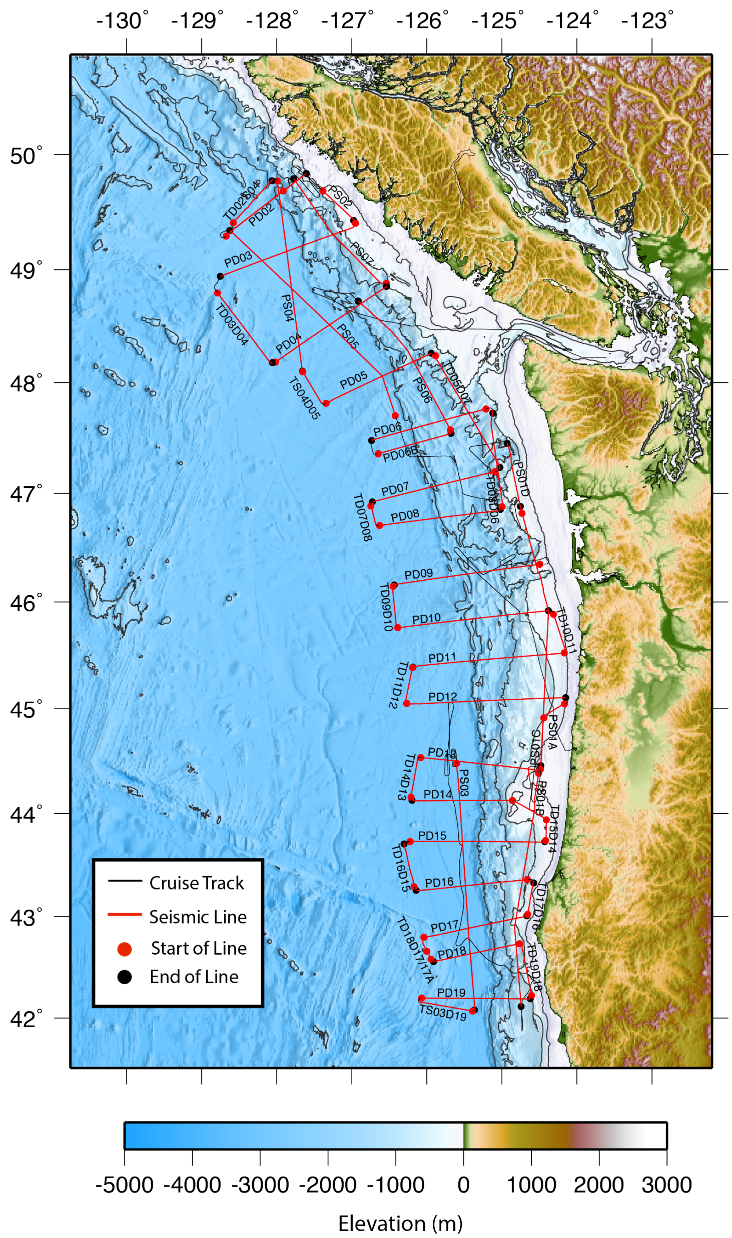
Cascadia Seismic Imaging Experiment - CASIE 21
R/V Marcus G Langseth MGL2104

June 1 - July 11 2021

Newport OR to Seattle WA



Chief Scientist: Suzanne Carbotte (LDEO of Columbia U)

Co-Chief Scientists: Shuoshuo Han (University of Texas Institute of Geophysics) and Brian Boston (LDEO of Columbia U)

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1. Scientific Objectives

Cascadia is notable among global subduction zones in the exceedingly low levels of instrumentally recorded seismicity from the plate interface for much of the margin [e.g. *McCrory et al., 2012; Obana et al., 2015*]. Given the paucity of historical seismicity little is known of the properties of the megathrust within the seismogenic zone and the transitions in slip behavior that bound this zone. The location and width of the locked/seismogenic zone is inferred at Cascadia primarily from thermal modeling, sparse seismic observations, and coupling estimates based on onshore geodetic data, with significant differences in estimated widths obtained from different approaches [*Wang and Tréhu, 2016* and references therein]. There are indications of along-margin variations in present-day coupling across the plate interface derived from the geodetic models [*Schmalzle et al., 2014,* Fig. 1] but these models are subject to large uncertainties for the offshore region where nearly all of the locked zone resides. Along-margin variations in slip during past earthquakes at Cascadia is inferred from records of coastal subsidence during the 1700 AD earthquake [*Wang et al., 2013*], from offshore turbidite records and coastal tsunami deposits [*Goldfinger et al., 2012*], and from forearc basins beneath the continental shelf inferred to be long-term asperities along the margin [*Wells et al., 2003*]. Whether the inferred paleo-rupture segmentation reflects the presence of persistent rupture barriers or dynamic rupture processes is not well understood. Along-strike variations in current coupling inferred from geodetic models [e.g. *Schmalzle et al., 2014]* and the limited present-day seismic activity [*Tréhu et al., 2015, 2018; Stone et al., 2018*] are generally correlated with the paleoseismic evidence for along-strike variability suggesting some geologic control. Understanding whether the record of paleorupture segmentation at Cascadia reflects the presence of persistent rupture barriers and the relationships to structural variations or heterogeneities in fault frictional properties along the megathrust is key for development of earthquake hazard scenarios. However, the current observations allow for a wide range of possible future earthquake scenarios, leading to large uncertainty in the anticipated ground motion and tsunami height along the heavily populated Pacific Northwest [e.g. *Walton et al., 2021; Wang and Tréhu, 2016; Priest et al., 2010*].

Modern long-offset multi-channel seismic (MCS) techniques provide the best tools available for subduction zone imaging at the depths of the seismogenic zone and provide constraints on geologic structure and material properties at the subduction fault that contribute to frictional state and slip behavior. The overarching goal of our study is to use long-offset MCS data to characterize the structure and properties of the megathrust, subducting plate, and accretionary wedge along the Cascadia Subduction Zone (CSZ). This regional characterization will be used to determine whether there are any systematic relationships among upper and lower plate properties, paleorupture segmentation, and along-margin variations in present-day coupling. The data will also be used to characterize down-dip variations along the megathrust that may be linked to transitions in fault properties, from the updip region near the deformation front (DF), which is of most interest for tsunamigenesis, to near shore where the downdip transition in the locked zone may reside.

The proposed survey was designed to make use of *Langseth*'s 15-km long streamer cable and 6600 cu in volume 36 airgun array to acquire a suite of dip and strike lines spanning the margin in order to characterize 1) the deformation and topography of the incoming plate, 2) the depth, topography and reflectivity of the megathrust, 3) sediment properties and amount of sediment subduction, 4) the structure and evolution of the accretionary wedge, including geometry and reflectivity of fault networks, and how these properties vary along strike along the margin and down dip across what may be the full width of the seismogenic zone at Cascadia.

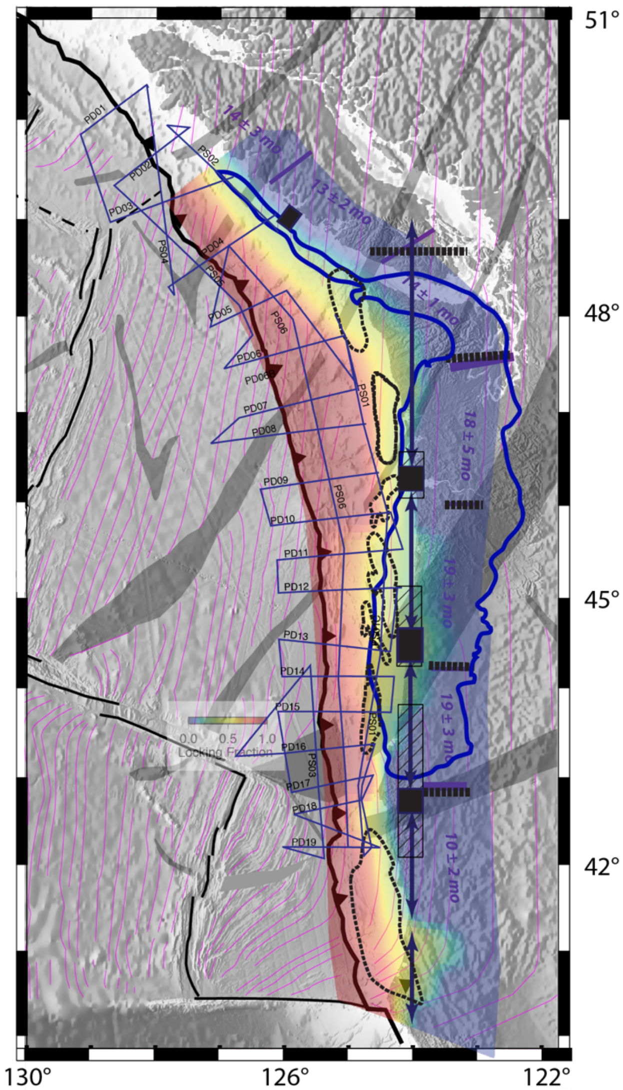

Figure 1. Regional map of JdF plate and Cascada subduction zone (SZ) including observations of SZ segmentation and showing the final permitted tracks for new experiment. JdF/Gorda/Explorer plate magnetic isochrons (purple) and propagator pseudofault zones (grey bands) interpreted from offset magnetic anomalies fare rom Wilson [*1993, 2002*]. JdF plate boundary and deformation front of Cascadia SZ are shown in thin and thick barbed thick black line respectively. Black dashed lines delineate forearc basins identified by Wells et al. [*2003*]. Thick black dashed lines show boundaries of ETS segments from Brudzinski and Allan [*2007*]. Outline of the Siletz terrane is shown in blue [*McCrory and Wilson, 2013*]. Also shown is one of the plate locking fraction models of Schmalzle et al [*2014*] (their ”gamma” model). Blue numbered lines show the cruise tracks permitted for the survey.

2. Survey Plan

The survey plan included 19 2-D dip profiles located at 50-75 km spacing, oriented perpendicular to the margin and located to provide an approximately uniform line spacing for a regional scale characterization (Fig. 1). Lines were modified from a strictly uniform separation in order to ensure sampling of the primary segmentation evident in different subduction zone characteristics at Cascadia. These include co-seismic rupture patches and their boundaries from the 1700 AD earthquake as inferred from coastal subsidence proxies of Wang et al., [*2013*]; locking status of the megathrust at present inferred from onshore geodetic data [*Schmalzle et al., 2014*]; paleorupture segmentation inferred from the offshore turbidite record (e.g. *Goldfinger et al., 2003; 2017*); the structure of the accretionary wedge including the vergence direction of thrust faults within the actively deforming and older portions of the wedge[(e.g. *Watt and Brothers, 2020*] and of landslides along the margin [*Goldfinger et al., 2000*]; and in the distribution and periodicity of episodic tremor and slip (ETS) further onshore [e.g. *Brudinzski and Allen, 2007*]. The location of the propagator wake shear zones in the incoming Juan de Fuca plate [*Wilson, 1993; 2012*] and of known buried seamounts [*Han et al., 2018; Webb, 2017*] were also considerations. The margin normal lines were planned to extend approximately 50 km seaward of the deformation front to image the region of subduction bend faulting in the incoming oceanic plate as inferred from the Juan de Fuca Ridge to Trench (R2T) study [*Han et al., 2016*], and landward of the deformation front to as close to the shoreline as can be safely maneuvered**.**

In addition to the primary rationale of ensuring near-regular characterization along the margin and sampling the primary segmentation evident in subduction parameters, most lines had additional targets to facilitate linking with and building upon existing MCS studies at Cascadia. Lines were located to fill key gaps in existing legacy crustal-scale MCS coverage, including regions of important transition in subduction zone properties from 43˚N to 44.3˚N, and from 45.2˚N to 46.5˚N. In regions with legacy coverage, lines were located to coincide with one profile from several of these surveys in order to facilitate the future incorporation of these older surveys into the regional framework provided by the new data and also to support 4D seismic studies post any future EQ rupture. These included one line of the 1980's era Canadian Geological Survey profiles offshore Vancouver Island [e.g. *Hyndman et al., 1993; 1994; Nedimovic et al., 2003; Calvert et al., 1990*], one line of the Orwell survey [*Fleuh et al., 1994; Booth-Rea et al., 2008; Adams et al., 2004*], the 2012 COAST study [*Peterson and Karenan, 2019; Webb, 2017*], and the1989 GT89 surveys [*MacKay et al., 1992, 1995*]. Lines were also located to complement recent high-resolution MCS studies including the UNOLS Chief Scientist training cruise RR1718 and the USGS Coral Sea survey of the southern Cascadia margin. An additional consideration was the location of existing DSDP/ODP/IODP drill holes and future planned holes with seismic lines located to coincide with existing sites where possible in order to provide deep structure context for the drilling data.

