Appendix G

White Papers

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Shallow Continental Shelves: a "no fly zone" for high precision sea floor geodesy, and a possible solution

Timothy H. Dixon, Chad Lembke, Jay Law, Rocco Malservisi, Randy Russel, and Surui Xie
University of South Florida

Marino Protti
OVSICORI-UNA

Giovanni Iannaccone
Istituto Nazionale di Geofisica e Vulcanologia, Italy

The giant earthquakes and tsunamis of 2004 (Sumatra) and 2011 (Japan) were wake up calls that our ability to estimate future earthquake magnitude and tsunami potential is weak. One factor that limits our understanding and forecasting ability is the difficulty of accurately measuring offshore strain accumulation in the challenging subduction zone environment. As pointed out in a recent review: "Despite the progress that has been made over the past three decades, seafloor geodesy is only slowly beginning to transition from demonstration projects to comprehensive monitoring systems" [*Burgmann and Chadwell*, 2014]. The main reasons for this discrepancy include the high cost of ship time, making instrument deployment expensive, and the fact that electromagnetic radiation, a key part of precision terrestrial geodesy, has a limited propagation distance in water. While acoustic energy can propagate long distances in water, the temporal and spatial variability of the speed of sound in the ocean degrade the performance of acousticbased geodetic systems, and is a particular problem on shallow continental shelves. Hence, a number of critical science needs, including monitoring of shallow subduction zone strain accumulation, remain unmet.

One target of interest is shallow slow slip events (SSEs). These are slip events on the plate interface that transpire over weeks or months, compared to seconds to minutes for normal earthquakes [*Schwartz and Rokosky*, 2007]. SSE's may be an important strain release mechanism, depending on their frequency and magnitude [*Dixon et al*., 2014]. Shallow SSE's have been identified in a few subduction zones, including New Zealand [e.g., *Wallace et al.,* 2016] and Costa Rica [e.g., *Dixon et al.,* 2014). They may be widespread, but for most subduction zones, on-land instrumentation is too far away for reliable detection. Offshore detection is challenging, requiring geodetic instrumentation that is simultaneously precise (typical signals may be less than 1 cm in amplitude), spatially dense (implying the need for low cost) and continuous (i.e., short campaignstyle observations may not be sufficient, since events can be irregular in time).

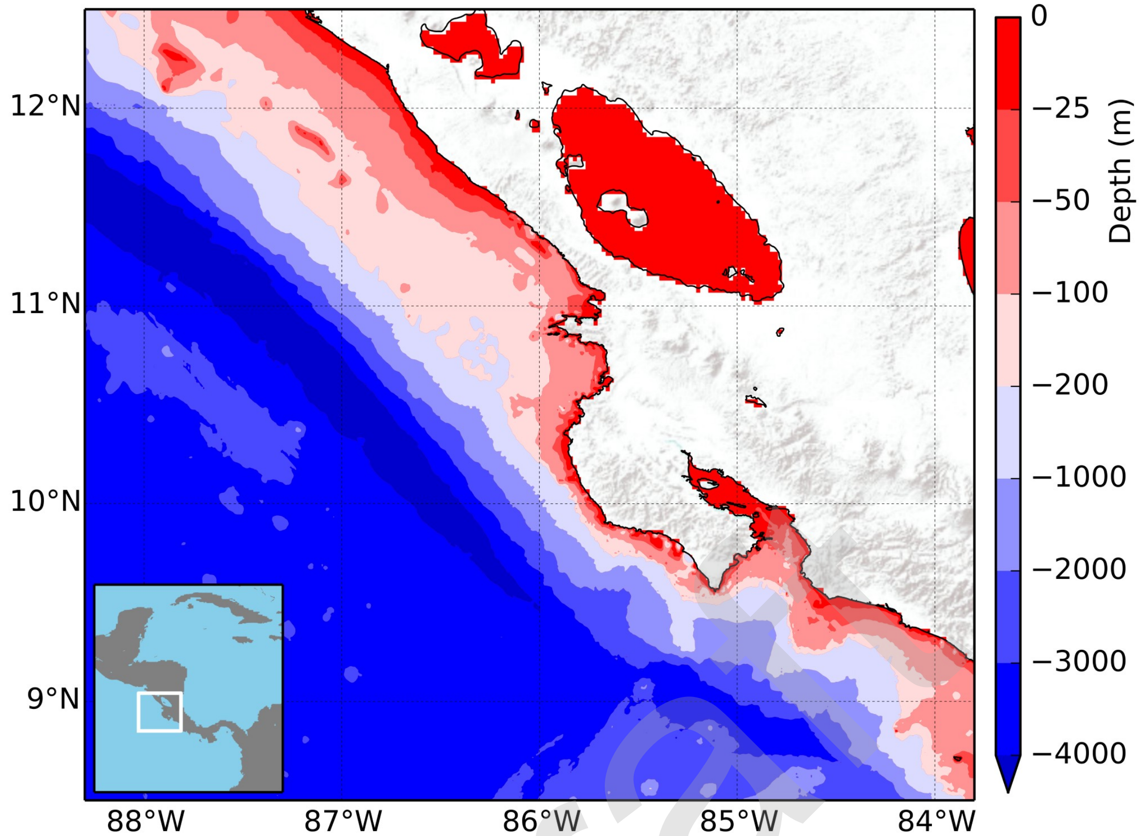
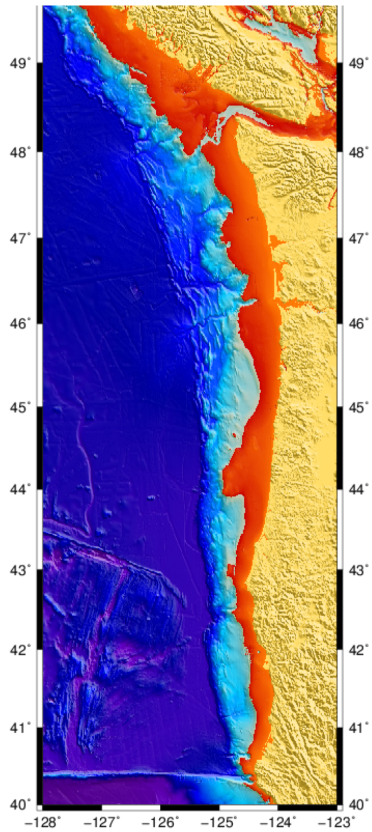


Figure 1. Bathymetry of the Nicaraguan fore-arc. Note that areas shallower than 200 m constitute approximately 50% of the marine forearc area.

Offshore pressure gauges and acoustic GPS have had some successes [e.g., *Wallace et al*., 2016; *Burgmann and Chadwell*, 2014] but work best in water depths of 1 km or more, far from the oceanographically "noisy" shelf environment. Fishing trawlers can also wreak havoc with underwater instruments deployed in shallower waters. Yet shallow (<200 m) shelves constitute a significant fraction of the offshore area in subduction zones between the coast and the trench (the marine forearc). For example, in offshore Nicaragua, the shelf area less than 200 m depth constitutes approximately 50% of the total marine forearc area (Figure 1). In Cascadia, the corresponding percentage is approximately 30% (Figure 2).



Red=areas less than 200 m depth

Figure 2. Bathymetry of Cascadia margin, highlighting areas less than 200 m water depth.

In 2011, INGV in Italy deployed an experimental sea floor geodetic system based on GPS without acoustic ranging, suitable for the shallow marine environment [*De Martino et al.,* 2014]. The system is based on a rigid spar buoy, and was designed to monitor vertical deformation of the sea floor associated with the Campi Flegrei volcanic area, two thirds of which is submerged in the Gulf of Pozzuoli in southern Italy. System performance for the vertical component is nearly equivalent to on-land high precision GPS, a remarkable achievement and a significant advance in sea floor geodesy. In principle, this system can be modified to generate horizontal positions, and operate in water depths up to about 200 meters. We were recently funded by NSF's Ocean Technology program to develop such a system. Our project aims to develop a lower cost version of the Italian system, and develop and demonstrate horizontal positioning capability.

Figure 3. Sketch of buoy, showing ballast (base), float (center) and superstructure (top) with GPS, batteries, and solar panels. Water-line is between float and superstructure. Ballast and float are scaled to water depth.

Our first buoy (Figure 3) is currently under construction, and has an estimated cost of $110K. It is scheduled for its first test deployment in the Gulf of Mexico in August 2017.
If successful, we hope to deploy one or two such units to the Golfo de Nicoya in Costa Rica (Figure 4). This shallow (less than 50 meter water depth) bay is important for defining the outlines of a large (M~7) repeating deep SSE that may be caused by subduction of a seamount [*Dixon et al.,* 2014; *Voss et al.,* 2017].

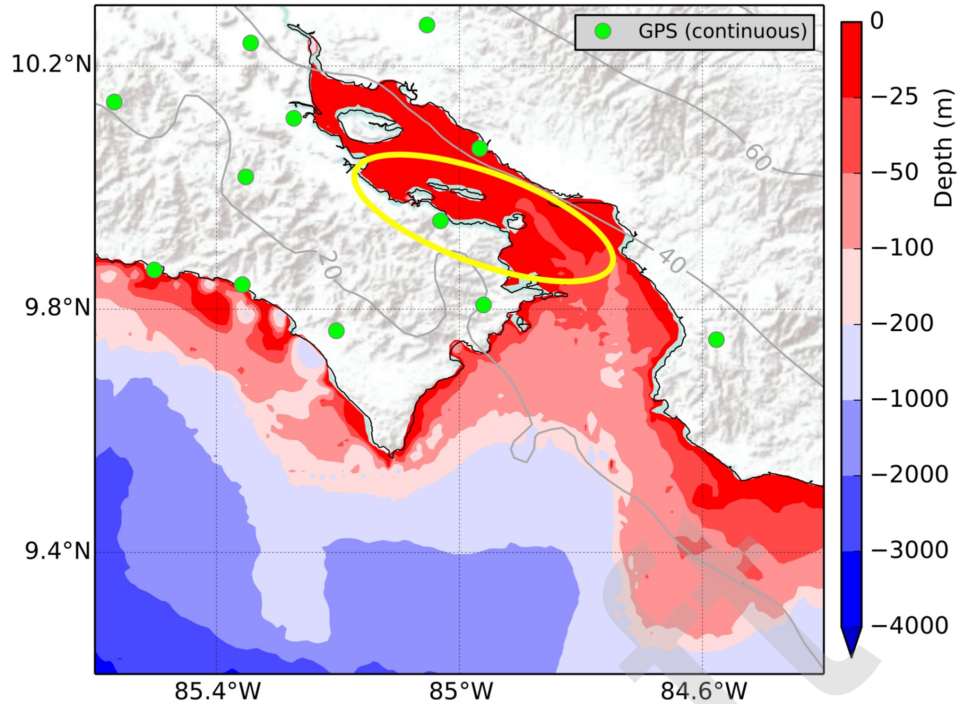


Figure 4. Bathymetry of the Gulf of Nicoya in Costa, showing location of on-land GPS stations and surface projection of the region of deep, frequent slow slip on the plate interface (yellow ellipse).

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Earthquake Early Warning; How long do we have?

R.D. Hyndman
Pacific Geoscience Centre, Geological Survey of Canada
9860 W. Saanich Road, Sidney B.C. V8L4B2, Canada and School of Earth and Ocean Sciences, University of Victoria Email:
roy.hyndman@canada.ca

Offshore Geophysical Monitoring of Cascadia for Early Warning and Hazards Research

Seattle | April 3-5, 2017

What is the minimum time we have for early warning of great earthquake shaking? Depends on:

(a) distance and travel time from initial rupture to nearest seismic station, coastal and offshore.

(b) time required to identify if the event is a megathrust; how much of the wave-train is required?

Also, do coastal and seafloor GPS data help?

This is a discussion is only for the first, the minimum travel time; there is much work being done on the second, event identification.

