pmel/publications-search/search_abstract.php?fmContributionNum=2937

Given, D.D., E.S. Cochran, T. Heaton, E. Hauksson, R. Allen, P. Hellweg, J. Vidale, and P. Bodin. *Technical Implementation Plan for the ShakeAlert Production System: An Earthquake Early Warning System for the West Coast of the United States*. USGS Open-File Report 2014-1097, doi: 10.3133/ofr20141097, 2014, 25 pp.

Given, D.D., R.M. Allen, A.S. Baltay, P. Bodin, E.S. Cochran, K. Creager, R.M. de Groot, L.S. Gee, E. Hauksson, T.H. Heaton, M. Hellweg, J.R. Murray, V.I. Thomas, D. Toomey, and T.S. Yelin, *Revised Technical Implementation Plan for the ShakeAlert System—An Earthquake Early Warning System for the West Coast of the United States*. USGS Open-File Report 2018–1155, doi: 10.3133/ofr20181155, 2018, 42 pp. [Supersedes USGS Open-File Report 2014–1097.]

Goldfinger, C., C.H. Nelson, J.E. Johnson, A.E. Morey, J. Gutiérrez-Pastor, E. Karabanov, A.T. Eriksson, E. Gràcia, G. Dunhill, J. Patton, R. Enkin, A. Dallimore, T. Vallier, and the Shipboard Scientific Parties. *Turbidite Event History: Methods and Implications for Holocene Paleoseismicity of the Cascadia Subduction Zone*. USGS Professional Paper 1661-F (2012) 170 pp. Accessed August 2019: https://pubs.usgs.gov/pp/pp1661f/

Gomberg, J. Cascadia onshore-offshore site response, submarine sediment mobilization, and earthquake recurrence. *J. Geophys. Res: Solid Earth*, 123, 1381–1404, doi:10.1002/2017JB014985, 2018.

Gomberg, J.S., K.A. Ludwig, B.A. Bekins, T.M. Brocher, J.C. Brock, D. Brothers, J.D. Chaytor, A.D. Frankel, E.L. Geist, M. Haney, S.H. Hickman, W.S. Leith, E.A. Roeloffs, W.H. Schulz, T.W. Sisson, K. Wallace, J.T. Watt, and A. Wein. *Reducing Risk Where Tectonic Plates Collide—U.S. Geological Survey Subduction Zone Science Plan*. USGS Circular 1428, doi: 10.3133/cir1428 , 2017, 45 pp.

González, F.I., E.N. Bernard, C. Meinig, M. Eble, H.O. Mofjeld, and S. Stalin. The NTHMP tsunameter network. *Nat. Hazards*, 35, 25–39, doi: 10.1007/s11069-004-2402-4, 2005.

Gusman, A.R., A.F. Sheehan, K. Satake, M. Heidarzadeh, I.E. Mulia, and T. Maeda. Tsunami data assimilation of Cascadia seafloor pressure gauge records from the 2012 Haida Gwaii earthquake. *Geophys. Res. Lett.*, 43, 4189-4196, doi: 10.1002/2016GL068368, 2016.

Hamlington, B.D., R.R. Leben, O.A. Godin, E. Gica, V.V. Titov, B.J. Haines, and S. Desai. Could satellite altimetry have improved early detection and warning of the 2011 Tohoku tsunami? *Geophys. Res. Lett.*, 39, doi:10.1029/2012GL052386, 2012.

Haque, U., M. Hashizume, K.N. Kolivras, H.J. Overgaard, B. Das, and T. Yamamoto. Reduced death rates from cyclones in Bangladesh: What more needs to be done? *Bull. World Health Org.*, 90, 150–156, doi:10.2471/BLT.11.088302, 2012.

Heidarzadeh, M., A. Muhari, and A.B. Wijanarto. Insights on the source of the 28 September 2018 Sulawesi tsunami, Indonesia based on spectral analyses and numerical simulations. *Pure Appl. Geophys.*, 176, 25-43, doi: 10.1007/s00024-018-2065-9, 2019.