The survey plan also included several strike lines designed to facilitate extrapolation of structure between lines and to provide seismic ties with the dip lines. These included one 2-part strike line along the continental shelf to investigate possible segmentation near the down-dip limit of the seismogenic zone and 3 strike lines ~ 10 km from the deformation front designed to complement the MARGIN transect (Line 3) of the 2012 Juan de Fuca Ridge-to-Trench survey [*Canales et al., 2017; Han et al., 2018*]. A final strike line along the slope was planned as a contingency line**.**

2.1 Complementary studies

Four complementary programs were planned around the *Langseth* survey, including two seismic programs designed to record *Langseth*'s soundings. These included an ocean bottom seismometer (OBS) study funded by NSF and USGS with a total of 120 instruments deployed along 10 of the MCS dip lines led by Pablo Canales (WHOI) and Nathan Miller (USGS), and a land deployment of 760 seismometers and node stations extending from 42° to 46.3°N, 75-100 km from the coast led by Anne Trehu (OSU), Emilie Hooft (UO), Kevin Ward (SDSM) and Erin Worth (USGS) and funded by NSF and USGS. The OBS program was supported by two legs: *Langseth* MGL2103 during which 60 OBS were deployed along 6 dip lines in the southern part of the survey and *Oceanus* OC2106A during which 6 OBS were deployed along line D13, all OBS for the southern survey then recovered and 54 OBS deployed along 4 dip lines in the north. The OBS study was planned with a complementary deployment of ocean bottom nodes (OBN) along 3 of the survey lines but this aspect was abandoned after unsuccessful attempts to deploy the OBNs from *Oceanus* using a custom ROV in late May. In addition to these geophysical studies, two marine wildlife studies took advantage of the *Langseth* experiment: an NSF funded study of potential impacts of marine seismic operations on fish populations led by Sarah Henckel at OSU and a whale stress study led by Leigh Torres, also at OSU, with funding from ONR and DOE.

3. Cruise Summary

On June 1, 2021, the **Ca**scadia **S**eismic **I**maging **E**xperiment 20**21** (CASIE21)-MCS expedition MGL2104 aboard the R/V *Langseth* departed from Newport, Oregon after more than 2 years of extensive planning due to both the complicated permitting process for our study and the impacts of the COVID-19 pandemic. The cruise was initially scheduled for June 2020 but was postponed approximately one month prior when the challenges and risks of operating that first year of the pandemic became too great. The expedition departed Newport with all science personnel having completed quarantine and testing requirements prior to boarding. We set sail with special COVID-19 precautions in place for the cruise including social distancing measures with restricted numbers in the mess hall for mealtime for the first 2 weeks of the cruise and mask requirements.

The survey was shot in three sections (Fig. 2, Appendix 3), first the offshore Oregon portion starting from just north of the Columbia River to south of Cape Blanco (lines D09-D19, S01, S03), then the offshore Vancouver Island (VanIs) portion (lines D02-D05, S02, S04, S05, S07), and finally the offshore Washington region (D06-D08, S06). The Washington portion was planned to be last as this was the only region with significant existing modern MCS coverage (the 2012 COAST survey and MGL1211-Line 2). During the expedition we experienced 3 streamer "events" that each involved a lengthy recovery and redeployment period and which used close to twice the planned contingency time. Weather conditions were also non-optimal for a much larger number of days than we expected with 4 separate periods lasting 1-3 days each with 25-35 kt winds and rough seas (3-5m). This rough weather with unseasonably cool temperatures in the low 50's occurred during the same period as the onshore Pacific NW was experiencing record-breaking heat domes. In spite of the challenges faced during our expedition, we acquired a very good dataset with overall coverage achieved equivalent to 89% of the planned prime survey lines (excluding our contingency line)**.** Details on the pre-cruise planning, the survey setbacks and survey coverage achieved are included below.

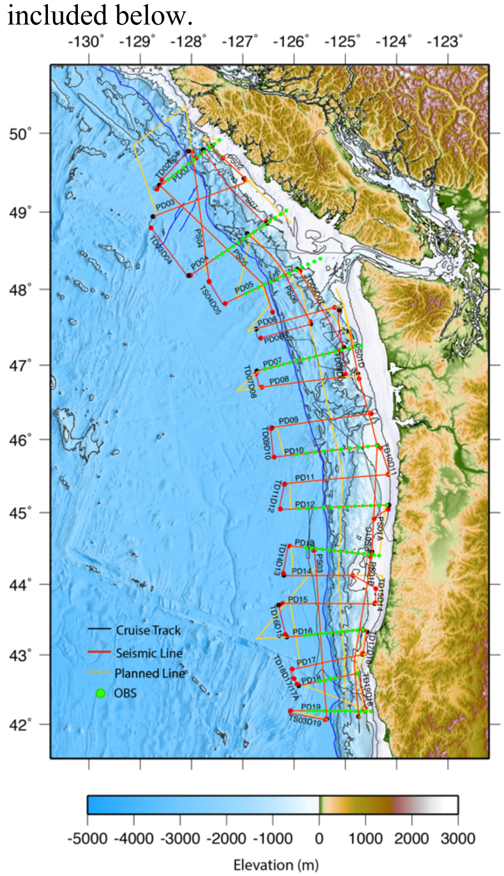

Figure 2. Final cruise track showing seismic lines in red with line start and end points indicated with red/black filled circles. The planned seismic lines (with modifications for permit requirements) are shown in orange. The locations of OBS deployed during MGL2103 and OC2106A along 10 of the seismic lines are also shown.

3.1 Pre-cruise planning and coordination

Our cruise was originally scheduled for summer 2020 and as permitting typically takes ~9 months, the survey design process occurred primarily in 2018-2019. The permit application and negotiation process involved multiple agencies, both US and Canadian. Originally planned seismic lines were modified to meet permit requirements focused on marine protected species mitigation measures while underway. In addition to typical requirements for continuous monitoring by a team of Protected Species Observers (PSO) onboard *Langseth*, final permit requirements included limits on operations in water depths <100 m in some areas and day-light only operations with a look-ahead vessel and additional PSO's while operating in the Olympic Coast Marine Natural Sanctuary (OCNMS) offshore WA state and while in water depths < 200 m in Canadian waters offshore Van Is. Portions of proposed lines crossing the Canadian Critical Habitat region for the Southern Resident Killer Whale and turn lines on the shelf in the OCNMS were removed from the planned lines. The R/V *Rachel Carson* operated by University of Washington was enlisted to serve as the look-ahead vessel for this portion of the survey and three additional PSOs were scheduled for the *Rachel Carson*.

The planning process also included consultation with tribal groups with offshore fishing grounds in the WA shelf survey region (the Hoh, Makah, Quileute and Quinalt), discussions and dissemination of information to local fishing groups through the Oregon Fisherman's Association and coordination with the OOI operators of infrastructure at Hydrate Ridge and the Oregon and Washington Endurance Arrays. The planning process for the complementary Canales/Miller OBS/OBN program and the land seismometer study of Trehu/Hooft/Ward/Worth was closely integrated with the *Langseth* study and involved coordination of survey lines, of permitting, and of scheduling. A communication plan for the cruise was developed to notify all these groups and agencies of our survey status on a daily basis while underway.

3.2 Operational Challenges

Streamer Events

During the expedition we experienced three major streamer events that resulted in lengthy recovery and redeployment times and that threatened to seriously impact the overall study. Two of these events occurred within the first ~11 days of the cruise. All planned contingency time (10%) was used by day 12 and by day 15, with 38% of the cruise time used, we had acquired only 21% of planned coverage.

Streamer event 1: occurred on June 8 while acquiring shelf line segment S01A crossing Heceta Bank. In late morning, we encountered tension spikes on the streamer of >10,000 lbs that stayed high and 6 birds mid cable registered at sea surface depths and were unresponsive to signals to dive to target depth of 12 m. On recovery of the streamer, we found fishing gear, including buoys and fishing line from crab pots, tangled along much of the streamer and birds mid-section with their SRDs deployed. Redeployment of the streamer was slow and involved difficult to troubleshoot power leakage and birdline communication problems with resumption of acquisition on June 10 after a total of 35.5 hours.

Streamer event 2: occurred on June 11 when the streamer broke entirely away from the ship after a tension spike to 10,050 lbs while we were nearing the southern end of shelf strike line S01B and in worsening weather conditions. After bringing in the gun arrays and other equipment, we were able to locate the tail buoy once we were back within range of the tail buoy AIS, which had been installed for our survey for the first time. Recovery of the streamer was from the tail section forward and required spooling it backward in 6 and 3 km sections onto reel 2 and then respooling from reel 2 to reel 3 and 4 to reorient properly. During recovery, 15 of the streamer birds were found missing their SRDs, 14 SRDs were recovered that had gone off, but only 1 with its SRD bag still attached. One bird was missing entirely and 2 were recovered with a broken wing-to-motor pin. No fishing gear was found at any location along the streamer but the last bird recovered (nearest the streamer break point) was found with its wings bent back toward the streamer suggestive of snagging an obstruction. After recovery, we decided to redeploy 12 km of streamer rather than the full 15 km due to lack of sufficient replacement SRDs and also to facilitate faster tow speeds to help mitigate the impacts on our survey of the lost time to these dramatic streamer events. Streamer redeployment was from reels 3 and 4 and was slow with extensive trouble shooting during deployment, then recovery and redeployment of almost 10 km of the streamer. In the end, the front sections 2, 3 and 4 of the streamer were swapped out and replaced, along with 2 LAUM units, the stretch section and front end. Equipment deployment was completed and acquisition resumed on June 15, close to 4 days after the streamer separated from the ship.

Although no fishing gear was found entangled on the streamer during recovery, the tension spike before the streamer parted indicates it must have snagged something. The first streamer bird next to the break point was recovered with its wings bent backward, suggestive of hitting an obstacle but the bird damage could also have occurred during the rough weather while the streamer was flapping around at sea surface before it was fully recovered. We suspect that the high strain the front sections of the streamer experienced during streamer event 1 pre-weakened this portion and contributed to the streamer break, along with hitting an obstacle as indicated by the tension spike at the end of line S01b. We note that the AIS in the tail buoy was critical to finding the streamer quickly. Overall, the recovery went more smoothly than initially feared as the streamer could have become entangled on itself while it drifted.

Streamer event 3: The third streamer event began on June 25 when we experienced power leakages and then power failure on the streamer cable. 9.5 km of cable were recovered and two birds were found with entangled crab pot lines. Redeployment was slow and frustrating as telemetry line problems and power leakages persisted and appeared to migrate to different locations along the streamer. Troubleshooting required breaking off every 3-4 sections to test on deck power and in the end a total of 5 sections were swapped out from the backward spooled streamer on reel 2. All gear was redeployed and we resumed acquisition on June 27 after a total down time of 33.5 hours.

Summary: All streamer deployments including the initial one took longer than expected and than was typical in our collective experience. The unusually lengthy process during the initial deployment involved additional effort to retension the cable on streamer reel 4. All later recoveries and deployments involved hard-to-diagnose problems that appeared to migrate to different locations along the streamer as deployment progressed with trouble shooting involving frequent breaking at section terminations to test on deck power and in some cases replacing sections that had previously tested fine. These electrical problems were likely linked to the high tension the streamer experienced with the snagged fishing gear, the rough weather and unknown depths to which the streamer was subjected during the streamer parting event. The lack of use of the streamer for the prior roughly 9 months may have also contributed to the problems experienced. The issues with power and communication appeared to be resolved with the last streamer deployment and we enjoyed almost 2 weeks of uninterrupted acquisition at the end of the cruise.