I don't bring a detailed analysis, only a discussion of what might be done to determine this minimum time, especially by looking at past great earthquakes globally. For a specific location of earthquake rupture initiation, the time depends mainly on, (1) where the rupture started along the margin and (2) its updip-downdip position.

A. Initial rupture location along the margin (Figure 1)

Where along the margin is a great earthquake most likely to initiate? No preference for the along-coast initiation of rupture is known as yet along the Cascadia margin, and it is unlikely that this can be estimated from paleoseismicity data. The initiation location may be random. However, since this would be very valuable information, it is worthwhile to look at global great earthquakes to see if there is any bias, a higher probability for some locations. Is there experience from megathrust events on other subduction zones that should be examined?

Some possibilities:

1. **Gorda rupture initiation**. Rupture may initiate along the Gorda margin because it appears to have more events than to the north. A Gorda M~8 event may initiate rupture over the whole margin, either by dynamic triggering or by Coulomb stress increase in the adjacent part of the thrust along the coast to the north. Such a local trigger also could occur for the Explorer Plate in the north, although no evidence for more frequent events has been found there so far.

2. **Narrowest (or widest) locked seismogenic zone**. Rupture may initiate along the margin where the locked zone is narrow. Since the stress may be distributed over a narrow width in that region, the stress may be higher than for areas with a wider locked zone.

3. **Steepest or shallowest dip**. Steepest seismogenic zone dip is off Oregon. Is this important?

4. Areas greatest bathymetry roughness on incoming plate; stress concentrators

5. **Area of small thrust events off Oregon; seamount asperity?** One form of stress concentrator, Or other local stress risers.
Other subduction zones are most relevant to Cascadia if they are almost completely locked, which is fairly unusual.

B. Updip-downdip rupture initiation preference

Location of initial rupture; downdip limit of "locked" zone? 350C?

Experience from recent megathrust events globally can give us information on where rupture initiation most commonly starts. The majority of previous megathrust events appear to have started near the landward limit of rupture. This needs a good global review. For older events, there is the question of whether the epicentre is a good indicator of where significant rupture started. Is detailed modern modelling required? If epicentre can be used, older events can give useful information.

For Cascadia, if the 350C thermal seismogenic limit is the likely start of rupture, the nearest approach to coastal seismic stations is 20-100 km or 4-10 seconds (Figures 1, 2).
For seafloor cable stations, the nearest approach to seafloor stations above 350C initiation is about 7 seconds. For a mid-slope station toward the updip limit of rupture, the first arrival is considerably earlier, about 3 s (Figure 3).

Global Examples

Haida Gwaii 2012 M7.8 event is the only recent well-studied megathrust where, like Cascadia, the downdip limit is inferred to be thermally limited. Rupture started deep and ruptured updip and laterally (Figure 4).

Tohoku, NE Japan M9. Rupture started near the downdip limit of major displacement and extended updip and laterally, although there was much high frequency energy from deeper (Figure 5).

Sumatra 2004, Started deep near but not at the base of rupture and extended updip (Figure 6).

Maule Chile 2010. Initial rupture as defined by the epicentre started deep and extended updip (Figure 7).

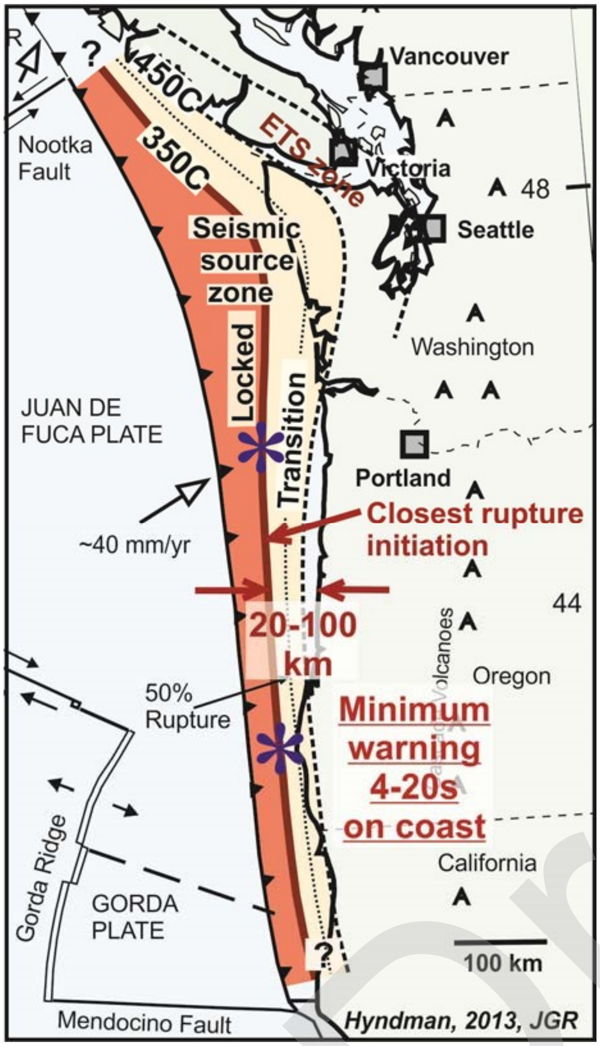

Figure 1. Map view of Cascadia great earthquake locked and transition zone that approximately correspond to full rupture and tapering to zero rupture displacement. The landward limit of the locked zone and 350C may be the preferred location down-dip for initial rupture.

The minimum distance to shore stations is about 20 km and maximum about 100 km, equating to about 4-20 seconds warning time.

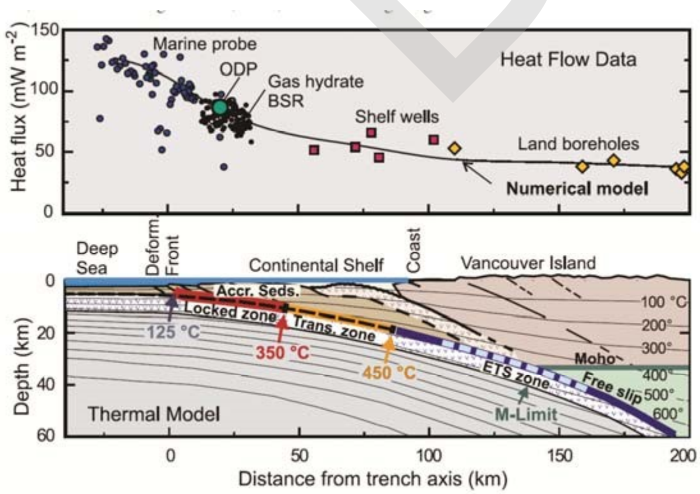

Figure 2. Cascadia subduction thrust. The down-dip limit of rupture is the closest approach to inland cities. The main high frequency energy for damaging small-scale structure usually comes from near the down-dip limit of rupture. Initial rupture may be at the landward limit of fully locked zone and 350C.

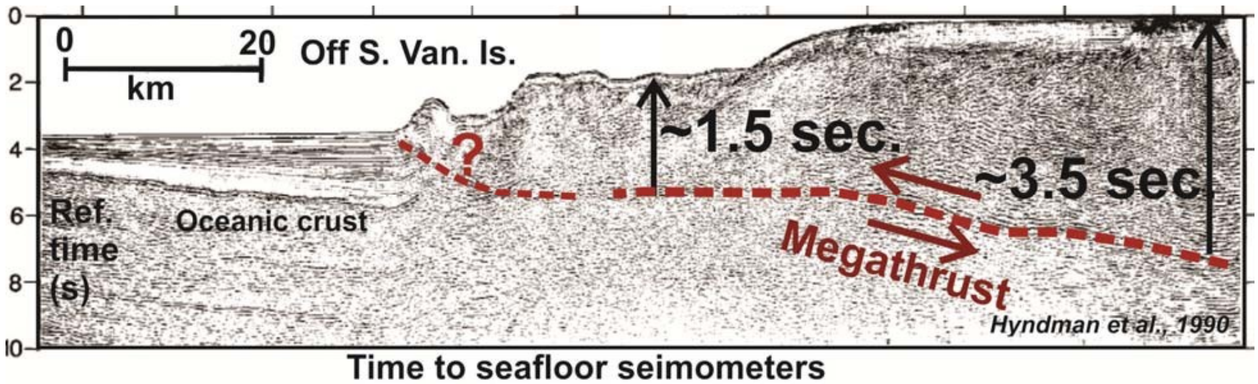

Figure 3. Seismic section across the margin off Vancouver Island, illustrating the sediment section above the subduction thrust. There is substantial travel time delay through the lowvelocity accretionary prism sediments. The time from the thrust to a seafloor station ranges from about 1.5 seconds on the mid-slope to 3.5 seconds on the shelf. The latter is near the estimated downdip limit of rupture which may be the rupture initiation.

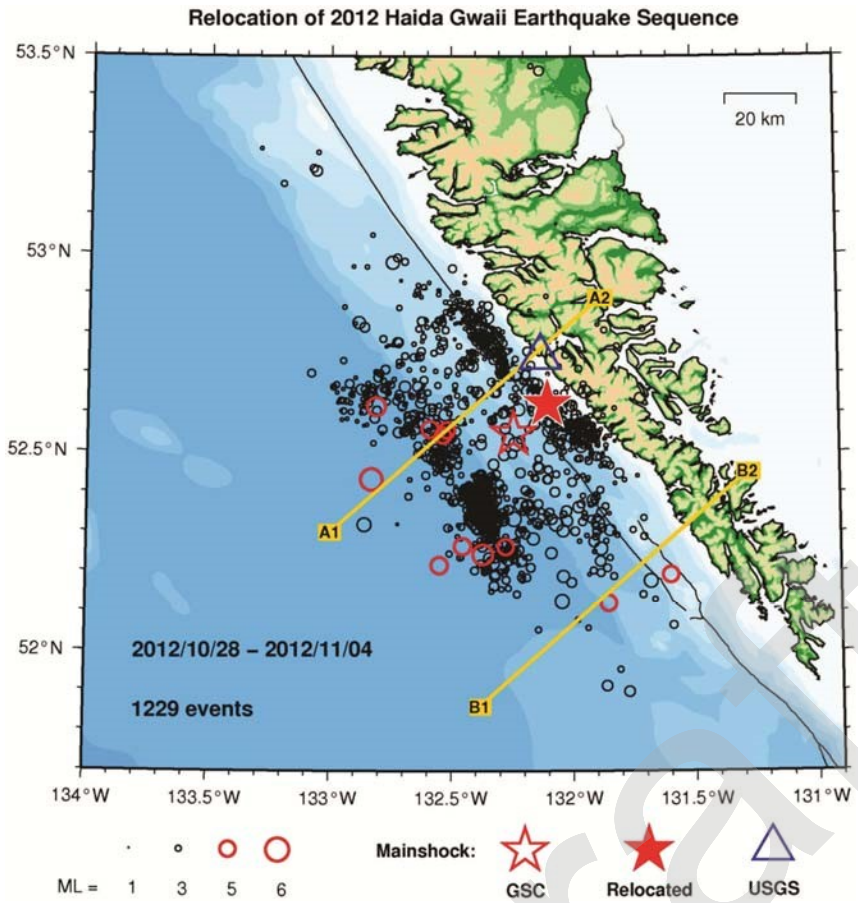

Figure 4. Initial rupture epicentre and aftershocks for the 2012 M7.8 megathrust off the coast of Haida Gwaii, Queen Charlotte margin. Initial rupture (red star) is close to the downdip limit of full rupture, and is close to the estimated position of 350C from thermal models.

