Final Report

Cetacean Studies on the Quinault Range Site in June 2012: Passive Acoustic Monitoring of Marine Mammals Using Gliders - Results from an Engineering Test

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14. ABSTRACT
A passive-acoustic glider survey was conducted in the Quinault Range Site (QRS) off the Washington coast between 11 June and 12 July 2012. This glider survey was conducted with funding from the U.S. Navy's Office of Naval Research (ONR); awards # N00014-10-1-0515 and # N00014-08-1-1082. The survey was part of the development effort of the passive-acoustic Seaglider, which is currently being used for a marine mammal monitoring project funded by U.S. Pacific Fleet through contract N62470-10D-3011, task orders KB23 and KB25, with Naval Facilities Engineering Command (NAVFAC) Pacific. The purpose of this field trial was primarily to test the general functionality of the passive acoustic monitoring (PAM) board and a new onboard acoustic data-storage system (Revision A). Funding provided by U.S. Pacific Fleet/NAVFAC enabled a thorough analysis of the previously collected data set, which is presented in this report. The results of this analysis will be used in an ongoing ONR effort, "Cetacean density estimation using slow-moving underwater vehicles," led by the University of St. Andrews, Scotland.

Results from the Seaglider survey showed that odontocete acoustic encounters were dominated by Pacific white-sided dolphins, which is consistent with acoustic results of previous studies in the region spanning the summer months (Oleson et al. 2009; Širović et al. 2011). Northern right whale dolphins (Lissodelphis borealis) were frequently detected

concurrently with Pacific white-sided dolphins (Lagenorhynchus obliquidens). Sperm whale (Physeter macrocephalus) clicks were recorded throughout the deployment, and six dives contained vocalizations of Risso’s dolphins (Grampus griseus). The only beaked whale detections were of Stejneger's beaked whales (Mesoplodon stejnegeri) during a single glider dive.

The results of the data analysis also revealed no baleen whale activity in the area at the time of the survey. This is also consistent with other passive acoustic efforts in the area; June/July is a time when very few baleen whale vocalizations are recorded off Washington (Oleson and Hildebrand 2012).

Throughout the glider trial, a scientific airgun survey took place in the study area (R/V Langseth, Lamont-Doherty Earth Observatory). It is therefore not surprising that airgun signals dominated the low-frequency band of the glider recordings. Furthermore, the high-energy airgun signals could have masked baleen whale vocalizations.

The QRS survey was engineering trial that focused on testing the proper functionality and robustness of the PAM system. Some technical issues, as described below, were expected during this phase of demonstration and validation. Identification of such problems during at-sea tests were a crucial part of the development effort.

The major lesson learned from the Washington coast field deployment in summer 2012 was that the data-storage system on the PAM electronics board needed to be modified for enhanced reliability. Therefore, Revision B of the PAM electronics board was developed, incorporating a switch from USB-based data storage to microSD cards. The change made the PAM storage-management system simpler and more reliable. Revision B is currently being used for the operational monitoring phase of the Seaglider PAM project.

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Executive Summary

A passive-acoustic glider survey was conducted in the Quinault Range Site (QRS) off the Washington coast between 11 June and 12 July 2012. This glider survey was conducted with funding from the U.S. Navy's Office of Naval Research (ONR); awards # N00014-10-1-0515 and # N00014-08-1-1082. The survey was part of the development effort of the passive-acoustic Seaglider, which is currently being used for a marine mammal monitoring project funded by U.S. Pacific Fleet through contract N62470-10D-3011, task orders KB23 and KB25, with Naval Facilities Engineering Command (NAVFAC) Pacific. The purpose of this field trial was primarily to test the general functionality of the passive acoustic monitoring (PAM) board and a new onboard acoustic data-storage system (Revision A). Funding provided by U.S. Pacific Fleet/NAVFAC enabled a thorough analysis of the previously collected data set, which is presented in this report. The results of this analysis will be used in an ongoing ONR effort, "Cetacean density estimation using slow-moving underwater vehicles," led by the University of St. Andrews, Scotland.