Weather related challenges, marine traffic, deployed buoys and fishing gear

Other operational challenges during the expedition included 4 periods of rough weather conditions that impacted acquisition with high swell noise observed on the streamer and periods where we increased streamer depth to 13 m accordingly, gun tangling during turns, frequent airleak and misfire problems and the inability to recover gun arrays quickly for needed repairs which led to significant acquisition without the full desired source volume. The rough weather periods with winds exceeding 30 kts and seas ~3 m and higher were from ~June 7-8, June 11, June 18-21 and June 30-July 3. All rough weather days were acquisition days and total ~38% of production acquisition time. Reshooting lines for weather was not possible due to time lost to the 3 streamer recovery/redeployment events.

During operations in the near shore region, abundant fishing and shipping traffic was encountered with the bridge handling frequent communications to notify mariners of our 15/12 km towed gear and requesting diversion and avoidance. There were a couple occasions where we needed to increase speed (resulting in lost shots and previous shot noise) to deal with ship traffic or lower the streamer for possible streamer crossings. Deployed fishing gear was also spotted in numerous locations and some track adjustments were needed including truncation of PD14 in order to avoid fishing gear observed during the southward transit across Heceta Bank on lines PS01A/PS01B. The fishing line entanglement on line PS01 appeared to involve crab pot lines in deeper water than we anticipated and as a result we truncated subsequent dip lines in this region as risk of additional entanglement was deemed to be high. We also needed to make a minor course adjustment on June 24 during acquisition of PS01C to avoid a NOAA buoy with an actual position somewhat west of the published position that informed our planning.

Summary coverage achieved

By cruise end, the majority of the survey goals for the CASIE21 expedition were met with a total of 5347 line km of 12-15 km offset MCS data acquired spanning the subduction zone from the north Gorda plate to the northern triple junction region near Nootka fault zone. Total acquisition time was 27.6 days (Table 1: acquisition + line change) which corresponds to 70% of total cruise duration for the 40 days of actual at-sea time. All planned dip lines were acquired except for Line D01 (crossing the Winona block offshore VanIs). The seaward extent of three dip lines near the end of the cruise were shortened by 10-15 km (D06, D07, D08) in order to leave time to acquire part of the slope strike line (S06) to crossing dip line D04. The landward edge of 3 dip lines on the Oregon margin were limited to avoid hazardous areas where abundant fishing buoys were encountered (D13, D14, D15). The landward edges of 3 dip lines on the Washington margin (D06, D07, D08) were also truncated due insufficient remaining time to accommodate the lengthy maneuvering time needed to come on line during daylight hours given our operational restrictions of no airgun operations in the OCNMS without our look ahead vessel. Six primary strike lines were planned, 4 were completed or majority acquired (S03, S05, OR-WA shelf line S01- 90% complete; Canadian oblique margin line S04- 77% complete), and 2 were partially completed (VanIs shelf line S02 - 26% complete; slope strike line S06 (22% complete). Alternate line segments on the slope were acquired parallel to the missing portions of the S01 and S02 shelf lines (TD06D08 and S07). Acquisition time lost due to marine mammal mitigation was very modest, only 28 hours with a total of 15 shut downs (Table 1) A large 4-hour gap due to marine mammal mitigation occurred along line D02 which was also a line with deployed OBS and this line was reshot as a result. Excluding/including slope line S06, which was a (high priority) contingency line, we acquired 89%/80% of prime line coverage planned. A summary of cruise operations by day is included in Appendix 5.

Table 1. Summary of Cruise Operations

Activity**	**Time in days (hours)**
Transit from Newport departing 18:50 June 1	0.49 (11:40)
Initial Deployment	1.58 (39)
Acquisition time (Prime and reshoot)	26.54 (637)
Line Changes	1.1 (26)
Shut downs for marine mammals	1.17 (28)
Equipment down time	7.1 (170)
Final Recovery	0.95 (21)
Transit to Seattle arriving 18:22 July 11	1.13 (27)

**Note: total port-to-port cruise duration was ~40 days but spanning 41 calendar days.

The modest shortfall in final coverage achieved in light of the large amount of lost time due to equipment issues early in the cruise required frequent modifications to survey shooting plans in order to optimize remaining time. Over the cruise duration, Alan Thompson generated 17 new shooting plans with time estimates to help in ongoing survey adjustments and we ended the cruise on plan "Q". One important factor contributing to the time gains was the change in operations to a 12 km streamer, necessitated by the streamer parting event. The shorter lengths allowed us to tow at faster average speeds of ~ 4.5 kts compared with 4.0 kts for the 15 km streamer. This loss of 3 km of source-receiver offsets diminishes the depth below sea floor for which we will be able to extract velocity information using the streamer by ~0.5-1 km. However, the availability of OBS for 10 of the 18 dip lines shot will help offset this loss by providing even larger offset ranges for these lines. There were also some planned inefficiencies in our original shooting plan that were designed to give the *Oceanus* adequate time to deploy OBS's for the VanIs and WA lines. With our equipment related delays, *Oceanus* had sufficient time for these deployments and we were able to revise line acquisition to be more efficient. Our daylight-only operation days were also limited to fewer than originally planned due to streamer event 3 and the rough weather that caused the early departure of the *Rachel Carson* on July 1.

With these changes we were able to acquire an excellent data set with coverage that meets the majority of the project science targets. The 12-15 km long MCS data acquired will support the application of advanced techniques for noise and multiple suppression, and we expect to derive excellent velocity information from the MCS data to ~5 km or more beneath seafloor for all of our lines. These high resolution, high-accuracy velocity models will contribute to improved imaging via pre-stack depth migration, and will support physical property studies of the incoming and accretionary wedge sediment sections and the megathrust. Throughout the cruise, all of the ship installed science sensor systems were fully operational, and we acquired multibeam echo-sounding bathymetry, backscatter and side-scan data, water-column, sub-bottom, gravity, ADCP and TSG continuously along with the MCS data. Magnetics data were acquired during streamer operations except for 2 rough weather periods; 1 when the magnetometer became tangled with the gun array in the southern part of the survey and 2. when it was pre-emptively recovered due to poor weather (Appendix 10).

The success of the cruise overall was due to the excellent support provided by all involved in the expedition; Captain Breck Crum and his officers and crew who ensured smooth and safe operations of *Langseth* throughout, the expert team of PSO's led by Amanda Dubuque who managed the protected species mitigation program, the enthusiastic science party of early career scientists and graduate students, and the science support team led by Shaun Shaver. Shaun and his team of seismic professionals including Alan Thompson, Cody Bahlau and Tom Spoto were highly experienced and knowledgeable and did an outstanding job managing the seismic acquisition. Gilles Guerin and Alan Thompson also provided excellent support for the serial data acquisition, and the comprehensive suite of QC tools and acquisition summaries that have been developed by *Langseth* staff are noteworthy. This aspect of the science support was at a higher level than during prior expeditions on *Langseth* and exceeds what the Chief Scientists have experienced on other UNOLS ships. The seismic equipment was in excellent shape overall with adequate spares on hand to cover most of the lost SRDs and birds in order to facilitate redeploying a 12 km streamer and to replace the streamer sections and LAUM units likely damaged during the fishing gear and streamer parting events of the cruise.

The experiment also required a high level of coordination on the part of many to ensure the success of the complementary OBS and land programs as well as the use of the *Rachel Carson* to support the near shore permit requirements for our study. The lost acquisition time in the early part of our cruise complicated this coordination but with the ability to frequent pivot and modify the survey acquisition order, we were able to near fully support these studies. We completed the southern survey offshore Oregon just in time for Trehu, Hooft and colleagues to begin recovery of their land seismometer array by their deadline of June 26 (determined by instrument battery life), with the streamer power failure event on June 25 happening just as we passed the northern limit of the land array. With the cancellation of the OBN deployment, we revised acquisition plans in order to leave time for the deployment of OBS from *Oceanus* to fill the node gap on line D13. The additional days NSF provided for *Oceanus* allowed for an earlier departure and Chief

Scientist Nathan Miller was able to recover and deploy all planned OBS as well as the fill-in OBS's for the line D13 OBN gap prior to our arrival to shoot these lines. The LDEO Office of Marine Operations led by Sean Higgins was instrumental in facilitating this coordination and the enormous effort of pre-cruise planning and onshore support provided by Sean and his team was essential for the success of the project. Finally, this project required extensive effort from many at NSF-OCE to manage the multi-project coordination, the challenges of figuring out how to safely operate during the COVID-19 pandemic and the permit application process, and we gratefully acknowledge NSF's operational and funding support throughout.

4. Data Acquisition and Processing

4.1 MCS Data

Seismic acquisition parameters for each of the seismic lines with start and stop shot numbers, positions and times are included in Appendix 4 (B15 MCS line log, SEAL408 Line Configuration by Sequence). Sequence lines 1-12 were shot with a 1200 hydrophone channel 15 km long streamer (prime and turn lines D09-D12, S01, S01A, S01B) and sequence lines 13-50 with a 960 channel 12 km long streamer. Sample interval for all lines was 2 ms for a 15 sec or 14.5 sec record length. Shot spacing was 37.5 m throughout, and the nominal tow depth for both streamer and source arrays was 12 m with the streamer lower to 13 m during rough weather conditions (see below). Technical reports and documentation of the seismic acquisition provided by *Langseth's* science support team include the Navigation and Observer logs for each seismic line and the towing configuration summaries with all offsets documented (MGL2104_Offsets_MCS_15000m_Streamer.xls and MGL2104_Offsets_MCS_12000m_Streamer.xls).

4.1.1 MCS data acquisition and issues

Most of the primary lines were shot with 4 gun-arrays with total volume above 6000 cu inches (Appendix 6). However, Lines PD15, 16, 17, 18, and a large portion of PS01B were shot with 3 gun-arrays because an extended period of rough weather conditions prohibited getting the misfunctioning gun array on deck for repair. The signature of the three-array source is different from four-array source in that the 1st peak is less focused and the bubble pulse is less attenuated (Figure 3). A different de-signature filter will need to be designed for lines shot with three gun-arrays.

The ultra-long offset of the 12-15 km streamer recorded pre-critical reflections from down to mantle depth as well as wide angle reflection and refraction arrivals from down to ~5-6 km beneath the seafloor. Over 98% of the 960 channels along the 12 km streamer functioned well and recorded clear signals. The problematic channels include 16 dead channels (Chan 1,9, 13, 24, 56, 301, 519, 529, 541, 549, 573, 589, 621, 637, 645, 646) and 3 channels (Chan 278, 282, 679) that showed high electrical noise between June 15-25. The sections with high electrical noise were swapped out during trouble-shooting for streamer telemetry line failure following streamer event 3. The 12 m tow depth of the streamer reduced the swell noise level on the streamer in general. Yet on acquisition days with rough weather, the swell noise level was still quite high. On three of the prime lines, the D02 reshoot, and 3 turn lines (Appendix 4B), the streamer depth was lowered to 13 m to further reduce the impact of weather near sea surface.

Prior shot noise was recorded with the 15 sec record length on some lines later in the cruise, when following currents led to faster than targeted tow speeds.

Source and receiver positions were derived from GPS recording on the vessel, gun arrays, and tail-buoy, and the compasses on the birds. P190 files were QC'ed by the science party onboard and no major issues were identified.

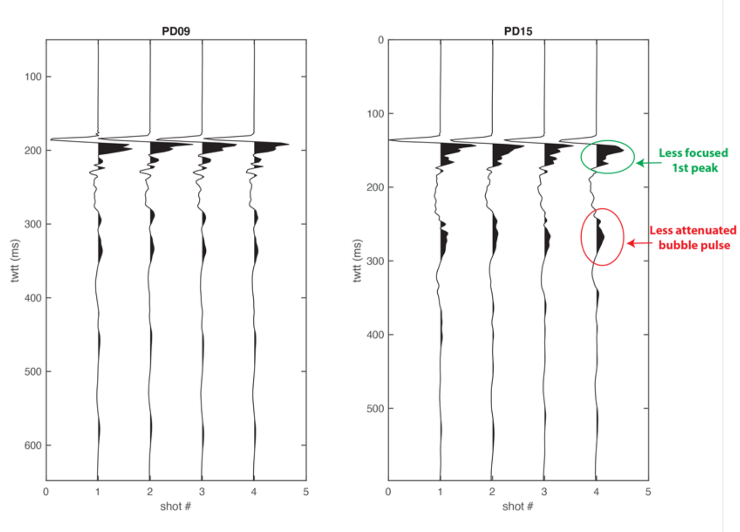

Fig. 3 Comparison of source waveforms of 4-array source (PD09) and 3-array source (PD15). Direct arrivals on Channel 2 (nearest offset live channel) of four shots along PD09 and PD15 are plotted. The 3-array source signature is characterized by a less focused 1st peak and less attenuated bubble pulse.

