Marine active-source seismic data: an essential ingredient of the SZO

Donna Shillington¹, Suzanne Carbotte¹, Adrien Arnulf², James Austin², Nathan Bangs², Daniel Bassett³, Anne Bécel¹, Andrew Calvert⁴, Pablo Canales⁵, Helene Carton⁵, Gail Christeson⁶, Will Fortin⁷, James Gaherty⁷, Shuoshuo Han⁸, Timothy Henstock⁹, Steve Holbrook⁹, Emilie Hooft⁹, Shuichi Kodaira¹⁰, Heidrun Kopp¹¹, Art Lerner-Lam¹, Daniel Lizarralde⁵, Maria Beatrice Magnani¹², Kirk McIntosh¹², Lisa McNeill¹⁰, Nathan Miller¹³, Timothy Minshull¹¹, Greg Mountain¹⁴, Mladen Nedimovic¹⁵, Robert Reece¹⁶, David Scholl¹³, Satish Singh¹, Anne Trehu¹⁷, Harold Tobin¹⁸, Maya Tolstoy¹, Doug Toomey⁹, Harm Van Avendonk², Anthony Watts¹⁹, Spahr Webb¹, Doug Wiens²⁰, Lindsay Worthington²¹

¹Lamont-Doherty Earth Observatory of Columbia University, ²University of Texas, Institute for Geophysics, ³Scripps Institute for Oceanography, ⁴Simon Fraser University, ⁵Woods Hole Oceanographic Institution, ⁶IPGP, ⁷National Oceanography Center, Southampton, ⁸University of Wyoming, ⁹University of Oregon, ¹⁰Heidrun Kopp, ¹¹JAMSTEC, ¹²Southern Methodist University, ¹³US Geological Survey, ¹⁴Rutgers University, ¹⁵Dalhousie University, ¹⁶Texas A&M, ¹⁷Oregon State, ¹⁸University of Wisconsin, ¹⁹Oxford University, ²⁰Washington University, ²¹University of New Mexico

Understanding fundamental deformational, seismogenic, sedimentary and magmatic processes in subduction zones requires high-resolution imaging of sedimentary, crustal and upper mantle structure. Because large parts of the subduction system are submerg ed, marine seismic reflection and wide-angle reflection/refraction data are the best and most cost-effective means to constrain these processes. No other geophysical method is capable of detailed imaging of sediment layering, faults within the forearc and subducting plate, and the subduction thrust interface, or of producing high-resolution velocity that can be calibrated with drilling data to obtain quantitative constraints on fault zone properties, stress conditions and fluid flow. As described below, marine seismic data have already provided transformative insights into subduction zone structure and properties, but the promise of modern capabilities is great; recent advances in seismic methodology and in the acquisition capabilities of the R/V Marcus G. Langseth, the most advanced academic seismic research vessel in the world, are enhancing the depth of penetration and resolution of velocities in both shallow and deep in subduction zones and elsewhere.

Marine active-source seismic data are essential for understanding nearly every aspect of subduction zone processes:

Deformation and hydration of the incoming plate. The incoming plate delivers water into the subduction zone in the pores of and in hydrous minerals in marine sediments, the crust and upper mantle. Deep-penetratin g seismic reflection data provided the first direct evidence that bending faults along the outer trench slope cut the entire crust, providing potential pathways for water into the deep crust and upper mantle ¹. More recent seismic reflection and reflection/refraction studies have elucidated significant variability within and between subduction zones in the style and amount of bending-induced faulting and hydration²⁻⁹ (e.g., Fig. 1) and the depth of hydration ⁹,¹⁰ with major implications for controls on hydration, the amount of water delivered into the subduction zone and a host of processes at depth.

Figure 1. Results from joint seismic refraction and reflection study at Cascadia ⁶,⁷ showing (A) reduced crustal velocities nearing the deformation front attributed to increased hydration of the Juan de Fuca plate associated with subduction bend faulting. Reflection data show fault-plane reflections extending through the crust and 6–10 km into the shallow mantle (B).

Thickness, pore-fluid pressure and lateral variability of sediments along plate boundary. The properties of sediments along the shallow part of the plate boundary exert an important control on shallow slip behavior. While drilling data provide essential ground truth information on in situ stress conditions and sediment properties, they necessarily only sample discrete locations. 2D and 3D seismic reflection data have been instrumental in quantifying the extent of overpressured sediments from disequilibrium compaction and dehydration reactions, controls on overpressure and fluid flow by temperature changes, faults in the overriding plate and other factors, and the relationship of overpressures to shallow slip behavior ¹¹⁻¹⁵ (Fig. 2).

Subduction of seamounts and other structures. The subduction of seamounts and other irregularities on the plate boundary may further influence fluid distributions and overpressures, localize shallow slow slip and modify seismicity. While such features can sometimes be inferred from gravity, magnetic or bathymetry data, seismic reflection imaging provides the definitive constraints on the geometry of such features and their relationship to slip behavior ¹⁶⁻²¹.
Splay faults and other structures in the overriding plate. Coseismic slip on faults in the overriding plate, such as out-of-sequence thrusts, can enhance tsunamigenesis. Faults in the overriding plate are also key to the hydrogeology of forearcs, controlling fluid flow and modulating overpressure on the megathrust. Seismic reflection and high-resolution wide-angle data have been instrumental in imaging these structures in the overriding plate, their relationship to the megathrust, the relative timing of activity of different faults, and their connection to fluid flow at the seafloor \(^{14,22-31}\).