Results from the Seaglider survey showed that odontocete acoustic encounters were dominated by Pacific white-sided dolphins, which is consistent with acoustic results of previous studies in the region spanning the summer months (Oleson et al. 2009; Širović et al. 2011). Northern right whale dolphins (*Lissodelphis borealis*) were frequently detected concurrently with Pacific white-sided dolphins (*Lagenorhynchus obliquidens*). Sperm whale (*Physeter* macrocephalus) clicks were recorded throughout the deployment, and six dives contained vocalizations of Risso's dolphins (*Grampus griseus*). The only beaked whale detections were of Stejneger's beaked whales (*Mesoplodon stejnegeri*) during a single glider dive.

The results of the data analysis also revealed no baleen whale activity in the area at the time of the survey. This is also consistent with other passive acoustic efforts in the area; June/July is a time when very few baleen whale vocalizations are recorded off Washington (Oleson and Hildebrand 2012).

Throughout the glider trial, a scientific airgun survey took place in the study area (R/V *Langseth*, Lamont-Doherty Earth Observatory). It is therefore not surprising that airgun signals dominated the low-frequency band of the glider recordings. Furthermore, the high-energy airgun signals could have masked baleen whale vocalizations.

The QRS survey was engineering trial that focused on testing the proper functionality and robustness of the PAM system. Some technical issues, as described below, were expected during this phase of demonstration and validation. Identification of such problems during at-sea tests were a crucial part of the development effort.

The major lesson learned from the Washington coast field deployment in summer 2012 was that the data-storage system on the PAM electronics board needed to be modified for enhanced reliability. Therefore, Revision B of the PAM electronics board was developed, incorporating a switch from USB-based data storage to microSD cards. The change made the PAM storage-management system simpler and more reliable. Revision B is currently being used for the operational monitoring phase of the Seaglider PAM project.

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Acronyms and Abbreviations

APL-UW	Applied Physics Laboratory, University of Washington
FM	frequency-modulated
Hz	Hertz
ICI	inter-click-interval
kHz	kilohertz
km	kilometer(s)
LTSA	long-term spectral average
m	meter(s)
MB	megabyte(s)
μs	microsecond(s)
NAVFAC	Naval Facilities Engineering Command
ONR	Office of Naval Research
PAM	passive-acoustic monitoring
QRS	Quinault Range Site
SDHC	Secure Digital High Capacity
UTC	Coordinated Universal Time

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1. Background and Objectives

This glider survey was conducted in 2012 with funding from the U.S. Navy's Office of Naval Research (ONR); awards # N00014-10-1-0515 and # N00014-08-1-1082. The survey was part of the development effort of the passive-acoustic Seaglider, currently being used for a marine mammal monitoring project funded by U.S. Pacific Fleet through contract N62470-10D-3011 task orders KB23 and KB25 with Naval Facilities Engineering Command Pacific.

This survey tested the functionality of the passive acoustic monitoring (PAM) board and a new onboard acoustic data-storage system. Because this survey was predominantly an engineering test, the glider was flown in deep waters (>1,000 meters [m]) along the shelf break of the Washington coast. During the survey, the glider traversed the Quinault Range Site (QRS) on multiple occasions.

After recovery, the data were exclusively analyzed for beaked whales to comply with the goals of the original ONR project. Additional funding by U.S. Pacific Fleet enabled a thorough analysis of the collected data set, which is presented in this report. The results of this analysis will be used in an ongoing ONR effort "Cetacean density estimation using slow-moving underwater vehicles," led by the University of St. Andrews, Scotland.

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2. Methods

2.1 General Glider Information

Underwater gliders use small changes in buoyancy to produce vertical motion, and wings to convert the vertical motion to horizontal movement, thereby propelling them forward with very low power consumption. This allows them to perform long-duration surveys autonomously (Rudnick et al. 2004). During a mission, a glider is piloted remotely, via Iridium™ satellite connection, from a control center onshore. This project used the Seaglider™, originally developed by Applied Physics Laboratory, University of Washington (APL-UW) (commercially available from Kongsberg Inc., Lynwood, Washington, USA), which is capable of repeatedly diving to 1,000-m depth and back at a typical horizontal speed of 25 centimeters per second (**Figure 1**). Dive durations are usually 4–6 hours for 1,000-m dives.