Recording Timing Issue: Comparisons of our shipboard sections with older legacy crossing seismic lines assessed using the Cascadia Kingdom Suite project (see below) revealed a 50 msec offset in our records. On further investigation Co-Chiefs Shuoshuo Han and Brian Boston determined a mismatch between shot times and Spectra recording times with Spectra beginning to record 50 msec prior to gun firing time. Alan and Jesus identified the problem as a configuration issue in wiring between GunLink, Seal and Spectra such that start of recording was set to initiate when the 50 msec pre-trigger time was sent to GunLink, rather than the actual shot time. The decision was made to fix the P1 and P2 files and the OBSIC shotlog files to the correct shot time and to change the Gun Link /Seal/Spectra configuration to begin recording at the actual shot time. This issue affects lines PD09-12, PS01, 01A, 01B and PS03 with the change made on June 17 during line change to PD19. SEGD files of these early lines are not changed, thus a 50 ms shift will need to be applied before processing. Further documentation of this issue is included in Appendix 4C and 4D.

Error in water depth in P190 files: A +12.8 m offset was discovered in the water depth value included in the P190 headers from the MBES center-beam depth value interpolated for at each shot location. This offset was present in the 2012 data from Ridge to Trench cruise and was discovered by Hanchao Jian during comparison of P190 and multibeam bathymetry for travel time tomography on streamer data. Investigation by Shuoshuo Han, Hanchao Jian and Alan Thompson led to the finding of the double application of a 6.4 m draft correction of seafloor depth for the depth of the multibeam transducer relative to the ship reference point during incorporation of the multibeam center-beam depth in the P190 headers.

4.1.2 MCS Onboard data processing

Brute stacks were generated on board after acquisition of each line was completed using an Echos workflow set up prior to the cruise. The stacking velocity for each line was built using a 1-D velocity function hung from the seafloor depth for each shot extracted from the SEGD headers. The 1D velocity function was derived from existing velocity models from the MGL1211 Ridge2Trench study. Brute stacks were migrated at water velocity to collapse seafloor diffractions and improve the image of the sediment portion of the sections. With completion of each MCS line, Alan Thompson processed the navigation to generate the P190 navigation files, which were provided usually within a day or two of acquisition. These files were checked after being read into Echos with no problems found. The onboard processing of the MCS data was setup and led by Shuoshuo Han and Brian Boston and details on the onboard processing including the Echos flows are included in Appendix 7.

4.1.3 Kingdom Suite Seismic Interpretation: The Kingdom Suite interpretation software was used extensively during the cruise and contributed to our ability to assess and develop first interpretations of the new MCS data. Jeff Beeson brought Kingdom Suite with him with a Cascadia project populated with legacy open access MCS datasets available from the NSF funded Academic Seismic Portal database as well as an extensive collection of industry lines acquired in the 1970's from the USGS NMSS database. This project was generously shared by Anne Trehu and Ben Phrampus from OSU. Our brute migrated seismic lines were loaded into the database, and preliminary interpretations were made on many of our new seismic lines in addition to the legacy database sections. This provided science party members new to seismic interpretation with the opportunity to learn about interpretation and to become familiar with the data from the area. The ability to make preliminary interpretations in the context of the regional existing data and the geographic framework was a great learning tool and a terrific asset for all.

4.2 Multibeam sonar data acquisition and processing

Multibeam sonar data were acquired throughout the cruise using a 1°x1° beam Kongsberg EM122 sonar providing measurements of seafloor bathymetry, backscatter intensity and side-scan, and water column backscatter (Appendix 8). The system was operated primarily in Deep water, FM high-density, dual swathe, equidistant mode and switched to Medium or Shallow mode on the shelf. Ping rates varied with water depth but on average, were one ping every 6-10 seconds. An AML Oceanographic Micro SV was used to measure sound speed at the transducer and the Kongsberg Seafloor Information System (SIS) was used to monitor and control the EM122. XBT's were acquired roughly daily (Appendix 9) and uploaded into SIS after they were collected and processed. The *Langseth* marine techs provided the science party with enough XBT's to deploy at minimum one per day. The science party used discretion as to when/where to deploy the allotted XBTs resulting in some 24 hour periods having no new XBT's and other 24 hour periods having more than one.

QPS Qimera was used to clean the multibeam bathymetry data throughout the cruise. All multibeam files were first converted from the raw *.all files to *.gsf, cleaned through an automated process, manually ping edited, and gridded at 50 m on a daily basis. By cruise end a total of 40,603 square km of multibeam sonar data had been acquired along roughly 7,021 line kilometers. The onboard processing of the multibeam data was led by Jeff Beeson and further details on the acquisition as well as maps of the total multibeam data coverage achieved and data examples are included in Appendix 8.

Multibeam water-column data: EM122 water column backscatter data were recorded continuously during the cruise. Minimal processing was conducted for these data and included merging navigation and gain adjustments. Each water-column swathe was reviewed on a daily basis for acoustic anomalies to identify bubble streams or seeps in the water column. Processing was done in Qimera/FMMidwater, which allows for interpretation of acoustic anomalies recorded in the water-column data. A total of 55 individual seeps were identified during the survey with locations included in Appendix 8.

4.3 Knudsen sub-bottom profiler and Serial data acquisition and processing

The sub-bottom profiler (SBP) used during the cruise was a Knudsen 3260 rack mounted echosounder connected to hull-mounted transducers. The system was used at a nominal frequency of 3.5 kHz to prevent interference with the EM122, and was synchronized to external triggering provided by the EM122 system. Further details on the acquisition as well as data examples are included in Appendix 8.

Gravity data were acquired continuously during the cruise using a Bell BGM-3 gravimeter. Dockside gravity ties were conducted immediately prior and after the cruise as well as land station ties at benchmark stations in Newport and in Seattle. Magnetics data were acquired with a Geometrics G-882 Cesium Marine Magnetometer with the maggie deployed during MCS operations except for periods of rough weather to avoid tangling in the gun arrays. Other serial data acquired include Thermosalinograph data (with a Seabird Electronics - SBE 45 – Thermosalinograph), GPS, and weather station data. *Langseth's* science support team generates a merged 1 sec and 1 minute file of the serial data strings that is updated daily (e.g. MGL2104_serial_data_1min.xls). From this file, time and data values were extracted for the EM122 center-beam bathymetry, raw gravity, magnetics, along with temperature and salinity from the TSG and line plots were generated (included in Appendix 13). Processing of the gravity and magnetics data was conducted onboard by Liam Moser to calculate free air anomaly and magnetic anomaly as described in the processing report included in Appendix 10.

4.4 Protected Species Observations

The combined total number of (potential) takes of protected species under observation throughout CASIE21 are summarized in Table 2. As summarized in the final PSO report (Appendix 12) three protected species, all humpback whales, were observed during acoustic operations within the predicted radius at which there is a potential for auditory injury (based upon each species hearing range and how that overlaps with the frequencies produced by the sound source), constituting a potential Level A take. A total of 317 protected species were observed within the predicted 160 decibel radius (where there is a potential for a behavioral response) while the acoustic source was active, constituting potential Level B takes. The numbers of takes that had been authorized for the study was many times greater than our actual detection numbers for all species except for Humpback whales with total takes (91) equivalent to 64% of the number authorized (141). Whereas our IHA covered 31 species only 6 species were involved in the incidents of species within the source radii defined for level A and level B takes. In Appendix 11 we also include a map and table showing locations of all detections. We had one detection of a Killer Whale which occurred before we started operations on June 2. Most of the Humpback Whale detections were on the shelf near Heceta Bank, near Rogue Canyon and on shelf south of Cape Blanco.

Table 2. Marine Species Detections

Species	**Authorized takes**	**Total combined Level A and (potential) B takes for survey**
Humpback Whale	141	94 (Level A = 3, Level B = 91)
Blue Whale	51	4
Fin Whale	95	10
Short-Beaked Common Dolphin	179	6
PacificWhite-Sided Dolphin	6084	176
Northern Fur Seal	4592	1
Unidentifiable Whales		20
Unidentifiable Dolphins		9
Total Protected Species within predicted 160 db radius		320

5. Recommendations for future operations

Extended Bandwidth: NSF is currently supporting extended bandwidth on UNOLS vessels for mission specific needs. We requested extended bandwidth for our survey in order to test feasibility of SEGD data transfer to shore for onshore data QC by our ION colleagues who will be processing the dataset. It took ~8 days to transfer all data (140 GB) for one line (PD09). Half of this time was due to data interruptions requiring Gilles to restart the transfer. This pilot was a successful demonstration that MCS data transfer to an onshore processing group is feasible. At the current achieved data transfer rates however, it wouldn't readily replace onboard data QC by the science party. Other benefits of the extended bandwidth included reliable ship-to-shore communication to support our complex operations (zoom calls with OMO) and the ability to download data and other information while at sea to help support the science program.

AIS in tail buoy: For our cruise, Alan Thompson configured the streamer tail buoy with an AIS beacon, which was a first for *Langseth* streamer operations. The AIS beacon proved essential for quickly finding the tail buoy and facilitating the streamer recovery after the parting event**.** After the streamer parting event, we tracked the tail buoy using the AIS for ~1 hour while the guns were recovered. Once guns were secured, we headed for where we projected we would cross the streamer based on last detected position of the tail buoy. We passed that position but picked up the AIS beacon location shortly after, indicating the tail buoy had drifted 7 nm to the NE. The AIS was also useful for later operations in this region of heavy ship traffic, as other ships could track both Langseth and the tail buoy. There were some issues related to MSN number in tail buoy being the same as the vessel, causing our AIS to seem intermittent to some nearby traffic and this will need to be changed for upcoming trips. We strongly recommend use of AIS in the tail buoy as standard practice for future expeditions.

Limitations of 15 km streamer/Survey speed: Use of the 15 km streamer appears to push the limits of operational capability particularly in rough weather conditions. While we were operating the 15 km streamer at the beginning of the cruise, it was challenging to keep tension levels within target and survey speeds at times needed to be kept at 3.6 to 3.8 kts. Shaun Shaver noted that the Sercel streamer we are operating is rated for up to 12 km. We recommend that these operational limitations should be clearly conveyed to science teams so they fully appreciate the risks and limitations of using the 15 km streamer. For all surveys planned with the 15 km streamer, time estimates should not be done with speeds above 4.0 knots. During our extensive cruise planning process speeds of 4.1-4.3 knots were used, but our achieved survey speeds were much closer to 3.9-4.0 kts. With the 12 km streamer, we were able to tow at speeds of 4.5 to 4.7 kts without tension issues even in the presence of significant currents.

Streamer front ends: We operated our survey with only one readily usable frontend (on reel 3) as the new frontend installed on reel 4 in Seattle was unusable due to issues arising from inadequate tension with manual spooling in port. This limited our options during our streamer redeployment events. The reel 4 tensioning issues were fixed at the end of the cruise as part of the streamer recovery process. Shaun Shaver noted that in industry, front end usage days are tracked carefully as they should only be used for 240 days at sea. This tracking should be done for *Langseth*.

Look-ahead vessels: Unfortunately, the *Rachel Carson* was unable to complete the mission of supporting our day-light only shooting operations due to rough weather conditions that exceeded her operational capability. We were unaware of this constraint until ~ 2 hours before the *Rachel Carson* was to meet us on July 1 to acquire the remaining shallow water portion of our survey in Canadian waters. Better coordination and communication of her operational limits was needed to inform our acquisition planning. In hindsight, a larger ship like the *Oceanus* would have been better suited for our working conditions. There were also significant issues concerning communication between the PSO's aboard the *Rachel Carson* and *Langseth*. Handheld radios on the *Rachel Carson* did not have the needed range to work with the *Langseth* and PSO's needed to make use of the bridge phones which was non-ideal, and a better communication plan will be needed for any future studies using a look-ahead vessel.