Figure 2. 3D seismic data acquired with the Langseth off Costa Rica showing down-dip variations in reflectivity of the plate boundary (left) that correlate with changes in seismicity (right) and are interpreted as related to changes in fluid content \(^{14}\).

Downdip and along-strike variations in plate boundary properties and slab geometry. Recent studies increasingly reveal downdip and along-strike changes in plate boundary deformation, including changes in geodetic locking, seismicity, radiated seismic energy during great earthquakes, and transitions from great earthquake rupture to tremor and slow slip, among others. Deep-penetration seismic reflection data are beginning to elucidate the changes in plate boundary properties that accompany such along-strike and downdip changes in behavior \(^{32-34}\). The unique contribution of seismic reflection data to this problem is its ability to resolve structures with scale lengths of hundreds of meters at 20–50 km depth. These seismic data can therefore provide direct evidence for contrasts in material properties or fluid pressure at the subduction interface, which is critically important for understanding slip behavior. Active source seismic data can also provide more detailed information on plate boundary geometry than seismicity or passive seismic imaging, and velocity models derived from wide-angle seismic data can also significantly improve earthquake relocations \(^{35,36}\).

Figure 3. Seismic reflection data acquired off the Alaska Peninsula with the Langseth clearly image the plate boundary to depths of ~50–60 km, and reveal substantial down-dip variations in the width of the plate boundary. A thin (~180 m) plate boundary is observed in the seismically silent patch that was at the center of past great earthquake ruptures, and a wide (~3–5 km) zone is observed in the region with significant seismicity transition to tremor \(^{34}\).

Composition, thickness and internal structure of arc crust. Arcs represent sites of substantial ongoing addition to Earth’s crust, yet many questions remain about the bulk composition of arcs, controls on magma evolution through the crust with consequences for subduction initiation, the stability of arc lower crust, and how magmatic addition at depth relates to the plumbing of major volcanic centers. Seismic refraction data have provided key constraints on arc crustal thickness, velocity structure and bulk composition \(^{37-46}\). Dense seismic refraction data, including via amphibious experiments, have the power to resolve variations in crustal structure at the volcano scale \(^{39,40,47}\) and to image the plumbing beneath active arc volcanoes, and thus address many of these questions.
Our understanding of subduction zones would be vastly impoverished without the unique constraints provided by marine active source seismic data. Such data will be even more critical in the future to advance knowledge of subduction zone hazards and processes.

The US academic community is poised to take seismic imaging of subduction zones to the next level, which offers many exciting opportunities for the SZO. The *Langseth's new* streamer can be towed as a four-array system for 3D imaging and as a single 15-km-long streamer for deep-penetration 2D acquisition – an entirely new capability that opens up exciting new avenues of research. Together with the excellent, large (6600 cu in) tuned air gun array of the *Langseth*, these enhancements enable deeper and better imaging and capacity for unprecedented velocity resolution in subducting sediments from streamer tomography and full waveform inversion providing new opportunities for studies of subduction behavior and associated natural hazards risks. Likewise, Langseth’s high-quality tuned air gun source recorded on dense lines and grids of ocean-bottom seismometers can be used for both 2D and 3D travel time and full waveform inversion to constrain overall subduction zone architecture as well as patterns of hydration and magmatic plumbing beneath arc volcanoes in great detail. The *Langseth* is the only academic vessel with capabilities comparable to industry seismic vessels. Integration of active-source seismic data with passive-source seismic imaging, detailed seismicity studies and controlled-source electromagnetic data provide exciting new frontier research opportunities.

Beyond yielding critical new insights on subduction zone processes, marine active-source seismic data provide essential foundational information for a broad spectrum of other studies, including identifying ocean drilling sites and extrapolating drilling results, resolving fluid flow in the forearc, elucidating seismicity patterns and seafloor deformation during and between great earthquakes, constraining slab geometry, understanding the evolution of arc magmas and stability of arc crust, and, very importantly for coastal global populations along subduction zones, in assessing earthquake hazards and tsunamogenic risk.

The existing coverage of subduction zones by seismic reflection/refraction data is sparse, particularly with the modern, long streamer data capable of providing images to great depth and detailed constraints on megathrust and forearc properties. In order to advance our understanding of fundamental processes in subduction zones and implications for seismic hazards, which are central goals of the SZO, seismic reflection/refraction data needs to be a critical component. However, the US marine seismic facilities are at risk. NSF has committed to continue operating the *Langseth*, the primary US marine seismic facility, only through early 2018 ([https://www.unols.org/news/mlsoc-updates/important-update-nsf-regarding-marine-seismic-planning](https://www.unols.org/news/mlsoc-updates/important-update-nsf-regarding-marine-seismic-planning)). The capabilities provided by *Langseth* cannot be replicated with other UNOLS vessels, no comparable seismic facilities exist globally in the academic community and commercial sector options are not feasible for an academic research program ([http://www.nsf.gov/geo/oce/pubs/Seismic_Workshop%20Report_final_2016.pdf](http://www.nsf.gov/geo/oce/pubs/Seismic_Workshop%20Report_final_2016.pdf)). We urge the interdisciplinary subduction zone community to consider the impact that losing this capability would have on our science, and to communicate to NSF the critical importance of continued access to a modern long-offset capable marine seismic platform.