Heinrich, P., A. Piatanesi, E. Okal, and H. Hebert. Near-field modeling of the July 17, 1998 tsunami in Papua New Guinea. *Geophys. Res. Lett.*, 27, 3037-3040, 2000.

Hilmo, R., W.S.D. Wilcock, E.C. Roland, P. Bodin, and J. Connolly. A comparison of high-frequency noise levels on Cascadia Initiative ocean-bottom seismometers. *Proc., American Geophysical Union Fall Meeting, 11-15 December, New Orleans*, Abstract T51E-1284 (AGU, 2017).

Howlader, N., A.M. Noone, M. Krapcho, D. Miller, A. Brest, M. Yu, J. Ruhl, Z. Tatalovich, A. Mariotto, D.R. Lewis, H.S. Chen, E.J. Feuer, and K.A. Cronin, eds. *SEER Cancer Statistics Review, 1975-2016* (Bethesda, MD: National Cancer Institute). Accessed August 2019: https://seer.cancer.gov/csr/1975_2016/, based on November 2018 SEER data submission, posted to the SEER web site, April 2019.

Inazu, D., T. Ikeya, T. Waseda, T. Hibiya, and Y. Shigihara. Measuring offshore tsunami currents using ship navigation records. *Prog. Earth Planet. Sci.*, 5, 38, doi: 10.1186/s40645-018-0194-5, 2018.

Kamogawa, M., Y. Orihara, C. Tsurudome, Y. Tomida, T. Kanaya, D. Ikeda, A.R. Gusman, Y. Kakinami, J.-Y. Liu, and A. Toyoda. A possible space-based tsunami early warning system using observations of the tsunami ionospheric hole. *Sci. Rep.*, 6, 37989, doi:10.1038/srep37989, 2016.

Kanamori, H. Mechanism of tsunami earthquakes. *Phys. Earth Planet. Inter.*, 6, 346–359, doi: 10.1016/0031-9201(72)90058-1, 1972.

Kanamori, H., and M. Kikuchi. The 1992 Nicaragua earthquake: A slow tsunami earthquake associated with subducted sediments. *Nature*, 361, 714-716, 1993.

Kanazawa, T. Japan Trench earthquake and tsunami monitoring network of cable-linked 150 ocean bottom observatories and its impact to Earth disaster science. *Proc., IEEE International Underwater Technology Symposium, 5-8 March, Tokyo*, doi: 10.1109/UT.2013.6519911 (IEEE, 2013).

Kato, A., K. Obara, T. Igarashi, H. Tsuruoka, S. Nakagawa, and N. Hirata. Propagation of slow slip leading up to the 2011 Mw 9.0 Tohoku-Oki earthquake. *Science*, 335, 705-708, doi:10.1126/science.1215141, 2012.

Kawaguchi, K., E. Araki, M. Hoshino, T. Yokobiki, H. Matsumoto, S. Nishida, J. Choi, T. Kimura, T. Narumi, T. Baba, M. Nakano, T. Nakamura, and Y. Kaneda. Decision-making on seafloor surveillance infrastructure site for earthquake and tsunami monitoring in western Japan. *Proc., OCEANS, 7-10 April, Taipei, Taiwan*, doi:10.1109/OCEANS-TAIPEI.2014.6964514 (IEEE, 2014).

Kodera, Y. Real-time detection of rupture development: Earthquake early warning using P waves from growing ruptures. *Geophys. Res. Lett.*, 45, 156–165, doi: 10.1002/2017GL076118, 2018.

Kodera, Y., Y. Yamada, K. Hirano, K. Tamaribuchi, S. Adachi, N. Hayashimoto, M. Morimoto, M. Nakamura, and M. Hoshiba. The Propagation of Local Undamped Motion (PLUM) method: A simple and robust seismic wavefield estimation approach for earthquake early warning. Bull. Seismol. Soc. Am., 108, 983-1003, 2018.