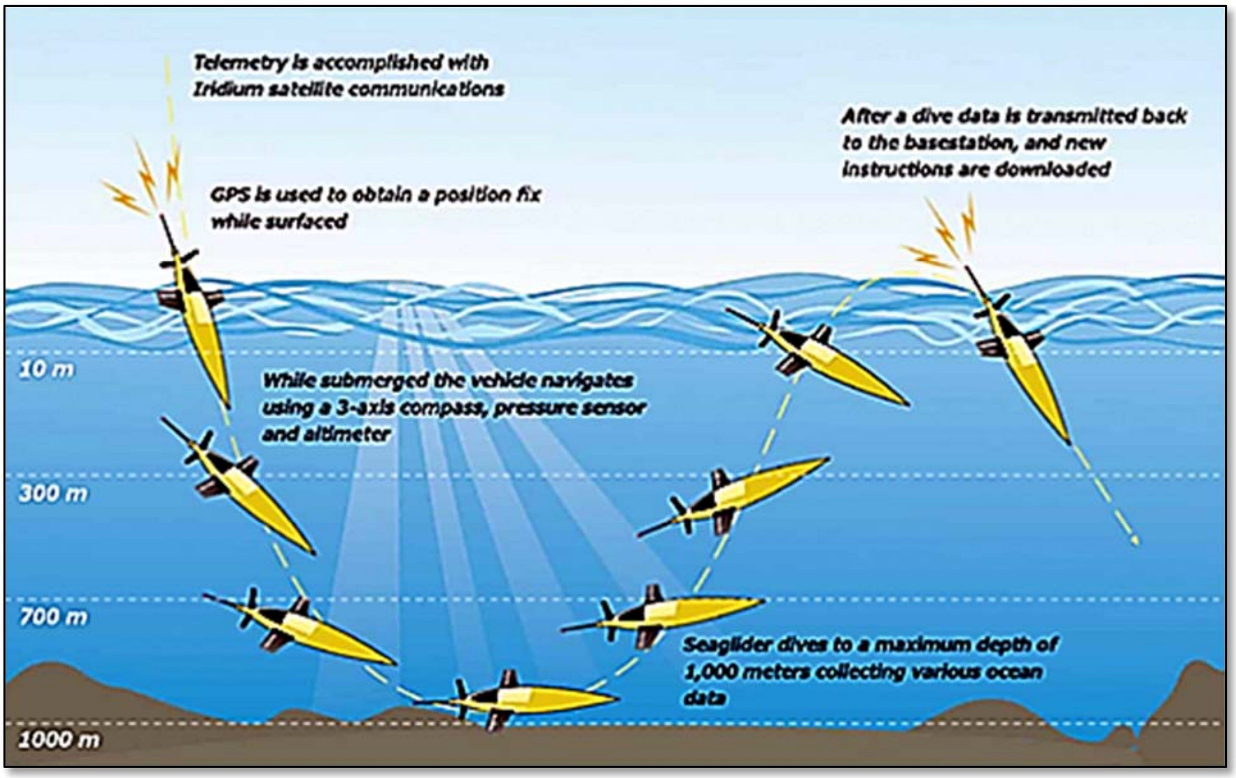

Figure 1: Mode of operation of the Seaglider™. Source: http://subseaworldnews.com.

The glider was equipped with a custom-designed and -built passive acoustic recording system (APL-UW, Seattle, Washington, USA; Rev. A board). Acoustic signals were received by a single omni-directional hydrophone (type: HTI-99-HF, High Tech Inc, Gulfport, Mississippi, USA; sensitivity: −164 dB re. 1 V/μPa), amplified by 36 decibels, and recorded at a 194-kilohertz (kHz) sample rate with 16-bit resolution. Acoustic data were compressed using the Free Lossless Audio Codec and stored on flash memory drives. The PAM system was optimized for continuously collecting data in the frequency range of 15 Hertz (Hz) to 90 kHz, and thus was well suited for the recording of both baleen and toothed whales. However, the bandwidth of the system did not cover the frequency range (>100 kHz) of vocalizations produced by pygmy and dwarf sperm whales (*Kogia* spp.) or harbor (*Phocoena phocoena*) and Dall's porpoise (*Phocoenoides dalli*).