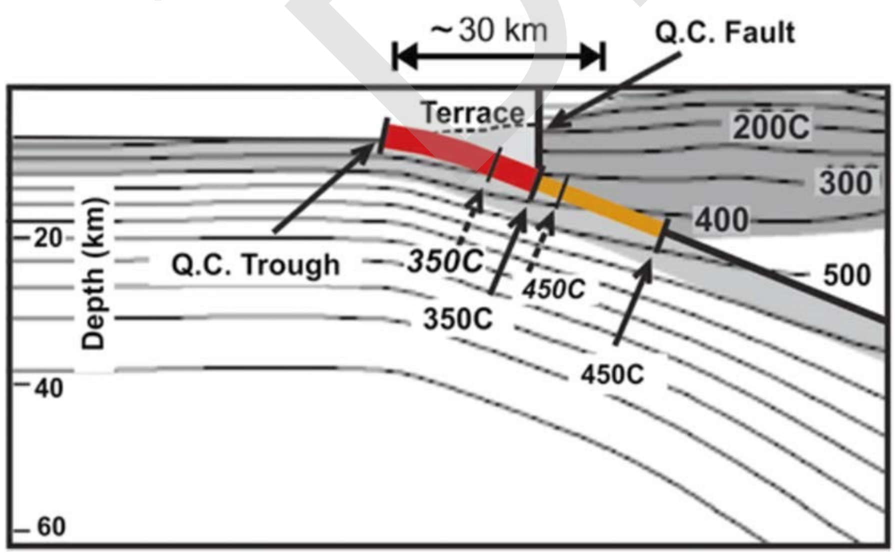

Figure 5. Thermal model across the margin of Haida Gwaii showing estimated temperatures on the thrust. Initial rupture was close to 350C on the thrust (italics are an earlier thermal model).

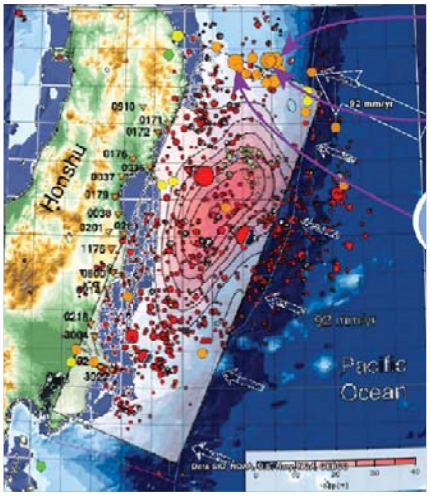

Figure 6. Aftershocks and model contours of rupture displacement for NE Japan M9 great earthquake. The initial rupture epicentre (red dot) is close to the downdip limit of substantial displacement, although much high frequency energy came from deeper.

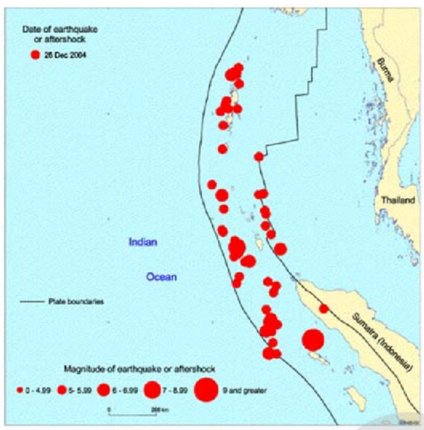

Figure 7. Aftershocks of Sumatra great earthquake compared to epicentre (large dot) which lies toward the base of rupture.

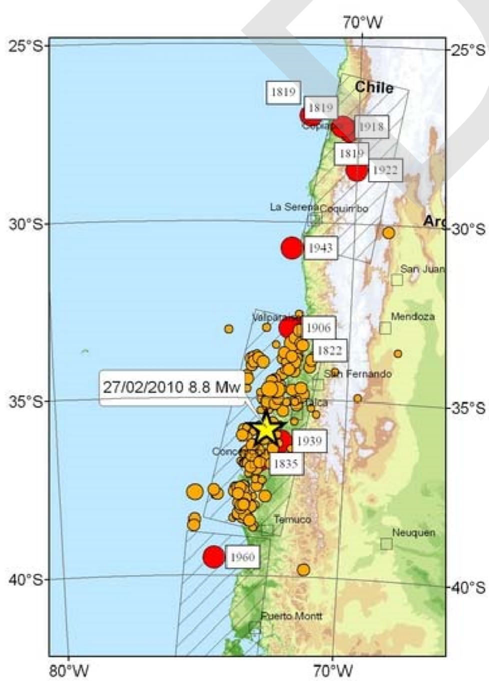

Figure 8. Aftershocks of Chile great earthquake compared to epicentre (large dot) which lies toward the base of rupture.

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Ocean Water Column Contributions to Bottom Pressure Determined by CPIES

Meng "Matt" Wei, D. Randolph Watts, and Kathleen Donohue
University of Rhode Island

Cascadia subduction zone is overdue for a major earthquake. A key question regarding natural hazards is whether such an earthquake can generate a large tsunami. Our ability to answer this question is limited by the lack of deformation measurements near the shallow portion of the subduction zone. Scientists from the University of Washington (UW) and the Scripps Institution of Oceanography (SIO) have established six benchmarks with ocean Bottom Pressure Recorder (BPR) and will periodically take measurements using the Absolute Self-Calibrating Pressure Recorder (ASCPR) with the intention to estimate the long-term vertical tectonic deformation. Seafloor pressure measurements are the sum of tectonic and ocean water column signals. To constrain the water-column contributions, the UW-SIO team will use output from a regional high-resolution numerical model through their collaboration with UW physical oceanographer co-PI (P. MacCready). Deep pressure variability arises from a number of ocean processes. In this region, the likely suspects are tides, deep mesoscale eddies, coastal-trapped waves, and meanders of the California Current and Undercurrent. Models, by assimilating sea surface height data and near-surface data, have become skillful at replicating the upper currents and their associated density and pressure fields, but presently and for the indefinite future, models have difficulty estimating the deep eddy and current variability across the topography of the slope – especially at the 1 cm level of desired pressure accuracy.

The Current and Pressure Recording Inverted Echo Sounder (CPIES) can be complementary and valuable to the current efforts. The CPIES, a bottom-mounted instrument, measures hourly bottom pressure, surface-to-bottom round-trip acoustic-travel-time and near-bottom horizontal currents (Figure 1). Combining these measurements, one can constrain the water signal within a better pressure accuracy than using pressure measurements alone. A spatial array of CPIES, a 1- or 2-dimensional configuration, can map the full water column circulation. The methodology is well established (Figure 2) and documented by Donohue et al. (2010). It has been employed in numerous oceanographic settings, for example, the Kuroshio Extension in the North Pacific (Tracey et al. 2012), the Loop Current in the Gulf of Mexico (Donohue et al. 2016), and the Antarctic Circumpolar Current in the Southern Ocean (Watts et al. 2016).

Funded by NSF and in late April 2017, the URI group will join the UW-SIO group for a cruise. The URI group will deploy four CPIES offshore Cascadia near the benchmarks and leave the instruments at the seafloor for about six months and recover them in November 2017. The URI group will collaborate with the UW-SIO for combining observations and modeling. The BPR measurements from the previous effort by the UW-SIO team have shown water column contributions of 3-5 hPa (equivalent to 3-5 cm water depth changes) on relevant 2-30 day time scales near the benchmarks offshore Oregon. Based upon this observed regional pressure variance and our experience with CPIES we expect to determine the water column signal to within 1 cm accuracy for these proposed four CPIES. Therefore, the CPIES method could very likely improve our ability to quantify the contributions from water column.

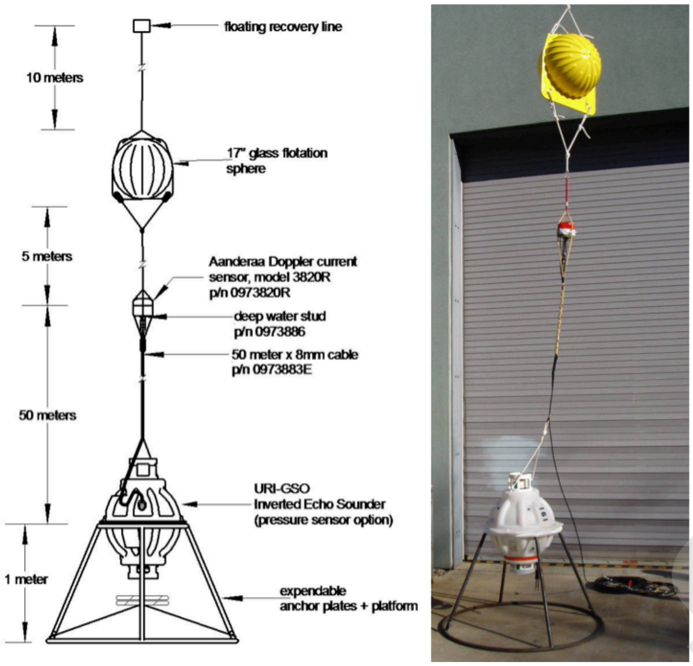

Figure 1. The CPIES is a bottom-mounted instrument that measures pressure at the sea floor, current speed and direction 50 meters above the bottom, and acoustic travel time from the sea floor to the sea surface and back. Instrumentation is self-contained with an acoustic release and flotation buoyancy. Instrument enhancements include a pop-up data shuttle where disposable capsules rise to the sea surface and send data to shore via satellite links, and an acoustic Doppler current profiler directly attached to the inverted echo sounder.

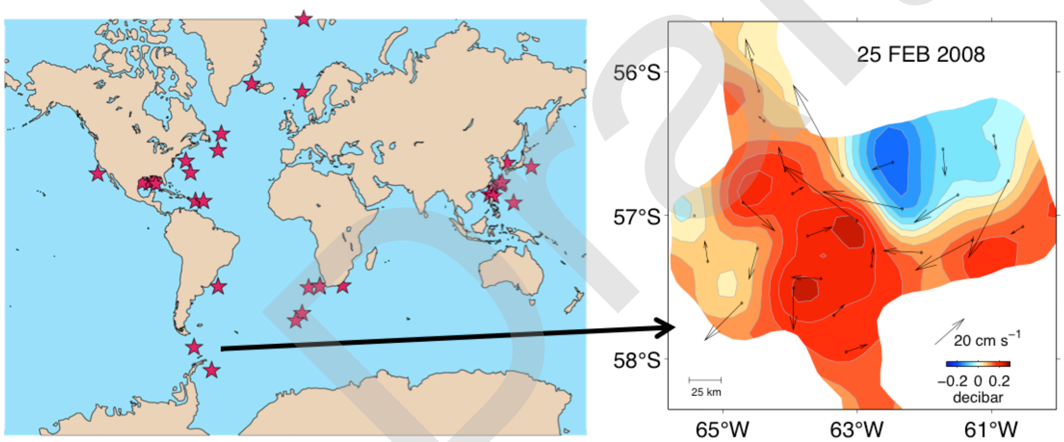

Figure 2. (Left) Locations of URI-fabricated PIES and CPIES deployments from 1988 to present. (Right) Powerful underwater storms in Drake Passage revealed from the CPIES array. Strong deep currents with speeds near 50 cm/s swirl around deep pressure systems.