Langseth Workstations: New workstations for seismic processing were installed with the Paradigm seismic package v15.5 before sailing. Onboard processing during our cruise was mainly done with a UTIG workstation brought onboard by co-chief scientist Shuoshuo Han and hence the new workstations were not fully tested for processing speed. From limited tests, migrations ran 3-5 times longer on the Langseth machines than on the UTIG workstation, and for an MCS-only cruise like ours, they may not provide a fast-enough turn-around time as the primary machines for onboard QC. We used these shipboard machines for students/postdocs to practice processing flows and to allow the science party to explore the processed data quickly. The new workstations have an issue with the resolution of the current old monitors, and could not be used in their current setup. Gilles quickly addressed this problem with setting up remote login from the Apple machines, but updated monitors for the new workstations should be purchased.

Habitability: There were issues of infrequent cleaning of public heads – perhaps a result of extra time spent on cleaning of hallway and stairway railings as part of the Covid-19 mitigation procedures for the ship. Hallway cleaning, certainly after the first 2 weeks of extra COVID precautions, should not take priority over keeping the public heads cleaned. The movie room was over air conditioned and uncomfortably cold, hindering its use.

6. Initial results

6.1 Incoming Plate

Most prior MCS studies of the Cascadia Subduction Zone have focused on the accretionary wedge with little coverage seaward of the deformation front for characterizing the incoming Juan de Fuca plate. Imaging to ~ 50 km seaward of the DF acquired during the CASIE21 study reveals marked variations along the margin in sediment and plate properties that likely contribute to variations in accretionary wedge structure and megathrust characteristics. North to south variations in sediment stratigraphy and sediment thickness are present with the thickest sediment section beneath the Nitinat and Astoria Fans in the north, a landslide-dominated region offshore southern Oregon and a thinner basin-turbidite section on the northern Gorda plate (Fig. 4).

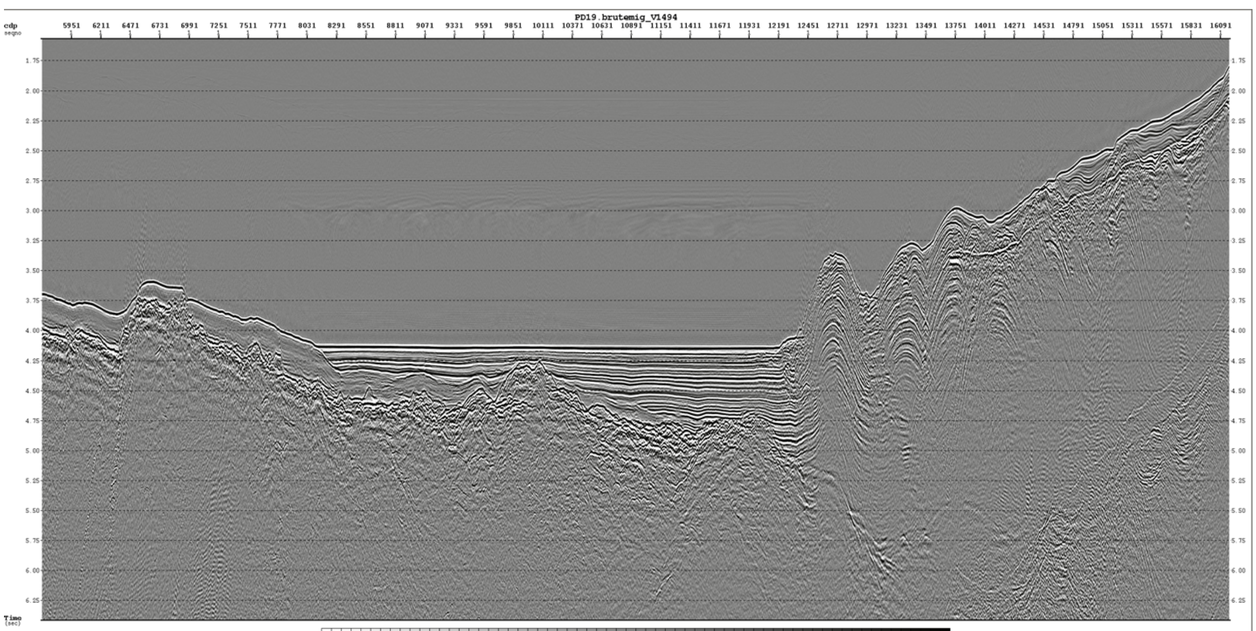

Figure 4. Line D019 crossing the northern end of Gorda plate showing an acoustically transparent draped sediment layer on top of oceanic crust which thins and disappears under a package of horizontally layered turbidite sediments.

Along the southern Oregon margin, discrete intervals of far-travelling (10's of km) mass-transport deposits are detected embedded in the sediment section, presumably older examples of the superscale landslide deposits identified in this region by Goldfinger et al [2000]. An erosional unconformity sampled during the early leg 18 DSDP study (hole 174) is crossed on a number of lines in the central Oregon region and will allow mapping of this unconformity which is believed to correspond with the base of the Astoria Fan. Buried seamounts of a range of sizes are found in a number of locations at different distances from the deformation front. Local intervals of reversed polarity bright reflections are found within the sediments above the crests of several of these seamounts and may be evidence of active fluid venting from the seamount and entrapment beneath less permeable sediment layers. Several line crossings of the Nootka fault region at the north end of the Juan de Fuca plate were acquired and reveal extensively faulted sediments with evidence for buried basalt flows within the sediment section as previously imaged in high resolution MCS studies [*Rohr et al., 2018; Reidel et al., 2020*] as well as deep reaching reflective faults within the crust and extending possibly into the mantle (Fig. 5).

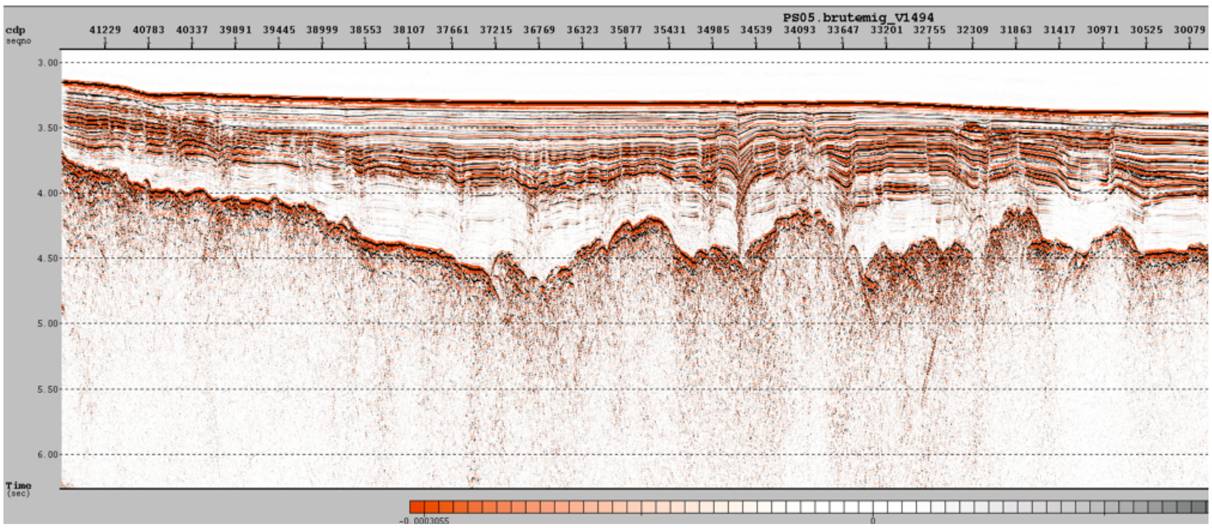

Figure 5. Line S05 crossing the Nootka fault region showing the extensively faulted sediments**.**

Comparison of dip lines also indicate variations in the distribution and depth extent of faulting within the sediments and oceanic crust likely related to the subduction bending deformation previously detected along this margin [*Han et al., 2018*]. Along some dip lines reflective faults are detected within the oceanic crust and possibly extending into the mantle, whereas along other lines little faulting is evident. Further processing including noise suppression, multiple removal and migration at appropriate velocities will be needed to confidently interpret the distribution and extent of this faulting deformation.

6.2 Accretionary Wedge Structure

The accretionary wedge along the Cascadia margin has a well-documented variation and contrasting structural style [e.g. *McKay et al., 1992; 1995; Watt and Brothers, 2020*]. However, a lack of regional MCS data coverage, the limited extent of legacy seismic lines to ~ the seaward edge of the deformation front, and lack of deep-penetration, means that there is still an unclear picture of the deeper structural controls along the margin. Here, we highlight a few of the regional variations found along the margin. We expect that additional processing including pre-stack depth migration, additional noise reduction, and multiple removal will greatly enhance the imaging and resolution of these structures.

Southern Oregon (Figure 6) has been one of the least imaged regions of the margin. Here we see small seaward-verging thrust faults, but much of the internal structure appears less well-defined than other portions of the margin. Initial processing suggests a significant amount of sediments being subducted beneath the prism. This is in contrast to the rest of the margin, shown below, and appears to correlate with the steeper seafloor morphology in this region.

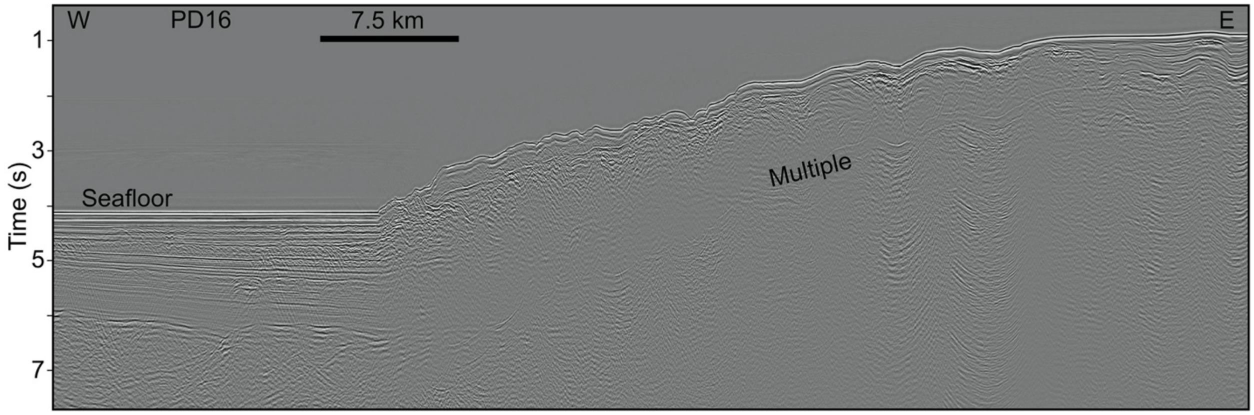

Figure 6. Line PD16 offshore southern Oregon potentially indicating large amounts of sediment subduction.

Moving from southern Oregon to northern Oregon (Figure 7) shows a rapid change in wedge structures and morphology. Landward-verging thrust faults are dominate, but there is a mix in vergence direction. Nearly all of the sediments of the incoming plate are accreted into the wedge, forming large seafloor ridges that appear as elongate trench-parallel ridges in the bathymetry. Slope basins pond sediments between most of the ridges and completely bury many ridges as well. This leads to a wide and low taper angle wedge for this region.

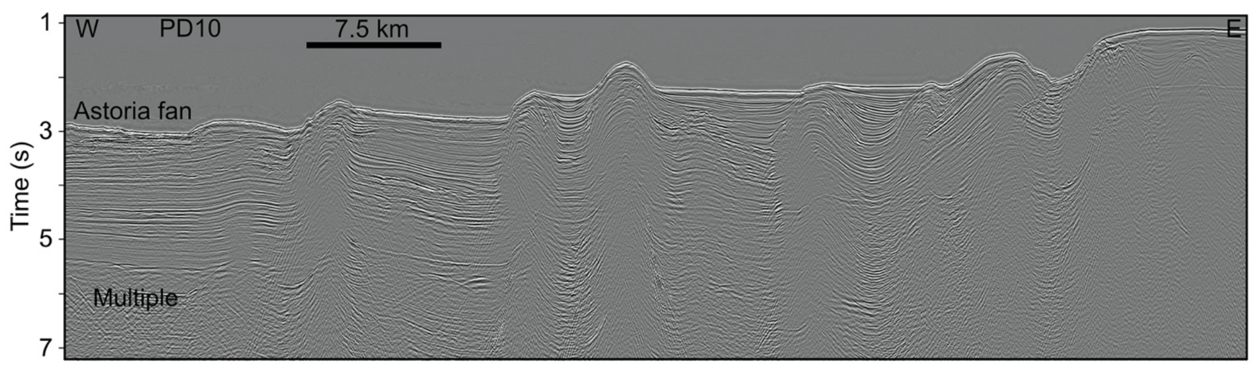

Figure 7. Line PD10 offshore northern Oregon showing accretion of all incoming sediments.