The system featured an automatic 'blanking mechanism' that mutes the PAM system during periods when the glider's noisy internal steering and buoyancy mechanisms were operated. During a typical 1,000-m dive, the associated data loss was between 5 and 10 percent. Because of high noise levels at the surface, recordings were made only at depths of 25 to 1,000 m.

These gliders are typically programmed to survey across diverse bathymetric features and cetacean habitats whenever possible. The instruments carried on-board digital bathymetric maps used for deciding how deep to dive in areas where the water depths are shallower than 1,000 m. The glider's depth-choice algorithm was designed to operate best when the instrument's course is orthogonal to the isobaths. Use of this map-reading method avoided the need to use active acoustics for altimetry, which would have hindered passive-acoustic recordings. The gliders transmit selected data packages via Iridium satellite link, including position and standard conductivity, temperature, and depth profiles, to shore when surfacing between dives. The instruments typically stayed at the surface for less than 10 minutes.

In 2007, the ONR Marine Mammals and Biology program started the Passive Acoustic Autonomous Monitoring (PAAM) of Marine Mammals program to develop near-real-time monitoring systems on autonomous underwater vehicles. The program focused on passive acoustic systems for autonomous detection, classification, localization, and tracking of marine mammals on Navy exercise areas for periods in excess of a month. The passive-acoustic Seaglider used in this study is a result of this development effort. The system has been validated during several surveys, including week-long deployments at both Atlantic Undersea Test and Evaluation Center (AUTEC) and the Southern California Offshore Range (SCORE) (Klinck et al. 2013). The passive-acoustic Seaglider is currently funded by U.S. Pacific Fleet to be used for marine mammal monitoring efforts exceeding one month in duration on various ranges in the North Pacific (Klinck et al. 2015a, 2015b). The PAM boards (Revision A used for the QRS trial and Revision B used in subsequent long-duration deployments) have been classified as a Demonstration and Validation (6.4) system. The 6.4 system encompasses integrated technologies ready to be evaluated in as realistic an operating environment as possible. The PAM board is a U.S. export-controlled item, both under the Department of State's International Traffic in Arms Regulation and the Department of Commerce's Export Administration Regulation programs.

2.2 Glider Survey

Seaglider SG179 (**Figure 2**) was operated for engineering tests in the vicinity of and within the boundaries of the QRS between 11 June and 12 July 2012.

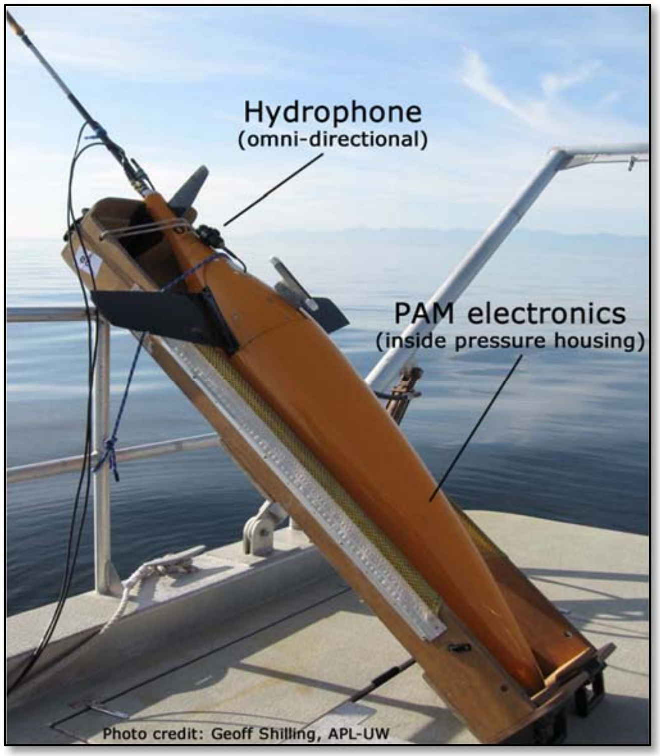

Figure 2: Passive-acoustic Seaglider. The Seaglider™ is a commercial off-the-shelf instrument sold by Kongsberg, Inc. (Lynwood, Washington, USA). The PAM system was developed and incorporated into the Seaglider by APL-UW (Seattle, Washington, USA).