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Seafloor and formation pressure, temperature, and deformation monitoring: Using IODP boreholes for studies of subduction zone geodynamics

Earl Davis
Pacific Geoscience Centre, Geological Survey of Canada

Keir Becker
Rosenstiel School of Marine and Atmospheric Science, University of Miami

(with support from and collaboration with T. Pettigrew, B. Carson, R. Meldrum, R. Maconald, M. Heesemann, H. Jannasch, M. Kinoshita, A. Fisher, H. Villinger, E. Araki, G. Wheat, M. Kaster, E. Solomon, P. Fulton, D. Saffer, A. Kopf, L. Wallace, J. McGuire, J. Collins, and others)

The primary goals of early ODP "CORK" borehole observatory installations (Fig. 1) were to determine the natural thermal state and driving forces for fluid flow through oceanic crust and subduction-zone accretionary prisms, and to obtain pristine pore-water samples in the absence of drilling and open-hole perturbations. CORK systems employ seals to maintain isolation of formations penetrated by drilling, and can host a variety of instruments for monitoring the static and dynamic formation state. Installations have been completed in over 25 holes, and several have been operational continuously for more than 15 years. All have included seafloor and formation pressure sensors, and most have included seafloor and formation temperature sensors. Most recently, downhole strain meters, seismometers, and tilt sensors have been added. The long records have provided a wealth of information beyond what was originally sought. For example, the formation response to variable loads imposed on the seafloor by seasonal ocean circulation, tides, tsunamis, and wind-generated ocean waves have provided constraints on elastic and hydrologic properties (compressional wave velocity, compressibility, shear modulus, permeability, hydraulic storage), with inferred properties being representative over scales that are much greater than that characterized by standard borehole or laboratory measurements. Another originally unanticipated application of CORK hydrologic monitoring has been the use of formation pressure as a proxy for crustal strain. Pressure changes have been observed at the times of many discrete episodes of seafloor spreading and fault slip along the Juan de Fuca Ridge and adjacent transform faults, and at the times of seismogenic and aseismic slip along the Nankai, Mariana, and Middle America (Costa Rica) subduction zones. Post-slip pressure transients have also been observed, as well as secular interseismic strain accumulation at Costa Rica and Nankai. In any particular case, quantitative estimates of strain can be made with the elastic properties estimated from seafloor loading response. The greatest sensitivity is provided in formations characterized by low porosity and high matrix compressibility (several kPa/μstrain; Fig. 2). Requirements for observing strain in this way are not nearly as stringent as those for direct measurements of strain, and clear strain-induced pressure signals have been observed in holes completed in semi-consolidated sediments at depths less than 500 m below the seafloor (Fig. 3). Observations made in permeable extrusive rocks of the upper igneous oceanic crust have the advantages of requiring much less penetration and of characterizing a large sampling volume, although hydrologic diffusion to the seafloor often limits their utility to relatively short-term transient signals (Fig. 4).

Various improvements to CORK hardware since the first deployments in 1991 now provide a means for monitoring pressure at multiple isolated formation levels, and for including downhole sensors such as seismometers and strain meters. Improvements to pressure monitoring electronics allow high resolution (e.g., 10 ppb full-scale pressure, or 0.4 Pa at 4000 m) reaching up to seismic frequencies (>1 Hz). The combination of this measurement capability and the sensitivity of pressure to strain in low-porosity (40%) sediment and igneous oceanic crust makes this observational technique viable and valuable for geodynamic studies.

Examples of strain-induced signals illustrated in Figure 4 include deformation associated with slow slip events at the Nankai and Costa Rica subduction zones, seen as uplift and contraction of the outermost accretionary prisms and dilatation of the incoming oceanic plates. Co- and post-seismic deformation has also been observed at these and other sites at times of large earthquakes (e.g., Fig. 3), and an expanded suite of observations is unfolding with recently installed and future sites at Nankai, Japan, and Hikurangi, New Zealand.

Achieving a transient signal resolution of a few tens of nanostrain with pressure monitoring is well demonstrated, but attention must be given to several things in order to optimize the quality of observations and understand the distribution of deformation and slip between and during slow, tsunamigenic, and seismogenic events at subduction zones. These include:

1) Achieving hydrologic isolation, with appropriate consideration of the depth of completion and the permeability of hydrologic pathways to the seafloor.

2) Monitoring in low porosity material to achieve good sensitivity of pressure to strain, with appropriate consideration of the depth of completion and the lithology.

3) Completing multiple monitoring levels, to expand the characterization of strain signals as a function of depth and to build confidence in the observations.

4) Making complementary observations, such as tilt, seismic ground motion, and strain, both in the borehole and at the seafloor.

5) Establishing monitoring site transects, including holes in the incoming plate immediately outboard of the prism toe, in the outer prism, and in the inner prism. A combination of the four existing monitoring sites at Nankai IF all were along a single transect, would serve as an ideal "template" (currently two are off Kii Peninsula in the inner part of the prism, and two are off Cape Muroto roughly 200 km away in the prism toe and in the incoming plate). It is also important to place offshore observations in the context of seismic and geodynamic observations made on shore.

6) Reducing or accounting for the effects of sensor drifts. This has always been done in boreholes via hydrostatic checks. Capabilities to carry out calibration against known-pressure references have been recently developed.

7) Experience has shown that penetration of the thrust interface itself is challenging, and while valuable information can unquestionably be gained there, observations within the prism and in the incoming plate have lower risk and provide highly diagnostic signals for geodynamics objectives.

Figure 1. Schematic of the primary CORK (Circulation Obviation Retrofit Kit) configurations.

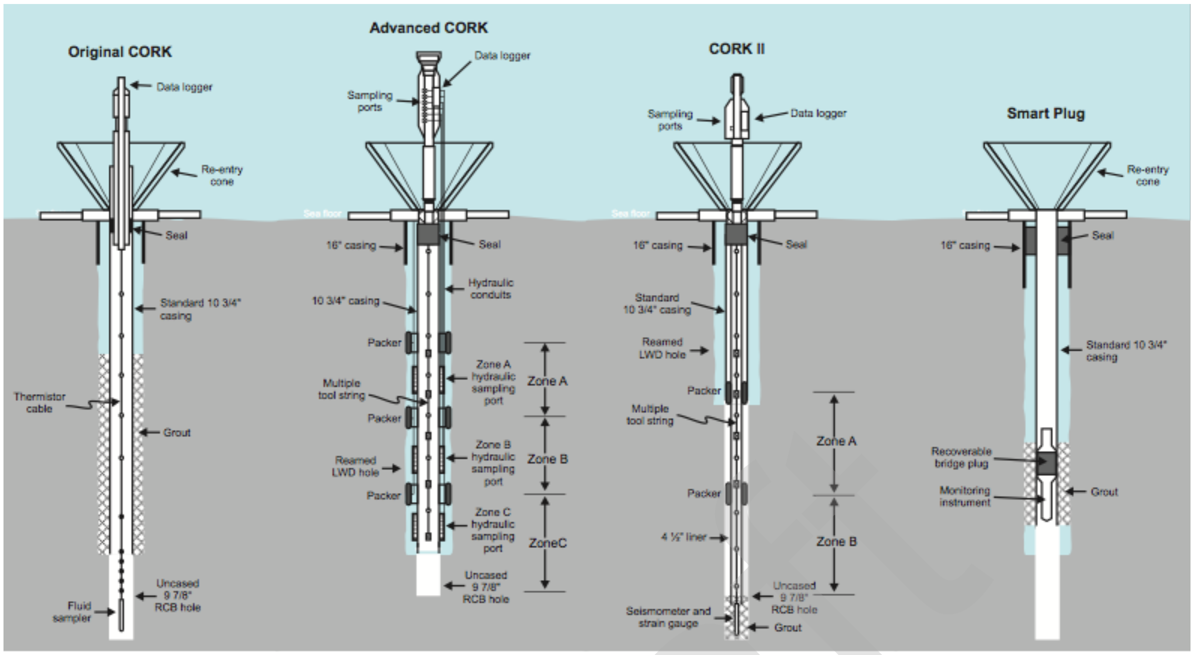


Figure 2. Sensitivity of formation fluid pressure to volumetric strain as a function of 1-D loading efficiency (defined by the response of formation pressure to ocean tides) for a range of porosity, estimated from poroelastic theory with an assumed matrix (drained) Poisson's ratio of 0.25.

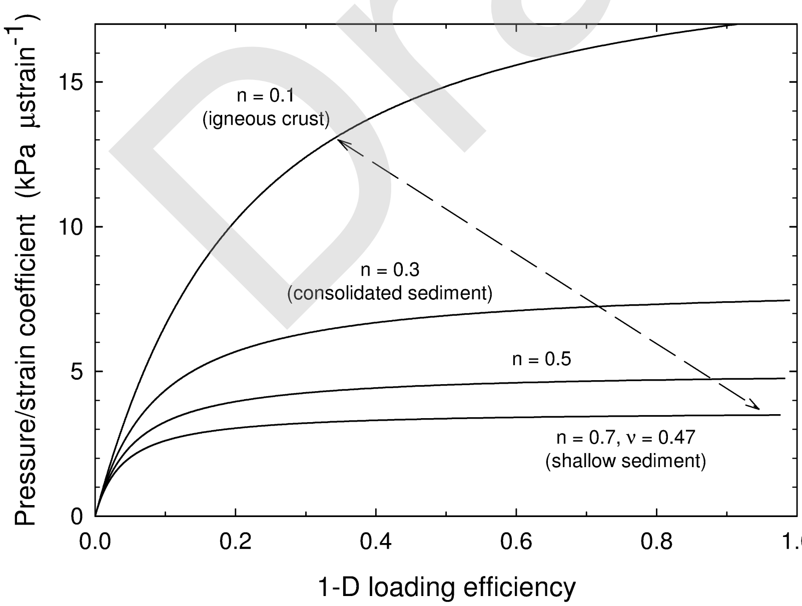


Figure 3. Pressures monitored in the subducting Philippine Sea plate roughly 10 km seaward of the Nankai accretionary prism frontal thrust. Secular changes at the two deeper levels (mbsf = m below seafloor) probably reflect interseismic contraction caused by the resistance to plate motion along the subduction thrust. Hydrologic drainage prevents storage of this signal at the two shallower levels. Shorter-term (hours to months) changes reflect regional strain related to distant earthquakes and afterslip, and to local triggered slow slip along the adjacent subduction thrust just landward of the site. Continuing data will be recovered in 2018.