Kulkarni, R., I. Wong, J. Zachariasen, C. Goldfinger, and M. Lawrence. Statistical analyses of great earthquake recurrence along the Cascadia Subduction Zone. *Bull. Seismol. Soc. Am.*, 103, 3205-3221, doi: 10.1785/0120120105, 2013.

Kuyuk, H.S., S. Colombelli, A. Zollo, R.M. Allen, and M.O. Erdik. Automatic earthquake confirmation for early warning system, *Geophys. Res. Lett.*, 42, 5266– 5273, doi:10.1002/2015GL063881, 2015.

Lay, T., S. Bilek, T.H. Dixon, and C. Moore. Anomalous earthquake ruptures at shallow depths on subduction zone megathrusts. *The Seismogenic Zone of Subduction Thrust Faults*, T. Dixon and J.C. Moore, eds., 476–511 (New York: Columbia University Press, 2007).

Lay, T., C.J. Ammon, H. Kanamori, Y. Yamazaki, K.F. Cheung, and A.R. Hutko. The 25 October 2010 Mentawai tsunami earthquake (Mw 7.8) and the tsunami hazard presented by shallow megathrust ruptures. *Geophys. Res. Lett.*, 38, L06302, doi:10.1029/2010GL046552, 2011.

LeVeque, R.J., P. Bodin, G. Cram, B.W. Crowell, F.I. González, M. Harrington, D. Manalang, D. Melgar, D.A. Schmidt, J.E. Vidale, C.J. Vogl, and W.S.D. Wilcock. Developing a warning system for inbound tsunamis from the Cascadia Subduction Zone. *Proc., MTS/IEE OCEANS'18, 22-25 October, Charleston, SC*, doi: 10.1109/OCEANS.2018.8604709 (IEEE, 2018).

Lindell, M.K., and C.S. Prater. Tsunami preparedness on the Oregon and Washington coast: Recommendations for research. *Nat. Hazards Rev.*, 11, 69-81, 2010.

Lomax, A., and A. Michelini. Tsunami early warning within five minutes. *Pure Appl. Geophys.*, 170, 1385–1395, doi:10.1007/s00024-012-0512-6, 2013.

Marshall, M. Mystery of deadly Indonesian tsunami cracked using social-media videos. *Nature*, 569, 463-464, doi: 10.1038/d41586-019-01544-5, 2019.

McGuire, J.J., T. Plank, et al. *The SZ4D Initiative: Understanding the Processes that Underlie Subduction Zone Hazards in 4D. Vision Document Submitted to the National Science Foundation.* (The IRIS Consortium, 2017) 63 pp. Accessed August 2019: https://www.iris.edu/hq/files/workshops/2016/09/szo_16/sz4d.pdf

McLean, S., C.S. McCreery, and E.N. Bernard. *NOAA Tsunami Program Strategic Plan 2012-2021* (NOAA, 2014) 31 pp. Accessed August 2019: https://www.hsdl.org/?view&did=762166

Meinig, C., S.E. Stalin, A.I. Nakamura, and H.B. Milburn. *Real-Time Deep-Ocean Tsunami Measuring, Monitoring, and Reporting System: The NOAA DART II Description and Disclosure* (NOAA Pacific Marine Environmental Laboratory, 2005) 15 pp. Accessed August 2019: https://www.ndbc.noaa.gov/dart/dart_ii_description_6_4_05.pdf

Melgar, D., R.J. LeVeque, D.S. Dreger, and R.M. Allen. Kinematic rupture scenarios and synthetic displacement data: An example application to the Cascadia subduction zone. *J. Geophys. Res.: Solid Earth*, 121, 6658–6674, 2016a.