The glider was deployed on 11 June 2012 at approximately 19:00 coordinated universal time (UTC) 59 kilometers (km) west of Westport, Washington (N46° 54.67', W124° 55.85'), and successfully recovered 11 km southeast of the deployment location (N46° 52.96', W124° 47.72') on 12 July 2012 at approximately 14:30 UTC.

Throughout the survey, various engineering tests were executed remotely:

- Turning the PAM system on/off
- Changing the amplification
- Changing the on/off depth
- Turning the detector on/off
- Changing detector settings
- Monitoring/evaluating power consumption of the PAM system
- Updating the firmware and control systems.

The sampling rate was not changed during the survey and remained fixed at 194 kHz.

2.3 Data Analysis

Because the dataset was only one week in total recorded duration, experienced analysts conducted the entire analysis manually. Detectors and classifiers were not used for the analysis. This approach, while more labor intensive, reduced the likelihood of missed marine mammal vocal encounters.

The Free Lossless Audio Codec files were decoded to standard waveform audio file format, and then low-pass filtered and decimated to produce three data sets with different sampling rates (194 kHz, 10 kHz, and 1 kHz) for specific analyses. Analysis was primarily done on a per dive basis, where vocalizations were summarized for each dive and the percentage of time during a dive when analysts detected marine mammal sounds for each species was calculated. Analysts also tallied marine mammal sounds on an encounter basis. An encounter was defined as a period when target signals were present in the acoustic data sets, separated from other periods of signal detections by 30 or more minutes of 'silence.' See **Appendix A** for encounter data summarized in tabular format.

2.3.1 Environmental Data

The glider collected conductivity/temperature/depth profiles as well as information on depth-averaged currents throughout the duration of the survey (including periods when the PAM system was deactivated). APL-UW processed the raw environmental data using custom software routines and provided temperature, sound speed, and depth-averaged current plots for this report.

2.3.2 Odontocetes

The full bandwidth data (194 kHz sampling rate) were used to calculate long-term spectral average (LTSA) plots with a temporal resolution (Δt) of 5 seconds and a frequency resolution (Δf) of 100 Hz using the Triton Software Package (Scripps Whale Acoustics Lab, La Jolla, California, USA). Data slices of 15 minutes in duration were visually and aurally inspected by experienced analysts for acoustic encounters with odontocetes. Species-specific acoustic encounters were expected to be from the following odontocete species: Stejneger's beaked whale (*Mesoplodon stejnegeri)*, Baird's beaked whale (*Berardius bairdii*), Cuvier's beaked whale (*Ziphius cavirostris*), Blainville's beaked whale (*Mesoplodon densirostris*), sperm whale (*Physeter macrocephalus*), killer whale (*Orcinus orca*), Risso's dolphin (*Grampus griseus*), Pacific white-sided dolphin (*Lagenhorynchus obliquidens),* and northern right whale dolphin (*Lissodelphis borealis*) (Calambokidis et al. 2004; Oleson et al. 2009; Širović et al. 2011).

Other odontocete species historically have been sighted visually or are thought to occur off the coast of Washington, and could produce vocalizations within the recording capabilities of the glider, but cannot acoustically be identified to the species level. These species could include false killer whale (*Pseudorca crassidens*), short-finned pilot whale (*Globiocephala macrorhynchus)*, short-beaked common dolphin (*Delphinus delphis*), bottlenose dolphin (*Tursiops truncatus)*, and striped dolphin (*Stenella coeruleoalba*) (Calambokidis et al. 2004; Oleson et al. 2009; Širović et al. 2012).

Vocalizations of odontocetes are typically placed into three categories: echolocation clicks, burst pulse sounds, and whistles. Echolocation clicks are broadband, impulsive sounds with peak frequencies from 5 to over 150 kHz. These signals aid in foraging and navigation. Burst-pulse signals are click trains, or rapidly repeated clicks with a very short inter-click interval (ICI), that sound like a buzz or creak. Burst-pulse signals are thought to have social implications. Whistles are frequency-modulated (FM) signals and cover (depending on species) a wide frequency range from a few hundred Hz to many kHz, have a longer duration (hundredths to tens of seconds) and are can be used in social contexts (Janik and Sayigh 2013). The analysts logged species information whenever possible. The first nine species listed above have species-specific call features that allow acoustic encounters to be identified to the species level.