The Canadian portion of the Cascadia margin (Figure 8) shows mix-vergence of thrust faults. Nearly all of the sediment is accreted, however, accreted sediments are less well imaged than in other regions of the margin. This may be geological in nature, but we expect additional processing will improve the imaging. Slope basins appear to be thinner than in northern Oregon, along with a much narrower wedge.

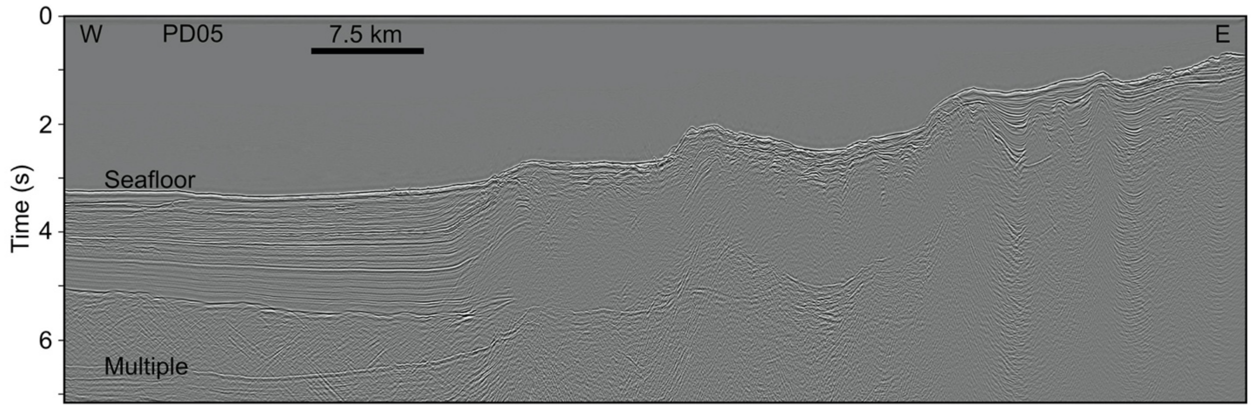

Figure 8. Line PD05 offshore Vancouver Island showing mix vergence of thrust faults.

6.3 Plate interface reflections beneath wedge and shelf

On most of our dip lines, the interface between downgoing and overriding plates can be identified near the deformation front by the depth to which the thrust faults shoal. North of 45˚N and south of 42.2˚N, thrust faults in the wedge extend close to the top of oceanic crust, indicating little sediment subduction (Fig. 9). Between 42.6˚N and 44.5˚N, frontal thrusts shoal into horizons 0.9-1.4 sec TWTT above the oceanic basement beneath the 1st thrust ridge, suggesting significant amount of subducting sediment near the deformation front. However, whether the plate interface stays at shallow depth or steps down further landward cannot be determined from current brute-migration, which were generated without multiple suppression.

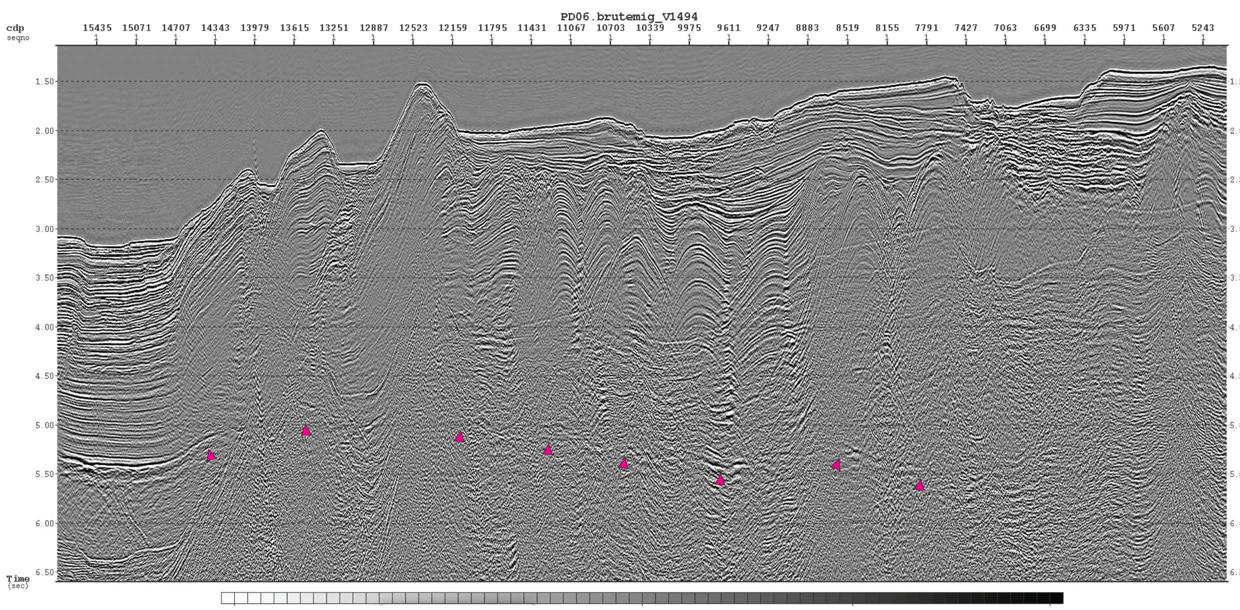

Figure 9. Plate interface beneath accretionary wedge along PD06

It is generally difficult to trace plate interface reflection from the deformation front to beneath the shelf on the brute-migration due to strong water bottom multiples. Yet, we do observe several deep reflections beneath the wedge and shelf on some of the lines, in the travel time range of 5.5-8.5 sec, which likely arise from strongly reflective patches of the plate interface and/or oceanic Moho. Deep reflections on one of the dip lines (PD12) are shown in Fig. 10. Here an ~20 km-long strong reflection (annotated by magenta triangles) is imaged at 6.5-7.2 sec, beneath a deep forearc basin. Two other reflections, ~0.5 sec (green triangles) and ~1.8 sec (yellow triangles) beneath this reflection are also observed. The nature of these reflections will be determined on future depth-migrated images.

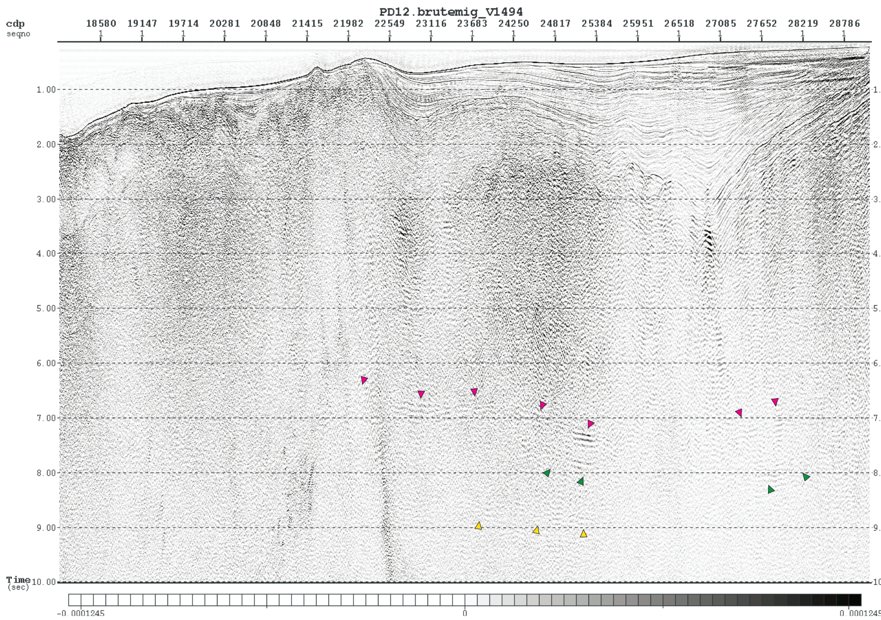

Figure 10. Deep reflections on PD12

Strike lines along the upper slope and shelf also show deep reflections. On strike line PS01B, one continuous reflection is observed at 7.2-7.5 sec, with variations of amplitude (Fig. 11). Some other reflections are also present above this event. Interpretation of deep reflections on strike lines will require tie to the dip lines.

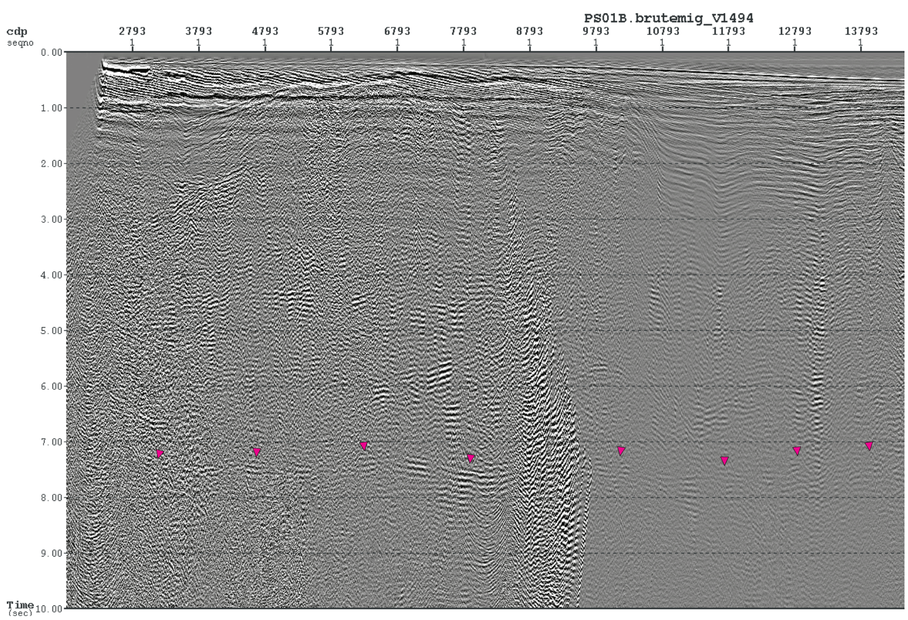

Figure 11. Deep reflection on strike line PS01B

We expect that future processing, especially multiple suppression and depth imaging, will reveal more deep reflections and allow for systematic examination of the geometry and reflection characteristics of the plate interface.

7. Cruise Narrative

(Note: 00:00 UTC=17:00 Local time, June 1- JD152)

May 31. The CASIE21 science party arrived at *Langseth* late morning after our one-week quarantine and settled into our cabins. During the pre-cruise quarantine we held daily zoom check-ins and socially distanced group walks were arranged for during the 1.5 hr allowed outdoor time. The quarantine time went well and all were excited to begin our expedition. During the afternoon Cody gave the welcome, safety and sexual harassment awareness presentations to the science party in the Main Lab. *Oceanus* was at the dock alongside *Langseth* and we met with the science party for the OBN program led by Pablo Canales and Dan Lizzaralde. *Oceanus* had departed earlier in the week to deploy OBN's along 3 of our lines but once at sea, the ship was unable to safely handle the ROV needed for deploying the OBNs and the program was aborted with the hope of re-scheduling on another vessel, perhaps *Langseth*, in the fall. Planned COVID-19 protocols on *Langseth* for our cruise included wearing of masks, only one person in exercise room, library and tv room at a time and restricted occupancy in the mess hall for meals for the first 14 days of the expedition.

June 1. Our expedition began with delayed departure from Newport at 18:50L (JD152 01:50 utc) as we awaited arrival of a shipment of filters for the ship's fresh water system. Our transit to the planned streamer deployment site was estimated to take ~9 hours. We completed set up of computers in the main lab with watches set to start at beginning of gear deployment. In the evening, lead PSO Amanda gave an overview presentation on the PSO activities in support of our expedition and Suzanne and Shuoshuo gave a science presentation on science goals of the project that was open to all. We established a schedule for Thursday and Sunday evenings for a science reading group focused on recent Cascadia publications. Captain Breck, Shaun and Suzanne set up our schedule for daily check-in meetings at 12:30 local to review survey plan for the coming day and any operational issues.