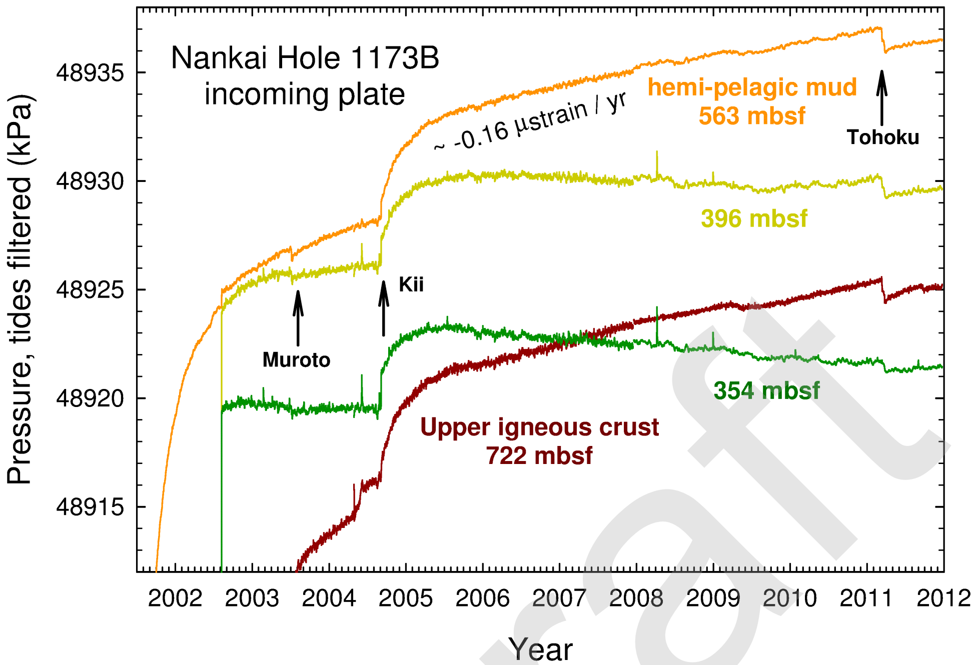
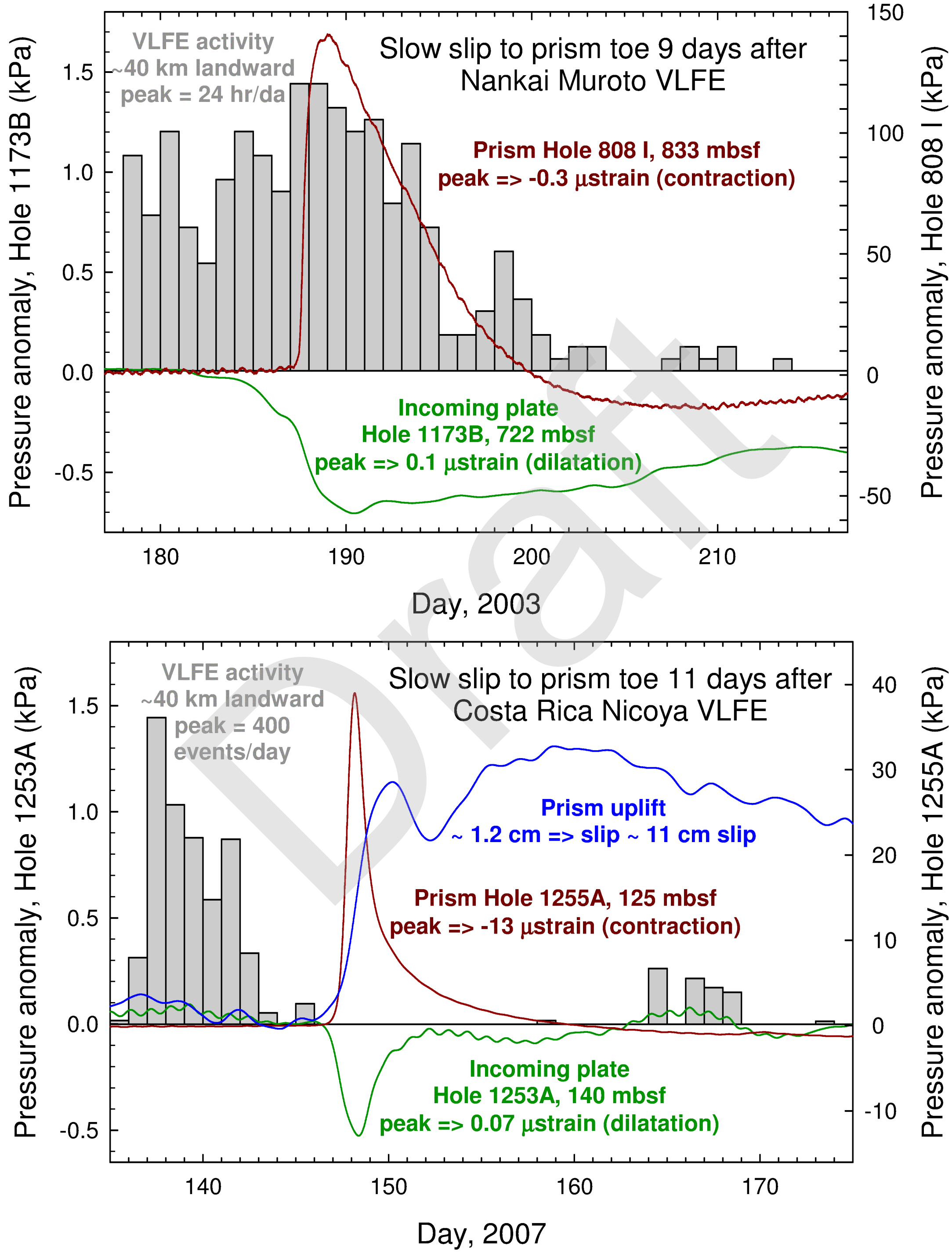


Figure 4. Formation and seafloor pressures recorded at ODP borehole sites seaward and landward of the frontal thrusts of the Nankai and Costa Rica subduction zones. These detailed records illustrate deformation associated with slow slip that begins several tens of km landward (as defined by very low frequency earthquake activity), and propagates to the prism toe over the course of several days. At Costa Rica, the reduction in pressure associated with dilatation is not maintained because of high crustal permeability and a short hydrologic drainage path.



Reducing Risk where Tectonic Plates Collide –A U.S. Geological Survey Plan to Advance Subduction Zone Science

Kristin A. Ludwig, Joan Gomberg, Barbara A. Bekins, Thomas M. Brocher, John C. Brock, Daniel Brothers, Jason Chaytor, Arthur D. Frankel, Eric L. Geist, Matthew Haney, Stephen H. Hickman, William S. Leith, Evelyn A. Roeloffs, William Schulz, Thomas W. Sisson, Kristi Wallace, Janet T. Watt, Anne Wein, Benjamin Brooks, Elizabeth Cochran, Todd Eriksen, Patricia McCrory, and Jessica Murray

Subduction zone hazards – earthquakes, tsunamis, volcanic eruptions, landslides - pose significant threats to lives, economic vitality, cultural and natural resources, and quality of life of the Nation. A new USGS Subduction Zone Science Plan outlines a comprehensive, scientifically-based foundation designed to make our nation more resilient to these inevitable events. The USGS Plan, to be published in Spring 2017, defines USGS science priorities and identifies potential partnerships with other organizations involved in relevant scientific research, emergency management, policy makinf and mitigation planning.

Priorities in this Plan address the needs of many stakeholders. Priorities include:

- Delivery of higher-resolution, more accurate maps, scenarios, and simulations.
- Collation of information to guide local land-use decisions and emergency response plans to minimize development in likely hazardous zones and to optimize evacuation routes.
- Development of new tools to assess the potential for cascading hazards (e.g., shaking-induced ground failure, eruption triggered lahars, landslide generated tsunamis).
- Construction of geospatial models identifying where permanent, widespread land- and sea-level changes may occur in the immediate aftermath of great subduction zone earthquakes.
- Fostering of strong partnerships between scientists and public safety providers.
- Continued refinement of accurate forecasts of far-reaching hazards (e.g., ash clouds, tsunamis) to minimize the effects of such catastrophes and avoidable disruptions in air- and sea-transportation.
- Continued refinement of aftershock forecasts to guide decisions about when and where to re-enter, repair, or rebuild buildings and other infrastructure, for all types of subduction-related earthquakes.

Addressing these priorities aligns with the three themes of the Plan: 1) advancing observations and models of subduction zone processes, 2) quantifying natural hazards and risk, and 3) providing forecasts and situational awareness. Realization of these scientific and technological goals will result in innovative products intended to promote development of resilient communities, broadly summarized in Table 1.

As has been demonstrated in Japan, Chile, and New Zealand, offshore seismic and geodetic measurements can alter our fundamental understanding of variable megathrust locking, coseismic slip distribution, and tsunami generation. Offshore monitoring of additional physical properties (e.g., acoustic waves, seafloor and water column temperatures, potential fields) across various temporal and spatial scales, accompanied by contextual observations (e.g., bathymetry, subsurface imagery), may also contribute to the broader scientific objectives and multiple hazards identified in the USGS's Subduction Zone Science Plan. Additionally, the West Coast earthquake early warning system, ShakeAlert, will issue alerts warning of incoming shaking based on seismic data, and efforts are underway to incorporate real-time GNSS data into

ShakeAlert to improve its capability for the largest earthquakes. While completion of the land-based system is the current priority, a quantitative assessment of the expected improvements to warnings through the addition of real-time offshore seismic and geodetic sensors is warranted. USGS goals are aligned with those of the academic community and other agencies involved in hazards mitigation activities, thus providing a broad foundation for decisions about future observational needs.

Table 1. Potential products and key investments for building resilience

Products	Description	Primary Scientific Inputs	Key Investments*	Application
High-resolution hazard and risk assessments	Neighborhood-scale estimates of ground shaking, tsunami inundation, ground failure, potential volcanic eruptions and associated lahar inundation, and their consequences.	High-resolution topography; bathymetry; 3-D models of Earth structure; well-characterized faults, unstable slopes, liquefaction prone areas, and active volcanoes.	A-I	Building design codes, prioritized retrofitting, urban planning, and evacuation routing.
Simulations	Science-based scenarios of hypothetical subduction zone events and their impacts.	Chronologies of past subduction zone events from geologic field and modeling studies, ground motion and other phenomenological databases.	G, H	Improved mitigation strategies and disaster response planning.
Warning systems	Notice of strong ground shaking, imminent volcanic eruptions and lahars, tsunamis, and ground failures.	Comprehensive monitoring systems, onshore and offshore.	A,B,C	Rapidly implemented life-saving and property-loss reduction measures.
New or improved types of forecasts	Continually updated projections of ground failures, lahars and volcanic ash clouds, and aftershocks.	Rapidly acquired satellite and surface measurements of land change. Improved real-time monitoring systems.	A,B,C,I	Safer, faster, and more cost-effective response and recovery.
Novel assessments of cascading subduction zone events	Likelihoods of submarine landslide-triggered tsunamis, earthquake-induced coastal land-level changes, and associated flooding, and erosion.	4-D models simulating linked earthquake, volcanic and geomorphic processes.	F,I	Rapid and effective mitigation, response, and recovery.

*Key investments for enabling forefront science and scientific products: A) Targeted, dense, land-based networks for monitoring earthquake, volcanic, and ground-failure processes. B) Routinely operated multidisciplinary monitoring. C) Partnerships to develop and operate permanent, seafloor monitoring instrumentation. D) Offshore sediment-core samples, images of subsurface geologic structures, temporary geophysical instrument deployments. E) High-resolution, multibeam bathymetry, adjacent to airborne and space-based topography onshore. F) Observationally constrained, three-dimensional models of the Earth's interior. G) Expanded geologic field programs. H) Laboratory capabilities for dating and analyzing the physical properties of rock samples. I) Synoptic, integrative multidisciplinary computer models.

DYNASEIS: GEO**DYNA**MIC AND **SEIS**CORK OBSERVATORIES IN THE CENTRAL AMERICA SUBDUCTION SYSTEM, COSTA RICA

Susan Schwartz[1], Evan Solomon[2], Andrew Newman[3], Nathan Bangs[4], Kevin Brown[5], Tim Dixon[6], Demian Saffer[7], Barbara Bekins[8], Rachel Lauer[9], and Marino Protti[10]

(1) UC Santa Cruz; (2) University of Washington; (3) Georgia Tech; (4) UT Austin; (5) UC San Diego; (6) Univ. of South Florida; (7) Penn State; (8) USGS; (9) Univ. of Calgary; (10) OVSICORI-UNA.

Almost 10 years ago, an IODP proposal was submitted to drill, core, case, log, and instrument three borehole sites that complete a transect connecting two existing ODP boreholes near the Middle America Trench to onshore Nicoya peninsula, Costa Rica seismometer and GPS installations. The overarching goal of this project, coined Dynaseis, was to improve our understanding of the mechanical behavior along a well-studied seismogenic plate interface. Although the proposal was favorably reviewed during the former phase of the IODP, at the time of resubmission there was little new data and proponents decided not to resubmit to the existing phase of IODP. However, new results, especially associated with the 2012 Nicoya earthquake, have opened up new opportunities. With the JOIDES Resolution scheduled to be in the Nicoya region between 2019-2021, the IODP Science Support Office invited the proponents to resubmit a revised proposal. This white paper describes some significant scientific advances since proposal submission that greatly enhance its importance and invites interested parties to join the proponent team for a new proposal submission.

The Nicoya Peninsula of Costa Rica is a unique environment that allows for easy access to details of the seismic cycle, due to its location and frequency of earthquakes. With coastal lands as close as 60 km from the Middle America Trench, subduction megathrust earthquakes occur here directly under land, allowing for near-field observations of geophysical activity associated with fault behavior. Two offshore Circulation Obviation Retrofit Kit (CORK) instruments were installed off the Costa Rica margin in 2002, providing continuous monitoring of formation pressure just above the prism toe décollement and formation pressure, temperature, and fluid composition within the incoming oceanic crust. Consequently, the seismogenic interface near Nicoya is one of the best monitored active subduction systems in the world. This region has undergone frequent earthquakes greater than about magnitude 7.5 approximately every 50 years, with the most recent occurring in September of 2012. GPS has also shown that slip along the Costa Rica margin does not all occur during regular earthquakes, but also includes frequent slow-slip events.