Melgar, D., R.M. Allen, et al. Local tsunami warnings: Perspectives from recent large events. *Geophys. Res. Lett.*, 43, doi:10.1002/2015GL067100, 2016b.

Melgar, D., and Y. Bock. Near-field tsunami models with rapid earthquake source inversions from land- and ocean-based observations: The potential for forecast and warning. *J. Geophys. Res.: Solid Earth*, 118, 5939–5955, 2013.

Morton, E.A., S.L. Bilek, and C.A. Rowe. Newly detected earthquakes in the Cascadia subduction zone linked to seamount subduction and deformed upper plate. *Geology*, 46, 943–946, doi:10.1130/G45354.1, 2018.

Mulia, I.E., A.R. Gusman, and K. Satake. Optimal design for placements of tsunami observing systems to accurately characterize the inducing earthquake. *Geophys. Res. Lett.*, 44, 12,106–12,115, doi:10.1002/2017GL075791, 2017.

Multihazard Mitigation Council. *Natural Hazard Mitigation Saves: 2017 Interim Report. An Independent Study*. Principal Investigator Porter, K.; co-Principal Investigators C. Scawthorn, N. Dash, and J. Santos; Investigators M. Eguchi, S. Ghosh, C. Huyck, M. Isteita, K. Mickey, and T. Rashed; P. Schneider, Director, MMC. (Washington, D.C.: National Institute of Building Sciences, 2017) 22 p.

Murray, J.R., B.W. Crowell, R. Grapenthin, K. Hodgkinson, J.O. Langbein, T. Melbourne, D. Melgar, S.E. Minson, and D.A. Schmidt. Development of a geodetic component for the U.S. West Coast earthquake early warning system. *Seismol. Res. Lett.*, 89, 2322-2336, doi: 10.1785/0220180162, 2018.

Nagai, T., T. Kato, N. Moritani, H. Izumi, T. Terada, and M. Mitsui. Proposal of hybrid tsunami monitoring network system consisted of offshore, coastal and on-site wave sensors. *Coast. Eng. J.*, 49, 63–76, 2007.

Nigbor, R.L. Six-degree-of-freedom ground-motion measurement. *Bull. Seismol. Soc. Am.*, 84, 1665–1669, 1994.

Onur, T., and M.R. Seemann. Probabilities of significant earthquake shaking in communities across British Columbia: Implications for emergency management. *Proc., 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, 1-6 August*, Paper No. 1065, 2004. Accessed August 2019: https://www.iitk.ac.in/nicee/wcee/article/13_1065.pdf

Obara, K., and A. Kato. Connecting slow earthquakes to huge earthquakes. *Science*, 353, 253-257, doi: 10.1126/science.aaf1512, 2016.

OSSPAC - Oregon Seismic Safety Policy Advisory Commission. *The Oregon Resilience Plan: Reducing Risk and Improving Recovery for the Next Cascadia Earthquake and Tsunami* (Salem, Oregon, 2013) 311 pp. Accessed August 2019: https://www.oregon.gov/oem/Documents/Oregon_Resilience_Plan_Final.pdf

Paduan, J. D., and L. Washburn. High-frequency radar observations of ocean surface currents. *Ann. Rev. Mar. Sci.*, 5, 115-136, 2013.

Parker, T., S. Shatalin, and M. Farhadiroushan. Distributed Acoustic Sensing–a new tool for seismic applications. *First Break*, 32, 61-69, 2014.

Parris, B.A., et al. An amphibious magnetotelluric investigation of the Cascadian seismogenic and ETS zones. *Proc., AGU Fall Meeting, 14-18 December, San Francisco*, Abstract T12C-08 (AGU, 2015).

Patel , S.S., M.B. Rogers, R. Amlôt, and G.J. Rubin. What do we mean by 'Community Resilience'? A systematic literature review of how it is defined in the literature. *PLOS Curr.: Disasters*, 1, doi: 10.1371/currents.dis.db775aff25efc5ac4f0660ad9c9f7db2, 2017.