June 2. Excellent weather. Sunny and winds 5-8 knots. During the transit, we ran a multibeam roll bias calibration test from 10:43 to 11:18 utc acquiring MBES data in opposite direction on near flat seafloor in a region with data acquired during OBS deployment cruise MGL2103. We began tail buoy and streamer deployment at 13:39 utc/20:39 local. Our initial plan was to deploy 6 km from streamer reel S2, 3 km from S4 and a final 6 km from S3, with towing from S3. However, once deployment started from S4, we ran into problems associated with the earlier manual respooling of S4 in Seattle and resulting mistensioning. Shaun decided we should deploy all of S4 and tow from S4. Revised plan was to deploy 6km from S2, 3km from S3 and 6km from S4.

June 3. Continued excellent weather. Winds ~10 knots, overcast. During the night after deploying the full streamer with final 6 km from S4, problems were encountered with the S4 lead-in and we lost communication beyond bird 15 indicating a bad section in S4. Decision was made to reel back in to bird 15 spooling the section onto the S3 reel, then swap out the bad section, and redeploy from S3 reel and tow using the S3 lead-in. The final streamer configuration included 52 birds, each 300 m apart. Streamer deployment was completed at 13:10 L/20:10 UTC followed by deployment of magnetometer and PAM. Gun deployment included work on new tow points and took 6:43 hours with guns configured, tested and the full array deployed by 19:53L/02:53UTC. Deployment took 38 hours total. We start acquisition with our first line PD09 located north of the Columbia River at 21.34L (04:34 utc June 4). Earlier in the day we had our emergency fire and boat drill. In the evening at 18:00 L, we started our twice weekly reading group.

June 4. Weather fair, winds ~17 kts. Continued today on Line PD09. No mammal shut downs so far. USGS reported two M5.9 eq occurred today on north Gorda plate, just west of our line D19 end point and we discussed possibility of extending our line PD19 to cross the EQ source location. Finished line D09 at 17:01L. Streamer feather was very low, <1° for much of this line. Estimated 12:15 hours behind schedule by end of line due to slow deployment and slower than expected streamer tow speeds needed to keep below streamer tension warning limits (set at 8000 lbs). Shortly after beginning turn, air leaks on both gun strings 1 and 2 was indicated. Both gun strings were brought onboard, fixed and redeployed in time to begin PD10. Began line PD10 at 22:54L/05:54UTC.

June 5. In early morning, trouble shooting was conducted on turn line TD09D10 for a suspected misfiring detected with the near source hydrophones on gun string 1 but no problem found. Winds picked up in the afternoon (20 kts) and a 6-8 foot swell developed that contributed to significant problems controlling streamer depth. Had an ~2 hour period from 15:15L (beginning ~shotpoint 95500) where the head section of streamer rose to near sea surface and then shallow region propagated along streamer to tail over next 1-2 hours. Our first marine mammal shut-down occurred near end of line PD10, and we ended this line early as a result (at 19:24 L/02:24 UTC).

June 6. Began line PD11 at 20:32 (03:32 utc June 07). Weather deteriorated during the day as winds picked up reaching 35 knots in the evening with seas up to 16 ft. With our heading on PD11 into the seas, maintaining target speed through water (STW) was difficult with frequent short period speed changes that led to strong surge noise on streamer and it was very difficult to control streamer depth at 12 m. The mid-section of the streamer developed a group of 6 birds not communicating and we discussed potentially bringing the streamer in to fix this. We completed line PD11 at 00:23L (June 7, 07:23 utc) and turned south to run turn line in the trough. This was very rough for people onboard but much better for controlling ship speed and streamer depth. Streamer feather was high on this line up to ~9°. Gun lines tangled on the turn and guns strings 2 and 3 were brought in just after we started the line. Average speed during operations so far has been much slower than was planned for (3.9-4.0 kts on average compared with 4.3kts planned). With this average speed we reassessed survey plan for options to recover time in coming days.

June 7. Began line PD12 at 5:22l (12:22 utc). Weather improved over the day with winds decreasing to 5 kts, but seas continued to be high. We settled on a revised shooting plan for the southern survey area that included turning onto PS01 after line PD12 and potentially dropping line PD17. Marine mammal shut down occurred from 14:20-15:17L (21:20-22:17 utc) with sighting of 5 whales with 2 in the exclusion zone. Shut down occurred just after crossing the deformation front along line PD12.

June 8. Winds 4 kts, seas 2 m. Ended line PD12 at 09:18 utc. During turn from PD12 to PS01, we experienced gun misfire problems and strings 1&2 were recovered. Line PS01A began at 13:51 utc. In late morning, we encountered tension spikes on the streamer of > 10,000 lbs that stayed high and a section of 6 birds mid cable that were on the sea surface that we were unable to control. We suspected fishing gear on streamer and decided to bring in streamer with EOL PS01A at 12:50 l (19:50 utc). On recovery, fishing gear, likely from crab pots, was tangled in first bird brought onboard and ultimately, found along much of the streamer. Most fishing gear with buoys could not be untangled and needed to be cut off the birds and sent overboard. Four birds mid-section were found with their SRDs deployed (28, 29, 30, 32), and a fifth bird was damaged. The location of fishing buoys cut off the streamer were marked for avoidance during our planned return transit through region.

June 9. Weather continued fair. Streamer redeployment was difficult and protracted with extended trouble shooting needed to find bad section(s) associated with inability to communicate with the birds in streamer mid-section. After frequent breaking of streamer by bypassing to reel 4 leadin to check sections, the offending module (2410) was identified near head of streamer at 23:10 utc. Completed streamer redeployment at 17:25 L (00:25 utc). Began deploying the guns. Found that the float for gun string 3 needed repair. Began ramp up at 21:43 local (04:43 utc) and online for Test2 at 22:26 local (05:26 utc).

June 10. At 04:01l (09:01 utc), began PS01b. Man overboard drill at 10:30L. Experienced gun misfire due to airleak problems on string 3 and needed to shut off 2 guns, continuing acquisition with reduced array of 5700 in^3. Shuoshuo and Brian investigated a possible 50 ms offset in our sections relative to older seismic data that Jeff discovered from comparisons with legacy seismic profile crossings in the Cascadia Kingdom Suite project.

June 11. Continued on PS01b until 11:37 local (18:37 utc, shotpoint 42732) when streamer broke away from the ship (quote from main lab log book "streamer parted – no longer connected to vessel") after a tension spike to 10,050 lbs. Winds were high at 37+ knots and weather had been deteriorating over the day. After ~ 3 hours, at 21:38 utc we completed bringing gun arrays onboard, the head float and remainder of streamer up to the breakage point which was at front of first active section and then turned to north to go look for the streamer. The weather was too rough to attempt a work boat recovery from the head section and we headed for last known location of the tail buoy. At 01:00 utc the tail buoy AIS was seen on ship's radar which enabled us to navigate to it with visual on tail buoy at 02:00 utc. We made several attempts to recover the tail buoy approaching it on the starboard side but were not able to get the grappling hook attached. We maneuvered to come starboard side to streamer near tail buoy, Shaun succeeded in getting the grappling hook onto the streamer and we were able to bring the end aboard and connect it to streamer reel 2. This operation was complete by 22:00 local (03:00 utc June 12) after which we towed the streamer slowly to deeper water and then began the recovery, spooling the streamer backward onto reel 2. We had communication with OBS and land groups to inform them about the parting event.

June 12. We completed recovery of the tail buoy at 12:17 utc and then began recovery of the first 6 km of the streamer from the tail section onto reel 2. During recovery, 15 of the streamer birds were found missing their SRDs entirely, 14 SRDs were recovered that had gone off, only 1 with it's SRD bag attached. One bird was missing entirely and 2 were recovered with a broken wing to motor pin. Given that the recovery was from the tail, each 6 km of streamer recovered would need to be respooled to another reel in order to reorient it correctly. We completed recovery of first 6 km at 18:00 utc, and then conducted tests for best size loop in water for transfer from reel 2 to 3 (150 m on a side). Operations to loop from reel 2 to 3 took 8.5 hours. We began recovery of next 6 km onto reel 2 at 04:07 utc June 13, swapped 3 km from reel 2 to reel 4, and then recovered final 3 km onto reel 2 (completed at 13:58 utc). During the day we had decided on a new survey plan with our streamer limited to 12 km length using streamer on reel 3 and 4. This new streamer length limit was necessitated by lack of sufficient spare SRDs to replace the 15 lost but also will enable us to tow at faster average speeds of 4.5 kts, which is required now given the large amount of time lost to the streamer parting and fishing gear events.

June 13. Completed recovering the final 3 km of the streamer at 06:58 local (13:58 utc). No fishing gear was found at any location along the streamer. The last bird recovered (nearest break point) was found with it's wings bent back toward the streamer which could be due to whatever the streamer caught on before breaking. We spent the rest of the morning preparing the birds and tail buoy for redeployment. Deployed the tail buoy at 13:39 l (20:39 utc) and then began streamer deployment from reel 3. Deployment was slow, initially due to the inadequate tension on the reel inherited from respooling 6 km from reel 2 to 3 in the water.

June 14. Streamer was almost fully deployed when communication to the birds beyond bird 23 was lost. Cody suspected problem was due to LAUM at ~6 km so streamer was retrieved to this point and we replaced the LAUM, but this didn't solve the problem. Began trouble shooting streamer sections testing every 2-4 sections on streamer 4 power, eventually bringing in ~10 km and then redeploying. Covid protocols within the mess hall were relaxed today with people now able to sit together at meal times and one-person limits on TV and exercise rooms removed. Earlier in the week, Coast Guard had relaxed mask rules while outside on deck.

June 15. Deployed streamer to front 4 sections – testing each and found 2-4 bad. We swapped out and replaced these sections and another LAUM unit and then complete streamer powered up with successful communication to all birds. We replaced the stretch section and front end from reel 4 and deployed head float completing streamer deployment at 16:47 utc. Deployed Maggie, PAM and gun array, gun ramp up and began line PS03 shooting from north to south at 14:35 local (21:35 utc), close to 4 days after the streamer separated from the ship on Friday. Coordination with Anne Trehu regarding impacts of lost time on our shooting plan for the Oregon margin and the need for the land team to begin their recoveries by June 26 due to both battery life and personnel availability. Over the prior few days numerous revised survey plans were developed given the time lost to date. At this point of 15 days into our expedition we had acquired only 5 days of data, and the planned contingency of 10% time (4 days) had been far exceeded.

June 16. Continued on PS03. Weather good. Streamer tension very good at tow speeds of ~ 4.5 knots. Had a coordination call with Sean, Pablo, Nathan, Alan, and Shaun to discuss revised shooting plans and timing impacts for OBS program and *Rachel Carso*n meet up.

June 17. Weather conditions deteriorated during the day as we began an anticipated ~4 day period with a stationary low pressure system sitting above us. Completed turn line TS03D19 and started dip line PD19 at 14:07 utc. Completed line PD19 at 22:04l (05:04 utc June 18). Coordination call with onshore team. During the night a sailing yacht had crossed over the streamer while the bridge tried to communicate with them. Streamer was dropped to 15 m, well below what was estimated to ensure a safe crossing, and it was shortly brought back to 12 m afterwards with no issues.

June 18. During turn line TD19D18 and as we were beginning PD18 we experienced persistent misfire problems on gun array 1 and the array was disabled. The plan was to try to bring in array 1 during the next turn if conditions improved. Winds were in the high 20s picking up to low 30's over the day with seas 8-10 ft. We completed line PD18 at 02:37 utc (June 19).

June 19. Weather conditions continued to be very challenging with winds NE 35 kts and seas 4 m. The forecast continued to show a stalled low pressure system in our region and rough weather conditions predicted to remain until Monday or Tuesday. During the night the maggie became tangled with the gun arrays due to the rough weather and at 07:09 UTC it appeared to have broken away from the vessel. Seas were too rough to bring in the maggie cable and the decision was made to hold off on retrieval and deploy the spare maggie when weather improved. The compressors stopped at 09:10 UTC triggered by low oil indicator probably connected to ship pitching. The oil was filled and compressors resumed with a loss of ~40 shots. We began line PD17 at 07:54 utc, EOL at 23:29 utc. During this line gun string 4 was disabled due to autofire problems.