With research funding from the National Science Foundation, the Nicoya Seismic Cycle Observatory (NSCO), a dense land seismic and GPS network was established and a number of studies conducted that investigated the geologic and geophysical characteristics of this environment, capturing the late-interseismic, coseismic, and postseismic periods. Much has been learned, but many questions remain as this plate boundary progresses through the next stage of the seismic cycle, the early-relocking phase: 1) How do subduction megathrusts transition from the coseismic and early postseismic period back into a regime that locks up again, storing energy for the next big earthquake? 2) How do slow slip events interact with earthquakes to relieve stresses built through the seismic cycle? 3) Has the 2012 Nicoya Earthquake advanced the clock for adjacent patches that remain locked and may be poised for failure? 4) What is the role of fluids in the transition to a locked interface? 5) How is the hydrological, thermal, and geochemical architecture of the system linked to subduction dynamics? 6) What is the role of incoming topography on the locking pattern and temporal variability in slip?

We seek to augment the NSCO and CORK installations in this region with a few additional borehole sites that will complete a transect covering the entire seismogenic zone, from the trench to its onshore downdip extent. The proposed sensors and geophysical instruments to be deployed in these boreholes including tiltmeters, seafloor pressure sensors, weak and strong-motion seismometers, hydrophones, thermistors, pressure sensors, and fluid flow meters, will monitor deformation, seismicity, heat, and fluid flow. The new borehole installations will bridge the transition from stick-slip behavior that causes large earthquakes to a largely aseismic zone that is home to frequent slow slip, episodic fluid pressure changes and an overall diverse crustal, thermal, and geomorphic structure. Changes in formation fluid pressures, fluid flow rates, and composition at the two CORK sites have been linked to volumetric strain disturbances caused by near-field slow slip events (SSE). More than five episodes of fluid pressure anomalies have been identified since 2002. All are delayed by about one week from the onset of SSEs recorded on-shore, leading to the hypothesis that SSEs initiate at depth and then propagate seaward to the trench. This has important implications for the frictional properties of the plate interface, the rheological properties of the sedimentary prism overlying it, and the tsunami potential of the region. A program of drilling and monitoring conditions associated with the upper plate and the plate interface is the only way to derive the kinds of data that can address how in situ conditions control fault slip behavior.

Given the occurrence of the 2012 Nicoya earthquake, validation that slow slip events occur frequently at shallow depth, likely extending all the way to the trench, and the future path of the JOIDES Resolution that will bring the ship to the Nicoya region between 2019-2021, we feel that it is the right time to positively respond to the JR Facility Board's encouragement to resubmit an updated version of this proposal. *We are seeking interested scientists to join the proponent team and participate in this opportunity.*

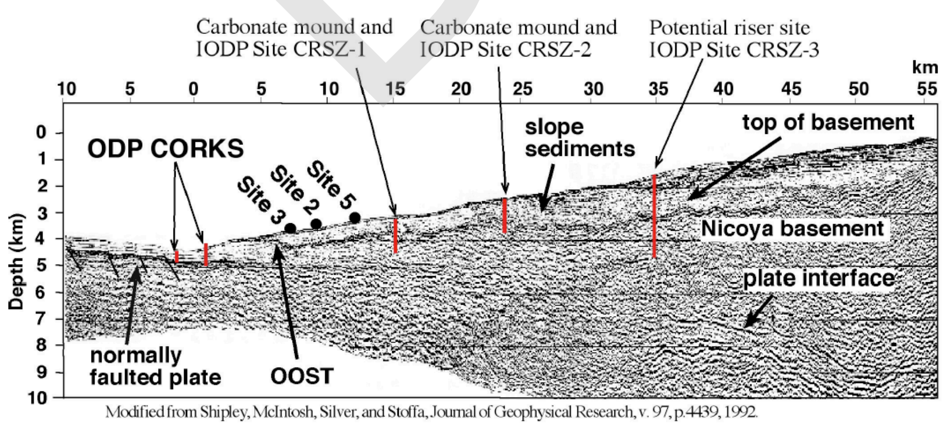


Figure 1. 2D Seismic cross section showing the overall structure of the Nicoya, Costa Rica subduction system. The proposed drill sites, and the locations of the ODP CORKS that recorded pressure changes during geodetically detected slow slip events are indicated.

Examples and Assessment of Geodetic Seafloor Instrumentation Benefits

Ronni Grapenthin
New Mexico Tech

Our understanding of convergent margins remains incomplete due to a lack of comprehensive geophysical networks on the seafloor. Complex ruptures like the 2012 Indian Ocean earthquake and large amounts of shallow slip as during the 2011 Tohoku-oki earthquake come as surprises and near-field observations for detailed study of such events are largely missing. While mostly onshore, the 2016 M7.8 Kaikora, NZ, earthquake presents a case in which highly spatially dense data are critical to resolving the most complex rupture pattern created to date (*Hamling et al., 2017).* Such examples should be taken into consideration when planning an onshore/offshore EEW system for Cascadia. For instance, is dynamic triggering considered for crustal faults following a Cascadia rupture, and vice-versa? More basic: will seafloor infrastructure accommodate 50+m displacements?

The value of seafloor geodetic measurements has been demonstrated repeatedly with recent findings from Japan. Following the 2011 M9.0 Tohoku-oki earthquake, *Tomita et al.* (2015) present the first post-seismic displacement observations on the Pacific plate, i.e., the subducting plate. Largely explained by a combination of plate velocity and post-seismic relaxation, they may dispel the hypothesis of accelerated slip following megathrust events, if only for that instance and measurement interval. Based on seafloor geodetic measurements, *Yokota et al.* (2016) refine slip-deficit rates for the Nankai Trough and find regions of thus far unknown slip deficit with important implications for seismic and tsunami hazards. For Tohoku-oki *Hooper et al. (2013)* show that seafloor geodetic data (particularly pressure gages) are instrumental to infer a slip distribution that predicts tsunami heights precisely.

It took ~36 s for Tohoku S-waves and static displacements to arrive onshore. Real-time geodetic seafloor instrumentation can eliminate most of this time from the estimation of earthquake size and slip distribution. While *Hooper et al. (2013)* find that seafloor positions were less important than seafloor pressure gages to constrain their slip model, it was not time dependent. Hence, it remains unclear how the early stages of the rupture would be constrained without seafloor GNSS, but simulations could and should help to evaluate the contribution.

Undoubtedly of high scientific value and likely and important contributor to evaluation of offshore rupture onsets, a real-time seafloor GNSS system requires a cost effective solution that streams geodetic data at $\geq$ 1 Hz with minimum latency. The proposed Cascadia cable design can provide power to acoustic transponder arrays on the seafloor. GNSS equipped buoys at the sea surface can position themselves relative to a fixed land station, transmit sea-floor and sea-surface data, and harvest power from solar and wave action. Position pollution by wave action could be reduced by a buoy-array above the seafloor transponders, which would also provide wave-height estimates for tsunami evaluation.

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California Earthquake & Tsunami Program

Kevin Miller
Tsunami Program Officer
Earthquake and Tsunami Program
California Governor's Office of Emergency Services (CalOES)
30 Van Ness, Suite 3300
San Francisco, CA 94102
kevin.miller@caloes.ca.gov

The California Governor's Office of Emergency Services (CalOES) Earthquake and Tsunami Program focuses on two of California's major hazards and seeks to increase awareness and preparedness, promote planning and hazard mitigation, and enhance warning, response and recovery capabilities. The primary target audience for planning and technical assistance is local government including counties, cities and special districts. The broader public in California is served through a comprehensive outreach and education program that addresses residents, businesses, critical facilities and special populations. In broad outline, the program can be divided into three basic components: 1) support to the California Integrated Seismic Network and Strong Motion Instrumentation Program; 2) earthquake planning, technical assistance and public education, 3) tsunami planning, technical assistance and public education, and 4) Earthquake Early Warning.

The CalOES Tsunami Program is funded by NOAA under the National Tsunami Hazard Mitigation Program (NTHMP). California is represented in the NTHMP by the Cal OES Earthquake and Tsunami Program Officer and a Senior Engineering Geologist from the California Geological Survey (CGS). Recent experience with tsunamis affecting the California coast includes the 2011 Tohoku Japan tsunami which caused $100M in damage to California coastal communities. These events helped demonstrate the importance of a statewide effort hazards to improve state and local planning, improve warning procedures and mitigate associated hazards. Local earthquakes, especially north of Cape Mendocino, can produce damaging tsunamis that will provide very little warning time. Integration into early warning systems is of interest to the tsunami research and emergency response communities.

In September 2013 the California Legislature authorized (Section 8587.8 of the California Government Code) CalOES, in collaboration with the California Institute of Technology (Caltech), CGS, the University of California, the United States Geological Survey (USGS), the Seismic Safety Commission and other stakeholders, to develop a comprehensive statewide earthquake early warning system through a public-private partnership. Gov. Jerry Brown signed legislation in September 2016 to expedite California's development of a system to provide advance warning of earthquakes. With Brown's signature on Senate Bill 438, California will compile a business plan for the project by early 2018. The bill creates a California Earthquake Early Warning Program (CEEWS) and Advisory Board to move the effort along. It will also ease financing by lifting a prohibition on using General Fund dollars for the statewide system, which is estimated to cost $28 million. This year's budget allocated $10 million to bolster a pilot program called ShakeAlert.

Within California, development of CEEWS has begun by the core members of the California Integrated Seismic Network (USGS, Caltech, UC Berkeley, CGS, and CalOES). A primary constraint on the timeline for implementation of CEEWS in the highest risk area of the country is funding. In addition, policy, management structure, user applications, and public education and training will impact the implementation of earthquake early warning. CalOES plans to carry out the provisions of the legislation by convening five committees that include those institutions identified in the Government Code and other stakeholders and subject matter experts. The product of these committees will be a well-articulated and comprehensive plan that describes an operational earthquake early warning system for California that is based upon a public-private partnership with clearly delineated organizational responsibilities and management structure, conforming to the highest scientific and technical standards of performance, and supported by a rational and feasible funding strategy independent of the California state General Fund.

Questions: What is the cost of an offshore monitoring system? How can it be made most cost effective? How will it be funded? How could implementation impact and integrate with relevant warning systems and hazard programs?

High-Rate Seismic Data Retrieval from Seafloor Arrays using Autonomous Underwater Vehicles and Optical Telemetry

John Collins, Norman Farr, Michael Purcell, Jon Ware, and Jeff McGuire
Woods Hole Oceanographic Institution, Woods Hole, MA 02543

Cabled seafloor seismic stations, such as the Japanese DONET array and the US and Canadian RSN and ONC stations, offer long lifetimes (tens of years), well-coupled seismometers, accurate timing, and real-time data telemetry. The downsides are substantial expense, limited geographical coverage, and a lack of flexibility once installed. Autonomous Ocean Bottom Seismographs (OBS) are relatively cheap to deploy, but telemetering data from such systems to shore is challenging. Seismic data from OBS can be telemetered ashore via a combination of acoustic and satellite/VHF links [*Frye et al., 2006; Berger et al., 2016*] but rates are constrained by the throughput through the water to be about 1 MByte/day. This is adequate to retrieve 1 Hz data and selected portions of high-rate data only, but not continuous, high-rate (50+ Hz) data.

WHOI is currently funded by NSF to develop the capability for complete data retrieval from autonomous OBS using high-speed optical telemetry and an Autonomous Underwater Vehicle (AUV). The concept is illustrated in Figure 1. This capability, coupled with OBS deployment durations of 2+ years and better clocks, will decrease the need for shiptime, and will allow sustained monitoring in regions not covered by seafloor cables. The capability will be particularly suitable for closely-spaced (km–10's of km) seismic arrays deployed on the continental shelf and slope to monitor earthquake hazards. While the system is not real-time, data can be delivered to shore with latencies of days, depending on distance from shore and the number of stations.