Percival, D.B., D.W. Denbo, M.C. Eble, E. Gica, H.O. Mofjeld, M.C. Spillane, L. Tang, and V.V. Titov. Extraction of tsunami source coefficients via inversion of DART® buoy data. *Nat. Hazards*, 58, 567–590, doi: 10.1007/s11069-010-9688-1, 2011.

Petersen, M.D., C.H. Cramer, and A.D. Frankel. Simulations of seismic hazard for the Pacific Northwest of the United States from earthquakes associated with the Cascadia Subduction Zone. *Pure Appl. Geophys*., 159, 2147-2168, 2002.

Pope, E.L., P.J. Talling, and L. Carter. Which earthquakes trigger damaging submarine mass movements: Insights from a global record of submarine cable breaks. *Mar. Geol*., 384, 131-146, doi: 10.1016/j.margeo.2016.01.009, 2017.

Porter, K., K. Shoaf, and H. Seligson. Value of injuries in the Northridge earthquake. *Earthquake Spectra*, 22, 555-563, doi: 10.1193/1.2194529, 2006.

Roarty, H., T. Cook, L. Hazard, D. George, J. Harlan, S. Cosoli, L. Wyatt, E. Alvarez Fanjul, E. Terrill, M. Otero, J. Largier, S. Glenn, N. Ebuchi, B. Whitehouse, K. Bartlett, J. Mader, A. Rubio, L. Corgnati, C. Mantovani, A. Griffa, E. Reyes, P. Lorente, X. Flores-Vidal, K.J. Saavedra-Matta, P. Rogowski, S. Prukpitikul, S.-H. Lee, J.-W. Lai, C.-A. Guerin, J. Sanchez, B. Hansen, and S. Grilli. The Global High Frequency Radar Network. *Front. Mar. Sci.,* 6, 164, doi:10.3389/fmars.2019.00164, 2019.

Rogers, D., and V. Tsirkunov. *Costs and Benefits of Early Warning Systems* (UNISDR, 2010) 16 pp.

Ruiz, S., M. Metois, A. Fuenzalida, J. Ruiz, F. Leyton, R. Grandin, C. Vigny, R. Madariaga, and J. Campos. Intense foreshocks and a slow slip event preceded the 2014 Iquique Mw 8.1 earthquake. *Science*, 345, 1165-1169, doi: 10.1126/science.1256074, 2014.

Sasagawa, G., M.A. Zumberg. A self-calibrating pressure recorder for detecting seafloor height change. *IEEE J. Ocean. Eng*., 38, 447-454, 2013.

Satake, K., K. Wang, and B.F. Atwater. Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami descriptions. *J. Geophys. Res*., 108, 2535, doi:10.1029/2003JB002521, 2003.

Saunders, J.K., and J.S. Haase. Augmenting onshore GNSS displacements with offshore observations to improve slip characterization for Cascadia subduction zone earthquakes. *Geophys. Res. Lett*., 45, 6008-6017, doi:10.1029/2018GL078233, 2018.

Savastano, G., A. Komjathy, O. Verkhoglyadova, A. Mazzoni, M. Crespi, Y. Wei, and A.J. Mannucci. Real-time detection of tsunami ionospheric disturbances with a stand-alone GNSS receiver: A preliminary feasibility demonstration, *Sci. Rep*., 7, 46607, doi:10.1038/srep46607, 2017.

Schiermeier, Q. Huge landslide triggered rare Greenland mega-tsunami. *Natur*e, doi:10.1038/nature.2017.22374, 2017.