June 20. Both arrays 1 and 2 were recovered during turn TD17D16 and redeployed, but we were not able to recovery string 4 during the turn due to weather conditions. Started line PD16 at 06:42 utc, shot with 3 arrays @ 4950 cu. in. Ended line D16 at 21:37 utc. Weather continued poor, wind 30 kts, seas 3 meters. We had planned to recover strings 3 and 4 in early evening during turn from D16 to D15 to fix the air leak on string 3, the misfiring guns on string 4 and disentangle the PAM which was wrapped around the string 3 leadin. However, the poor weather conditions were such that we would only be able to operate with PAM off for 30 minutes and then would need to shut down. Given the uncertain time to fix PAM, the upcoming nighttime, and the rough conditions for recovering the array, we decided to continue shooting with 3 of the 4 arrays and wait to fix the guns and PAM once weather improved on Monday at end of line D15. Inspection of the data records shot with 3 arrays after completing this line shows clear bubble pulse artifacts (either 2 or 4 arrays appear to be well tuned but 3 arrays are not).

June 21. Continued on turn line from D16 to D15 and began line D15 at 05:36 utc. Weather conditions were much improved with winds decreasing to 26 kts, seas 3 m. At end of line D15 at 23:15 utc, we brought in PAM and gun strings 3 and 4. We found the magnetometer tangled but attached to the last gun on string 4. Airleak problems on array 3 and the gun that was misfiring on array 4 were serviced and the gun arrays redeployed along with the magnetometer. Turn line from D15 to D14 (TD15D14) was modified to avoid the fishing gear buoys detected on line PS01A as well as a NOAA buoy and the seafloor shoals on Heceta Bank. At this point in the cruise, we were very concerned about running into further fishing gear along the shelf with the streamer and hence decided to truncate lines prior to reaching the 100 m contour. Coordination with Anne Trehu regarding shooting schedule and recovery plan for land array.

June 22. Acquired Line D14 (07:37 -20:36 utc) and turn line TD14D13 (21:04- 02:09 utc June 23) and began D13 at 19:32 local (02:32 utc June 23). Redeployed the magnetometer that had been recovered the previous day. Weather conditions were good. Line PD13 was located close to an OOI surfacing piercing mooring and we coordinated with OOI personnel prior to beginning this line so that they could signal the mooring to remain submerged until we completed the line. These operations were successful.

June 23. Continued on Line PD13 (EOL 18:22 local) and then began next portion of the shelf strike line PS01c heading north to offshore Washington.

June 24. Continued on Line PS01c with *Rachel Carson* joining us at ~ 02:00 am local, south of the required meeting point offshore Tilamook Bay**.** During our transit north on PS01c we encountered fishing buoys and moorings that required modest course adjustment to avoid. We received OBS deployment plan from Nathan Miller on *Oceanus* for northern lines and confirmed that our current shooting schedule aligns. Coordination with Anne Trehu regarding timing of the land instrument recovery. Last week, Shaun's team set up the pingpong table for us to use in the Wetlab. With the challenging weather last week, we were slow to start playing, but today the CASIE21 ping-pong tournament began.

June 25. Ended PS01c last evening at 21:45l /04:45 utc to begin nighttime stand down for daylight only operations along line PS01. We used the nighttime period to recover, fix and redeploy gun array 2, and after sunrise and required PSO watch period we began PS01d at 12:37 utc. Acquisition continued for ~ 8 hours until we experienced a power failure and leak detection on cable at 14:48 local/20:48 utc and we turned off Line PS01d to begin to gear recovery. Suspected problem was at 3.3km along streamer. The original estimate based on where the problem seemed to be located was that we could be redeployed by morning.

June 26. Continued with streamer recovery, slowly due to high tension on the streamer and trouble shooting multiple leakage points with section breaks as recovery progressed. Swapped out a suspected problematic LAUM but continued to see power leakage and high tension on streamer and hence continued to recover back to bird 37 (~10 km along streamer). Found two birds (32, 33 out of 42) with entangled fishing gear-crab pot lines. During redeployment continued to see power leakages with the full streamer not powering up and we needed to break at every 3-4 sections to test on deck power. There were suspected issues in section connectors related to inadvertent use of soap spray rather than alcohol. A total of 5 sections were swapped out from reel 2. Three were swapped in at the front of the original cable on reel 2 but 1 of them was bad and was immediately removed. 1 was swapped out from ~1 km behind the front end and another 1 section at ~3 km back. The swapped out sections came from the head of original streamer that parted and the mysterious power leakage problems are likely related to problems associated with the high tension sustained on this part of the streamer during the first fishing gear event or possibly due to the front end of the streamer sinking beyond rated depth before we were able to fully recover it. Finally completed streamer deployment at 23:15 L (06:15 utc June 27). Ongoing communication with Nathan Miller aboard *Oceanus* to coordinate timing of OBS deployment schedule for northern half of survey in light of latest streamer event.

June 27. We completed gun deployment and prewatch/ramp up and resumed acquisition at 02:18 local (09:18 utc) on Line PS05. We were relieved to be back acquiring data again and acquisition continued without interruption for the day. Weather continued excellent. Entered Canadian waters at 12:00 utc.

June 28. Ended line PS05 at 14:34 utc and turned to begin line PD02 at 17:08 utc. We experienced a long marine mammal shutdown for almost 4 hours (20:04-23:44 utc) but had uninterrupted acquisition after this and reached end of line before nighttime. Operations ceased to stand by for daylight shooting on shelf line PS02. Weather excellent.

June 29. At daybreak (13:00 utc), fog was too dense for the 1 km visibility required for the clearance watch and we could not begin shooting until 19:18 utc, with shutdown due to a detected whale shortly after (20:13-21:38 utc). After this mitigation shutdown, we had uninterrupted acquisition for rest of day**.** We turned off PS02 onto PD03 beginning line at 00:28 utc with the *Rachel Carson* leaving us at dusk as we left the 200 m water depth mark. Winds and seas picked up during night. Birthday today (for Suzanne) and the head steward Juanita made a cake and the science party organized a very nice celebration.

June 30. Weather was building over the morning with winds reaching 35 kts by noon. Maggie was recovered at 12:29 utc due to deteriorating weather. We completed line PD03 at 17:38 utc. Turning onto turn line TD03D04 the gun strings tangled and additional maneuvering was needed to untangle them. After untangling, a major airleak on array 2 developed. String 2 was disabled and once weather cleared adequately, the array was brought onboard, fixed, and redeployed during turn onto PD04.

July 1. Weather conditions continued poor. We began PD04 at 00:36 l/07:36 utc and completed deploying array 2 shortly after at 08:00 utc. As we were about to reach the meetup point with the *Rachel* Carson in the mid-afternoon, the Captain of the RC called to let us know that weather conditions had become too rough for their operations and they decided they could not accompany us for the end of D04 and rest of PS02. We evaluated the weather forecast as well as remaining time in program and decided there was time to either reshoot PD02 or acquire PD01. We discussed impacts of the missing 4 hours on the OBS data along this line with Pablo Canales and Nathan Miller and decided the priority would be to reshoot D02. We then turned to port to run a line parallel to PS02 (S07) heading back to D02, planning to then reshoot the missing portion of D02, then turn north to merge onto PS04. Start of line PS07 was at 00:46 utc (July 2).

July 2. During PS07, gun string 2 was recovered and then redeployed at 08:46 l/15:46 utc. Gun misfire problems were then experienced with array 3 and it was recovered. We completed line PS07 at 15:32 local (22:32 utc) and turned onto RD02a (SOL 00:55 utc). Deployed array 3 while on line RD02a but in region already shot during PD02. Winds were high – 35 kts with seas growing to over 3m over the day. We began work on the cruise t-shirt design.

July 3. Weather conditions continued poor with 30 kt winds and 3 m seas. Completed RD02a at 01:17 l (08:17 utc) and started TD02S04 at 02:27 l (09:27 utc). Experienced airleak problem again on gun array 3 and it was disabled but could not be recovered due to poor heading with respect to seas. On turning toward PS04 (SOL 11:12l/18:12 utc) we were able to recover array 3 which was fixed and redeployed by 20:48 utc.

July 4. Weather conditions improved with ~20 kt winds by mid-day. We completed PS04 at 16:36 utc. With gun misfire problems on array 3 (40 cu in gun), the array was brought onboard during turn line and redeployed prior to start of PD05 at 15:13 l/ 22:13 utc. The persistent ongoing problems with array 3 may be related to the water flooding of the array during the southern Oregon part of the survey when all air was cut as gun misfires continued at low air volumes and weather conditions were too rough to recover the array**.** We decided to change the acquisition plan for the remaining lines of our survey in order to acquire line D07 next (last OBS line), with the advantage of acquiring a longer turn line roughly parallel to the portion of the shelf line within the OCNMS that we could not acquire earlier in the survey due to streamer event 3. Given the short amount of time remaining in the survey and the constraints of not being able to operate the airgun array in the OCNMS and the prewatch required after shutting down the array, we realized we would not be able to acquire the near shelf edge portions of the WA lines D06, D07 or D08 and inside turns from the turn lines were planned for these final dip lines.

July 5. Weather conditions good with 15 kt winds, 1.5 m seas. We completed line PD05 at 12:14 utc and began long turn line (TD05D07) to last OBS line PD07. Redeployed the maggie at 13:41 utc which was pulled on June 30 due to poor weather conditions. At 13:35 UTC we re-entered US waters. With the short time remaining for completing our survey we discussed options for acquiring a portion of slope strike line PS06 with the advantage of ending acquisition close to Straits of Juan de Fuca, making for a shorter transit to port. We decided to shorten seaward ends of the remaining dip lines (D06, D07 and D08) in order to ensure adequate time to acquire along S06 from south of D06 to north of D04, providing line ties for 3 dip lines.

July 6. Winds 20 kts, seas 1.5 m. Began line PD07 at 05:11 utc, ended PD07 at 20:19. We ran short turn line to PD08 with SOL at 00:00 utc July 7.

July 7. Close to end of PD08, gun arrays 1 and 2 were disabled and brought part way in to fix broken tow points. Arrays were back in position and online within 1 hour. We ended line PD08 at 14:59 utc and turned onto long turn line TD08D06 (SOL 15:27 utc).

July 8. Weather fair, winds 4 kts, seas 1 m. Started line PD06 at 04:37 utc, ended line at 18:34 utc. Turned for parallel turn line PD06B in order to merge onto the slope strike line S06.

July 9. Weather continued fair – 10 kts, seas 1 m. Finished line PD06b at 06:25 utc. Started final line, slope strike line PS06 at 06:57 utc heading north with plan to end line 12 km north of crossing with D04 to ensure full fold at line crossing. We corresponded with Canadian colleagues Kelin Wang and Earl Davis about potentially adjusting the S06/D04 intersection point to support their planning for future IODP drilling in this region and decided on a line adjustment to cross at location of hole 1329. At 14:40 utc we re-entered Canadian waters and continued north on line PS06 until a PSO shutdown on July 10/01:30 utc ~ 30 minutes before the planned EOL and thus ending our survey. The final full volume shot point number was 173,213. At 01:57utc/July 10 we began recovery of gear.

July 10. The streamer recovery work began with recovery of 6 km onto reel #3 and then transfer of tow point for remaining 6 km in water to reel #1. Following this, work began to try to fix the "kink" in the leadin for reel 4 due to mis-tensioning prior to the cruise. The plan was to deploy the leadin to 5 wraps on drum, secure in-sea portion so that tension could be released on reel and then spin reel 4 to loosen the leadin and hopefully release the "kink". This recovery work was successful. Following this, the remaining ~6 km of backward streamer on reel 2 was transferred to reel 4 and the last 6 km in the water was recovered. Operations were complete and the streamer tail buoy was on board by 22:25 utc when we began transit to Juan de Fuca Strait Sea Buoy.

July 11.
At 08:30 UTC on July 11 we re-entered US waters. During the day we sailed through the Straits of Juan de Fuca and Pudget Sound enjoying the views of the shoreline of Washington and Vancouver Island and the sunshine and warmth after the long period of grey skies and temperatures in the 50's offshore. We took our cruise photo after lunch at ~13:00 local. We arrived in Seattle at Pier 90 at 18:22 local (01:22 utc) ending the CASIE21 expedition MGL2104.

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