The LED-based optical telemetry system has field-proven data delivery rates of 10, 20, and 500-1000 Mbits/second at ranges of 100 m, 40 m, and 10-0 m, respectively. At 10 Mbits/s, a week's worth of loss-less compressed 100 Hz data on 4 channels can be offloaded in less than 5 minutes. The optical modem has now been integrated with a WHOI REMUS AUV. The REMUS family of AUVs have depth capabilities of 100 – 6000 m, mission durations 8 – 70 hours, and top speeds of up to 5 knots. The AUV has demonstrated the ability to swim in a circle of 20 m radius about a seafloor target for sustained durations.

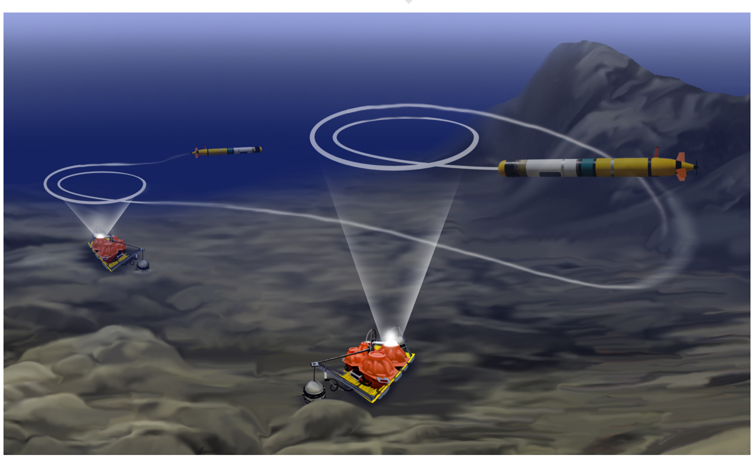

Fig. 1. Graphical illustration showing the capability that the WHOI group is developing using NSF funds. In the foreground, a REMUS AUV 'loiters' above an OBS as it downloads data at rates of up to 10-20 Mbits/s via the Optical Modem. The OBS measures the offset of its clock relative to the GPS-synchronized clock carried on the AUV. The AUV then moves to the next station and repeats the procedure.

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Cost Benefit Analysis for Earthquake Early Warning in British Columbia: A Case Study of the Port of Vancouver

Ziming Wang, Teron Moore, and Ivan Rincon
Ocean Networks Canada

As part of the Eartquake Early Warning (EEW) Project funded by the Province of British Columbia (BC), Ocean Networks Canada (ONC) is conducting a Cost Benefit Analysis of the EEW system in BC. We will be using the results of this case study to engage in discussions related to the quantitative value of just a few seconds of advanced warning. By demonstrating the quantitative value of EEW in BC, decision-makers will be able to assess the potential return on investment for future advancements to a fulsome EEW system.

Given the challenges the conducting a systematic cost benefit analysis and considering our study's time constrains, we decide to conduct a case study focused on the operations of the Port of Vancouver and associated infrastructure, to explore the potential values of EEW within the Port Community. Our study is constructed based on the PEER (2016) research undertaken for the state of California's EEW system. For the British Columbian context, we interviewed individuals from four different sectors of the Port Community. We explained a given earthquake scenario and estimated amount of warning time an effective EEW system could provide. We then asked each interviewee to describe some of the mitigation methods that could be applied in this scenario.

For a production-based industry, the organization participated in an earthquake assessment conducted by the City of North Vancouver in 2015 so they are fully aware of the potential impact of an earthquake. They have designed emergency response procedures especially for the case of earthquake, employees are well educated about the earthquake risk and have been trained for responding to the emergency. This organization also participates in the ShakeOut earthquake drill each year, so the level of awareness and preparedness is considered high. The emergency manager said that any ability to provide early warning for an incoming earthquake would be extremely valuable to the organization. If the factory received 30 seconds of warning, employees would be able to get away from dangerous situations and take cover in safe locations. The interviewee stated that employees could have time to move to safe locations and take precautions to prevent injuring or even death. Also, if EEW was considered accurate and reliable, the factory could also initiate automatic shutdown procedures. Although it would take about two hours to safely shutdown the entire factory, even 30 seconds of advance warning could be useful in preventing some damage to equipment.

For the Container Port, The interviewee indicated that damages to the facility would be expected during the event of an earthquake. Given the shaking intensity and duration in this scenario, the containers, which are 2 meters high and 2-30 tones in weight, may topple from their stacks in the stock yard. The berth and railway would likely be damaged due to the strong shaking and liquefaction effect. It is highly probable that ships would be loading and unloading at the time of the earthquake. In this case, swinging containers could cause damage to the vessel as well. Cranes could also be damaged even though stringent seismic performance requirements are adopted by the crane industry. These requirements demand that cranes remain operational after small earthquakes and will not collapse in a large earthquake. Thus, crane drivers would be considered to be relatively safe during the earthquake. Berth, railways, and overpass could expect damaged at some level. People working in the docking area may be injured or killed by falling containers and other objects. The office building would likely remain standing after the earthquake but business operation would be interrupted. Estimations about potential monetary losses due to earthquake damage were not able to be provided.

For the Oil terminal, the emergency manager from the oil company contends that there would be relatively little damage from the earthquake given in our scenario due to the long distance (~200km) from the epicenter. They expect impact limited to staff that are working onsite potentially getting injured by falls and falling objectives. The oil terminal facilities were built in 1950s. Although most of facilities are seismic reinforced, limited damage may still be expected. The onsite oil storage tanks are constructed with steel and are designed to absorb shock waves from an earthquake. In the event of a leak, each storage tank has containment berms, or dykes, that are designed to store the full capacity of each tank. The pipeline itself is constructed with high-quality steel designed to be flexible for high seismic resistance. For these reasons, the possibility of pipeline break is considered low in this earthquake scenario. However, if an oil spill does take place and the berms don't hold, the impact on the environment would be considerable. To clean up the oil spill could cost hundreds of million dollars.

Finally, for the Port management, the interviewee related that the largest impacts from a major earthquake would be to its work force and infrastructure. The mitigation of injuries or death is the number one priority. The earthquake may damage the infrastructure as well. It was noted that business operations of the company would likely be interrupted during such an event. Given the importance of the employees in this company, they are well prepared for earthquake events and participate in the ShakeOut earthquake drill annually. The company has an earthquake-specific emergency response plan as well as a business resumption plan, which guides people back to work as soon as possible after an earthquake.

In summary, British Columbia is facing an earthquake threat. A magnitude 9 mega-thrust earthquake has capability to cause damage to the entire BC coast. Real-life examples and academic research combine to illustrate the potential of EEW to save lives and protect critical infrastructure during a major earthquake event. Through this case study, we find the consistency with this previous work. Our interviewees have identified some of the possible applications in manufacturing, transportation, and management sectors within the Port of Vancouver community. Those interviewed especially recognized the potential benefit that EEW could make in protecting human lives. We believe that these applications can be also implemented in other sectors across BC.

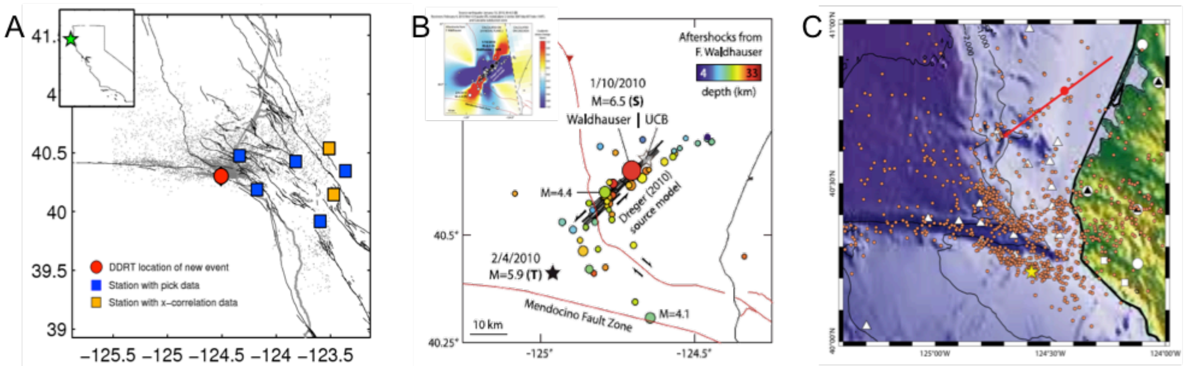
Given the limitations and the time constraints of this study, we focused on the port communities as an example to show the potential benefits of a province-wide EEW system. We hope that this study can serve as a tool to engage and communicate with the potential End-users from across BC to discover more ways benefit from this technology. With the support of these End-users, we hope to construct a more systematic and comprehensive cost benefit analysis on EEW in the near future.

White paper: Precision seismic monitoring of Cascadia

F. Waldhauser
Columbia University, LDEO

Much effort in observational seismology is spent on the acquisition of new data through the deployment of temporary networks. In contrast, comparably little effort is spent on getting the most out of existing data sets – which include archives produced during standard routine monitoring at permanent seismic networks like the Pacific Northwest Seismic Network (PNSN). Many of these long-term data archives are ripe for comprehensive, waveform based re-analysis due to the increasing amount and quality of the data, affordable computing power, and the availability of efficient algorithms that achieve orders of magnitude improvement in the resolution of existing estimates of earthquake locations and magnitudes over large spatial and temporal scales. Integrated in a real-time environment as part of routine monitoring operations, these advanced analytical tools, and the relational data bases they operate on, not only improve detection and location capabilities, but also provide a framework that allows the monitoring of changes in seismic signals and fault properties over time periods ranging from seconds to decades. In this way, they provide invaluable information that is critical to operational hazard forecasting. Furthermore, a template matching based monitoring system provides a platform that allows for rapid processing and analysis of temporary network data, automatically updating routine catalogs, if they exist for the study area, with improved solutions and backfilling them with events that were not previously detected. Systematic retro-active and real-time application of such techniques to Cascadia seismicity would likely lead to significant improvement in monitoring capabilities for both on- and off-shore events, especially when future temporary and/or permanent OBS arrays directly contribute to the PNSN.

The figures below aim at demonstrating the potential benefit of the approach outlined above. A prototype system for real-time, double-difference earthquake location and analysis as described above has been developed for the Northern California Seismic Network (NCSN) (Waldhauser, 2009), and has been operational at the USGS for several years now (http://ddrt.ldeo.columbia.edu). The DD-RT system includes seismicity near the Mendocino triple junction at the southern tip of the Cascadia subduction zone, where it computes reliable relocations even for events that occur several tens of kilometers off-shore (Fig. A, shown is a M2.7 event relocated with 7 land stations). Rollins and Stein (2010) used DD-RT aftershock relocations of the January 10, 2010 M_W6.5 earthquake in the Gorda plate to constrain fault orientation and rupture characteristics, an analysis that can potentially be carried out in near real-time for rapid hazard evaluation. Finally, Fig. C shows preliminary locations (orange circles) of earthquakes recorded by the Cascadia Initiative OBS array (white triangles) and NCSN land stations (Toomey et al., 2014). Much of the OBS data processing workload could be reduced by developing an integrated workflow that allows for automatic processing of the temporary data within the routine/DD-RT system, likely resulting in lower detection threshold and improved locations as well as association with previously active faults.