Schmidt, D.A., W. Wilcock, P. Bodin, F. Gonzalez, M. Harrington, R.J. LeVeque, D. Manalang, E. Roland, and J. Vidale. *Offshore Geophysical Monitoring of Cascadia for Early Warning and Hazards Research, Workshop Report, Seattle WA, April 3-5, 2017* (University of Washington, 2018). Accessed August 2019: http://cascadiaoffshore.org/files/workshop_report-20180710061005.pdf

Schreiber, K.U., J.N. Hautmann, A. Velikoseltsev, J. Wassermann, H. Igel, J. Otero, F. Vernon, and J.P. Wells. Ring laser measurements of ground rotations for seismology. *Bull. Seismol. Soc. Am*., 99, 1190-1198, doi: 10.1785/0120080171, 2009.

Schulz, K. The really big one. *The New Yorker*, July 20, 2015, pp. 52-59. Accessed August 2019: https://www.newyorker.com/magazine/2015/07/20/the-really-big-one

Shoaf, K.I., H.R. Sareen, L.H. Nguyen, and L.B. Bourque. Injuries as a result of California earthquakes in the past decade. *Disasters*, 22, 218-235, doi: 10.1111/1467-7717.00088, 1998.

Spiess, F.N., C.D. Chadwell, J.H. Hildebrand, L. Young, G.H. Purcell, Jr., and H. Dragert. Precise GPS/acoustic positioning of seafloor reference points for tectonic studies. *Phys. Earth Planet. Int*., 108, 101–112, 1998.

State of California Emergency Plan. Governor's Office of Emergency Services, 2017, 189 pp. Accessed August 2019: https://www.caloes.ca.gov/PlanningPreparednessSite/Documents/California_State_Emergency_Plan_2017.pdf

Stone, I., J.E. Vidale, S. Han, and E. Roland. Catalog of offshore seismicity in Cascadia: Insights into the regional distribution of microseismicity and its relation to subduction processes. *J. Geophys. Res.: Solid Earth*, 123, 641–652, doi:10.1002/2017JB014966, 2018.

Strauss, J.A., and R.M. Allen. Benefits and costs of earthquake early warning. *Seismol. Res. Lett*., 87, 765-772, 2016.

Suppasri, A., N. Shuto, F. Imamura, S. Koshimura, E. Mas, and A.C. Yalciner. Lessons learned from the 2011 Great East Japan tsunami: Performance of tsunami countermeasures, coastal buildings, and tsunami evacuation in Japan. *Pure Appl. Geophys*., 170, 993–1018, 2013.

Tanioka, Y., and A.R. Gusman. Nearfield tsunami innundation forecast method assimilating ocean bottom pressure data: A synthetic test for the 2011 Tokoku-Oki tsunami. *Phys. Earth Planet. Inter.*, 283, 82-91, doi: 10.1016/j.pepi.2018.08.006,2018.

Toguchi, Y., S. Fujii, and H. Hinata. Tsunami waves and tsunami-induced natural oscillations determined by HF radar in Ise Bay, Japan. *J. Geophys. Res.: Oceans*, 123, 2965-2980, 2018.

Toomey, D.R., R.M. Allen, A.H. Barclay, S.W. Bell, P.D. Bromirski, R.L. Carlson, X. Chen, J.A. Collins, R.P. Dziak, B. Evers, D.W. Forsyth, P. Gerstoft, E.E.E. Hooft, D. Livelybrooks, J.A. Lodewyk, D.S. Luther, J.J. McGuire, S.Y. Schwartz, M. Tolstoy, A.M. Tréhu, M. Weirathmueller, and W.S.D. Wilcock. The Cascadia Initiative: A sea change in seismological studies of subduction zones. *Oceanography*, 27, 138–150, doi:10.5670/oceanog.2014.49, 2014.

Early Warning Practices Can Save Many Lives: Good Practices and Lessons Learned (Bonn, Germany: United Nations Secretariat of the International Strategy for Disaster Reduction (UNISDR), 2010) 67 pp. Accessed August 2019: https://www.unisdr.org/files/15254_EWSBBLLfinalweb.pdf

U.S. Tsunami Preparedness: NOAA Has Expanded Its Tsunami Programs, but Improved Planning Could Enhance Effectiveness. GAO-10-490 (Washington, D.C.: United States Government Accountability Office, April 2010) 39 pp.

Vallée, M., J.P. Ampuero, K. Juhel, P. Bernard, J.P. Montagner, and M. Barsuglia. Observations and modeling of the elastogravity signals preceding direct seismic waves. *Science*, 358, 1164-1168, doi: 10.1126/science.aao0746, 2017.

Washington State Emergency Management Division. *Catastrophic Disaster Planning, A Presentation to the State of Washington Cabinet 14 October 2014*. Accessed August 2019: https://mil.wa.gov/uploads/pdf/emergency-management/seoccatastrophicplanningtrainingpresentation-04081small.pdf

Wilcock, W.S.D., D.A. Manalang, M.J. Harrington, E.K. Fredrickson, G. Cram, J. Tilley, J. Burnett, D. Martin, T. Kobayashi, and J.M. Paros, New approaches to in situ calibration of seafloor geodetic measurements. *Proc., MTS/IEEE OCEANS'18, 28-31 May 2018, Kobe, Japan*, doi: 10.1109/OCEANSKOBE.2018.8559178 (IEEE, 2018).

Williamson, A.L., and A.V. Newman. Limitations of the resolvability of finite-fault models using static land-based geodesy and open-ocean tsunami waveforms. *J. Geophys. Res.: Solid Earth*, 123, 9033-9048, doi:10.1029/2018JB016091, 2018.

Witter, R.C., Y. Zhang, K. Wang, G.R. Priest, C. Goldfinger, L.L. Stimely, J.T. English, and P.A. Ferro. *Simulating Tsunami Inundation at Bandon, Coos County, Oregon, Using Hypothetical Cascadia and Alaska Earthquake Scenarios*. Oregon Department of Geology and Mineral Industries Special Paper 43, 2011, 57 pp. Accessed August 2019: https://www.oregongeology.org/tsuclearinghouse/resources/sp-43/SP-43_onscreen144dpi.pdf

Witter, R.C., Y.J. Zhang, K. Wang, G.R. Priest, C. Goldfinger, L. Stimely, J.T. English, and P.A. Ferro. Simulated tsunami inundation for a range of Cascadia megathrust earthquake scenarios at Bandon, Oregon, USA. *Geosphere*, 9, 1783–1803, 2013.

Wood, N., J. Jones, J. Schelling, and M. Schmidtlein. Tsunami vertical-evacuation planning in the U.S. Pacific Northwest as a geospatial, multi-criteria decision problem. *Int. J. Disaster Risk Reduct.*, 9, 68-83, 2014.

Yun, N.Y., and M. Hamada. Evacuation behavior and fatality rate during the 2011 Tohoku-Oki earthquake and tsunami. *Earthquake Spectra*, 31, 1237-1265, 2015.

Zumberge, M.A., W. Hatfield, and F.K. Wyatt. Measuring seafloor strain with an optical fiber interferometer. *Earth Space Sci*., 5, 371–379, doi:10.1029/2018EA000418, 2018.

Appendix A
Glossary of Terms

Abyssal Plain
The smooth, flat ocean bottom that begins seaward of the continental slope base.

Accretionary prism
The geologic structure that forms at a subduction zone where an oceanic tectonic plate slides below a continental tectonic plate. Accretionary prisms are mostly composed of sediments scrapped off of the oceanic plate, as well as terrigenous sediment eroded off the continental plate.

Bandwidth
The range of frequencies used to make a digital transmission. Higher bandwidth implies higher rates of data transfer.

Continental slope
The steepened slope between the continental shelf and the deep ocean basin.

Continental shelf
An undersea platform on the margin of a continent.

Dark fiber
An unused optical fiber, available for use in fiber optic communication.

Earthquake
A movement in the earth's crust where two faces of rock slide past each other, resulting in violent shaking.