From: http://ddrt.ldeo.columbia.edu

From: Rollins & Stein, 2010

From: Toomey et al., 2014

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Transforming Offshore Fiber Optics into Dense Seismic Arrays

Nate J. Lindsey*[,1,2], Eileen R. Martin[3,4], Douglas S. Dreger[1], Barry Freifeld[2], Steve Cole[5], Stephanie R. James[6,7], Biondo L. Biondi[3,4], and Jonathan B. Ajo-Franklin[2]

**Corresponding Author: natelindsey@berkeley.edu*
[1]Earth and Planetary Science Department, University of California, Berkeley, CA, [2]Lawrence Berkeley National Laboratory, Berkeley, CA, [3]Institute for Computational and Mathematical Engineering, Stanford University, Stanford, CA, [4]Department of Geophysics, Stanford University, Stanford, CA, [5]OptaSense, Inc., Brea, CA, [6]Department of Geological Sciences, University of Florida, Gainesville, FL, [7]Sandia National Laboratory, Albuquerque, NM

INTRODUCTION

Dense broadband seismometer arrays have become a useful tool in modern earthquake seismology, however in an offshore setting this type of sensor poses many challenges, including deployment, risk of damage or loss, power supply, and data management. Distributed Acoustic Sensing (DAS) is a new seismic recording technique that configures a standard fiber optic cable as a dense seismic array. DAS uses a laser to illuminate a fiber optic from one end and then continuously records the Rayleigh backscattering from the fiber using an interferometer. The result is a long-range (<40km), dense (1 sensing point per meter) array of single-component, inline seismic sensors. Fiber optics are common in offshore telecommunications and buried beneath parts of the seafloor already. These fibers could potentially be leveraged as the sensor of a DAS component of an offshore early warning system. Given the novelty of DAS, there are many outstanding questions related to sensitivity, instrument response, recording geometry, and ground coupling in various settings. We have installed three fiber arrays onshore in Richmond, CA, Stanford, CA, and Fairbanks, AK to investigate these open questions.

FIBER EARTHQUAKE OBSERVATIONS

On-shore earthquake recording with DAS instruments (Silixa iDAS; OmniSense ODH-3) using directly buried and conduit-shielded fibers demonstrate that a single DAS channel records data with an overall lower signal-to-noise ratio when compared directly with co-located broadband sensors; however, body wave arrival times are clearly visible on single DAS channels even when the fiber is not optimally oriented in the seismic wavefield. Figure 1 shows the 29-Sep-2016 M3.6 Manly Hot Springs, AK earthquake as recorded in Fairbanks, AK approximately 130 km away using a fiber optic cable directly buried at 50 cm in soil, and the Silixa iDAS instrument. This seismic gather highlights how a 600 m long fiber optic cable records 600 individual seismic channels. P- and S-wave arrivals are registered above the background noise level in the bandpassed strain-rate data. The instrument response to the seismic event is spectrally broad, with amplitudes in the 0.1 - 1.0 Hz band changing by several orders of magnitude when the S-wave arrives.

COMPARISON WITH BROADBAND SENSORS

A triaxial Nanometrics Trillium Posthole Compact 120s broadband seismometer buried at 1m depth was used to provide co-located ground motion recordings at a position in the DAS array where two fiber trenches crossed orthogonally. Figure 2 compares two DAS channels with the equivalent horizontal components of the broadband instrument. Prior to the comparison, broadband instrument and digitizer responses were removed, and the horizontal broadband components were rotated into the axes of the fiber optic trenches. Particle velocity peak amplitude and phase estimates show a good match with ground motion, however there are differences. P-wave phases are not recorded with the same fidelity as S-wave and surface wave phases, most likely because of the inherent axial sensitivity of the DAS sensor and the vertical P-wave polarization with respect to the horizontal fiber. The DAS channel noise floor is visibly higher than the broadband sensor, and so DAS has a lower overall signal-to-noise ratio.

SUMMARY

The potential to leverage existing fiber optic telecommunications networks as large seismic array sensor networks represents a new opportunity for many areas of seismology. Field tests demonstrate the feasibility of DAS to record earthquake wavefields, and determine S-P phase arrival times. For offshore earthquake early warning, DAS offers an array-based observation with high sensor density (1/meter) and long range (<40km), which could be used to estimate earthquake location and magnitude characteristics over a broad region. Our findings suggest a potential to leverage existing telecommunications fiber capacity, already installed on the ocean floor, for seismic imaging or as an offshore earthquake early warning system.

ACKNOLWEDGEMENTS

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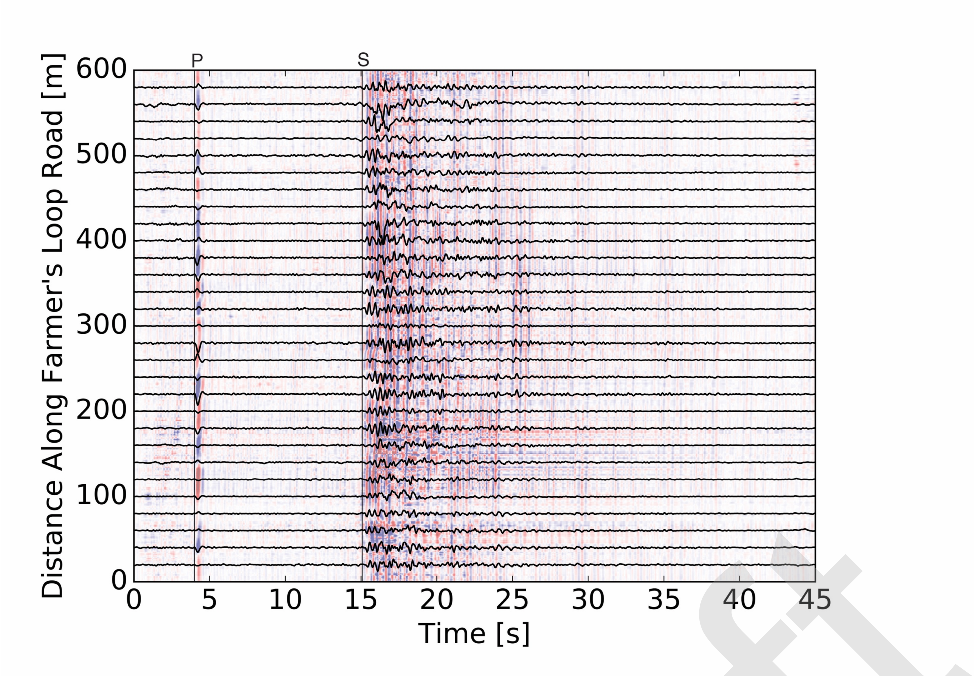

Figure 1. Earthquake observation (2016-09-23 M3.6 Manly Hot Springs event) from 132 km offset using using 600 m of the Fairbanks, AK linear fiber optic cable and a Distributed Acoustic Sensing (DAS) interrogator unit (Silixa iDAS). The fiber sensor was buried in a 0.5 m trench along Farmer's Loop Road. Amplitude-normalized traces show one seismic channel for every twenty channels recorded in the dataset. Background gather shows all 600 records without trace normalization. Data are bandpass filtered (0.01 - 2 Hz). The P- and S-wave arrivals show temporal move-out across the fiber array that is not visible at this scale. Differences in phase amplitude may indicate variability in near surface site response, or changes in soil coupling.

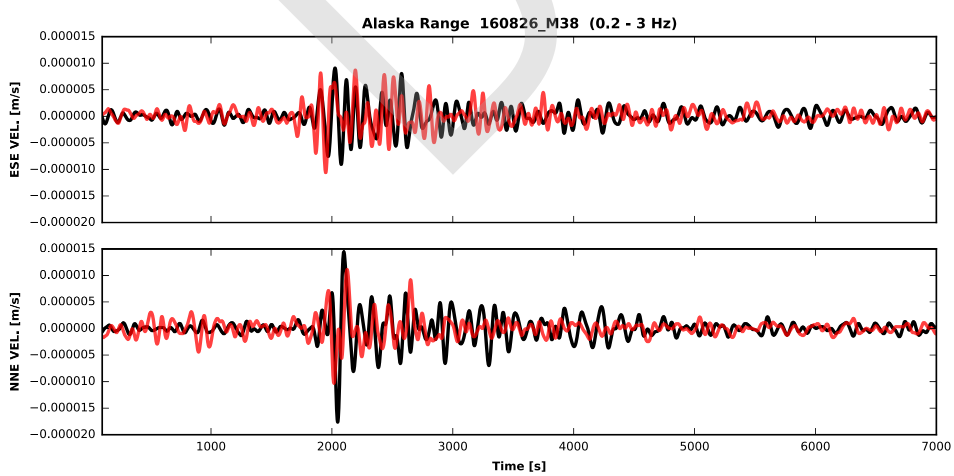

Figure 2. Example earthquake waveform comparison between collocated Silixa iDAS (red) and Trillium Posthole Compact 120s (black) showing the radial (Top) and (Bottom) transverse directions. Broadband horizontal components were rotated into the fiber array directions (NNE and ESE), following removal of the instrument and digitizer responses. One DAS channel is plotted in each of the directions. The earthquake was a M3.8 in Central Alaska over 100 km to the south. The bandpass filter was 0.2 – 3 Hz.

Real Time Local Tsunami Warnings: the case for an offshore network.

Paul Huang
Deputy Director,
NWS, National Tsunami Warning Center (NTWC)

Barry Hirshorn,
Lead Geophysicist,
NWS, Pacific Tsunami Warning Center (PTWC).

When a tsunamigenic earthquake occurs, the Tsunami Warning Centers (TWCs) must issue a warning within minutes, as this is the time frame during which the tsunami will first arrive at nearby coastlines. In these few minutes, scientists at the TWCs rapidly estimate the location and moment magnitude, Mw, of the earthquake and issue a warning with severity dependent on this Mw. For great earthquakes, however, initial seismic estimates of Mw are usually too low, which severely underestimates the danger of the impending tsunami in the near field.

The TWCs have employed various methods to speed up accurate estimation of Mw. NTWC has been using a statistically-derived empirical moment magnitude-distance correction look-up table, which has worked well in the past decade; estimates of Mw so derived for the 2010 Chile 8.8 and the 2011 Japan 9.0 earthquake were within 0.2 units of the final magnitude within 8 minutes of the origin time. PTWC also uses the W-phase method, in addition to Mwp, which results in an accurate moment magnitude and CMT in about 20-30 minutes, which is adequate for a distant earthquake and tsunami threat. For areas with sufficient sensor density in the 5 to 8 degree epicentral distance range, the W-phase can provide accurate moment magnitudes and CMTs within 5 minutes. As good as these are, for local events, we need faster methods to accurately determine earthquake source parameters and tsunamigenic potential.

The next step in improving tsunami warning involves combining seismic and coastal GPS networks and has been underway at the TWCs for over a year. This prototype of Global Navigation Satellite System – Tsunami Early Warning (GNSS-TEW) system, involving a partnership between NTWC, PTWC, JPL, UCSD, and Central Washington University and focusing on the Cascadia region. The basis is to use GPS and seismogeodetic data to determine an accurate earthquake magnitude, three-dimemensional co-seismic crustal deformation, and fault slip parameters within a few minutes after earthquake initiation (Obana et al., 2000; Ikuta et al., 2008; and Hoechner et al., 2013). The earthquake-induced sea floor deformation can then be used as an initial condition in a tsunami propagation and coastal inundation model for coastal warnings.

We can close the gap further— determine more robust source parameters in even less time—by complementing our coastal GPS and seismic stations with offshore acoustical GPS, accelerometer, broad band seismic sensors, and ocean-bottom pressure sensors on the sea floor. Connected by a submarine cable and transmitting in real time, these sensors will form a sea floor observatory (SFO) which will better constrain measurements of co-seismic ocean floor deformation. In order for this submarine observatory to contribute to the GNSS-TEW system, there are several requirements. It must have a reliable backbone cable system, replaceable sensors, extendible interfaces, and it must provide real-time transmission to the TWCs from all sensors (GPS, accelerometers, broadband seismic, and pressure).

It is imperative that this combined seismic, GPS, and sea floor observatory tsunami early warning system be able to continually operate during the conditions likely following a large or great earthquake—a major power outage, strong shaking, and wide-spread earthquake damage. Lastly, the system should be a turn-key system, including hardware (receivers, computers, and storage systems), software (data analysis, algorithms, and alerting parameters), and messaging and communication system (satellites, radio, cell, and web pages).