Epicenter
The starting location of an earthquake, projected to the earth's surface.

Fault
A geological break in rock where earthquakes occur.

Fiber optic cable
Long strands of glass or transparent plastic capable of transmitting a communication signal over long distances using a pulsating light source.

Geodetic
Pertaining to geodesy, a discipline focused on the curvature, shape, and dimensions of the earth, as well as changes due to physical movements (i.e., earthquakes).

Inundation
The spreading of water over dry land, particularly when the flooding is permanent, such as when the land drops below sea level.

Latency
The time delay for a signal to be transmitted from a sensor to a central receiving location.

Liquefaction
A loss of strength in soil due to extreme shaking, typically occurring when the soil is fully or partially saturated with water.

Megathrust
The primary fault interface in a subduction zone where large earthquakes occur.

Neotectonics
Pertaining to active movements of the earth's crust that have occurred in the recent past (within several million years ago).

Resilience

The ability to quickly adapt to or recover from a disaster.

Strong ground motion

The extreme shaking that occurs near the source of an earthquake.

Subduction zone

A boundary between two geological plates where one plate descends below the other.

Tectonics

The study of the structure, properties, evolution, and movement of the earth's crust.

Turbidity current

A volume of water containing suspended sediment that moves downslope off the continental slope.

Turbidite

The geological deposit of sediment resulting from a turbidity current.

Trench

A linear depression on the seafloor that marks the boundary of two geological plates at a subduction zone.

Tsunami

A series of waves resulting from the instantaneous uplifting or dropping of the ocean surface. Tsunamis can be caused by earthquakes, landslides, and undersea volcanic eruptions.

Tsunami earthquake

An earthquake that produces a larger tsunami than might be expected for the size of the earthquake. It is thought that this type of earthquake slips more slowly than a typical earthquake, resulting in diminished shaking.

Wet-mate connector

A receptacle that allows for two wires to be connected or disconnected underwater.

Appendix B
Acronyms

AUV
Autonomous Underwater Vehicle

DART
Deep Ocean Assessment and Reporting of Tsunamis

DAS
Distributed Acoustic Sensing

DONET
Dense Oceanfloor Network System for Earthquakes and Tsunamis

EEW
Earthquake Early Warning

FEMA
Federal Emergency Management Agency

GNSS
Global Navigation Satellite System

GPS
Global Positioning System

HF
High Frequency

JAMSTEC
Japan Agency for Marine–Earth Science and Technology

NSF
National Science Foundation

NOAA
National Oceanic and Atmospheric Administration

OBS
Ocean Bottom Seismometer

OOI
Ocean Observatories Initiative

OOI–CA
Ocean Observatories Initiative–Cabled Array

ONC
Ocean Networks Canada

RF
Radio Frequency

ROV
Remotely Operated Vehicle

S-Net
Seafloor Observation Network for Earthquakes and Tsunamis

TEW
Tsunami Early Warning

USGS
United States Geological Survey

Appendix C
Resources

ShakeAlert
www.shakealert.org

Project Safe Haven
www.facebook.com/ProjectSafeHaven/

Paroscientific Series 800 Submersible Depth Sensor Data Sheet
paroscientific.com/paf/D50_Series_8000.pdf

Deep Ocean Assessment and Reporting of Tsumanis (DART)
www.ndbc.noaa.gov/dart/dart.shtml

NOAA Integrated Ocean Observing System
ioos.noaa.gov/project/hf-radar/

DONET
www.jamstec.go.jp/donet/e/

S-Net
www.ctbto.org/fileadmin/user_upload/SnT2015/SnT2015_Posters/T3.1-P30.pdf

OOI-CA
oceanobservatories.org/array/cabled-array/

Ocean Networks Canada NEPTUNE
www.oceannetworks.ca/observatories/pacific

Scientific Monitoring and Reliable Telecommunications (SMART) Cable Systems
www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx

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