- **Beaked whales:**
  - Stejneger's beaked whale clicks have the typical beaked whale FM upsweep and a peak frequency above 50 kHz, with a consistent ICI of 0.1 second, allowing them to be differentiated from other beaked whales (Baumann-Pickering et al. 2013).
  - Baird's beaked whale echolocation clicks have the lowest peak frequency of all documented beaked whales, with spectral peaks at 15, 30, and 50 kHz (Baumann-Pickering et al. 2013; Dawson et al. 1998).
  - Cuvier's beaked whale clicks are uniquely identified by an FM click with a peak frequency of 40 kHz and an ICI of over 300 milliseconds (Baumann-Pickering et al. 2013).
  - Echolocation clicks recorded from Blainville's beaked whales have the characteristic beaked whale FM pulse, a long click duration, and long ICI (Baumann-Pickering et al. 2013). Such upsweep clicks with peak frequencies near 35 kHz and ICIs of around 200 milliseconds were identified as Blainville's beaked whales.
  - Any clicks with the stereotypic long click duration, FM upsweep, and relatively long ICI (compared to other odontocetes), but with a recording quality too low to identify to the species level, were marked as possible beaked whales.
- **Sperm whale:** Regular echolocation clicks produced by sperm whales contain energy primarily from 2 to 20 kHz with peak energy from 10 to 15 kHz (Møhl et al. 2003). Clicks are observed during foraging dives and are characterized by a metronomic ICI of about one second (Møhl et al. 2003). Sperm whale click trains can be readily identified in the LTSA plots.
- **Killer whale:** Killer whale pulsed calls are the best described and well documented of their call types, and serve well to differentiate them from other species. Pulsed calls have energy between 1 and 6 kHz, with high-frequency components occasionally reaching over 30 kHz. Duration is typically 0.5 to 1.5 seconds (Ford 1987). Aural and visual detections of pulsed calls were used for killer whale encounter identification.
- **Risso's dolphin:** Risso's dolphin echolocation clicks have a unique band pattern observable in bouts of clicks on an LTSA. Peak energy bands are located at 22.4, 25.5, 30.5, and 38.8 kHz, with distinct notches at 27.7 and 35.9 kHz (Soldevilla et al. 2008). This peak and notch pattern is not as apparent when looking at individual clicks, but the LTSA (see **Results** section below) shows the characteristic appearance of many hundreds of clicks that was used to identify Risso's dolphins in this report.
- **Pacific white-sided dolphin:** Pacific white-sided dolphins also have a unique banding pattern easily measured in the LTSA of a click bout. They can be differentiated from Risso's dolphins because the spectral peaks are located at 22.2, 26.6, 33.7, and 37.3 kHz. Notches occur at 24.5 and 29.7 kHz (Soldevilla et al. 2008).

- **Northern right whale dolphin:** Northern right whale dolphins are known to make clicks and stereotyped burst pulses, but no whistles. Echolocation clicks have a peak frequency of 31.3 kHz. Burst pulses occur in stereotyped series of 6 to 18 pulses (Rankin et al. 2007). The burst pulses were used as the identifying feature for this analysis.

The remaining delphinid species that could occur in the area are currently not distinguishable to the species level reliably from only acoustic data, using spectral or temporal characteristics (Roch et al. 2011, 2007). Thus, recordings that could not be classified to species level, including recordings of echolocation clicks, burst pulses, and whistles, were grouped as unidentified delphinids, similar to Širović et al. (2012).

2.3.3 Mysticetes

The low- and mid-frequency data were used to calculate LTSA plots with a Δt of 1 second and Δf of 1 Hz (1-kHz data) and a Δt of 2 seconds and Δf of 10 Hz (10-kHz data) using the Triton Software Package. Both LTSAs were coarsely screened visually and aurally by analysts for bioacoustic activity and general quality assurance. The logging of low-frequency marine mammal acoustic encounters was done in Raven Pro v 1.5 (Bioacoustics Research Program, Cornell University, Ithaca, New York, USA). Both data sets were imported into Raven Pro, time aligned, and simultaneously screened for increased efficiency (**Figure 3**).

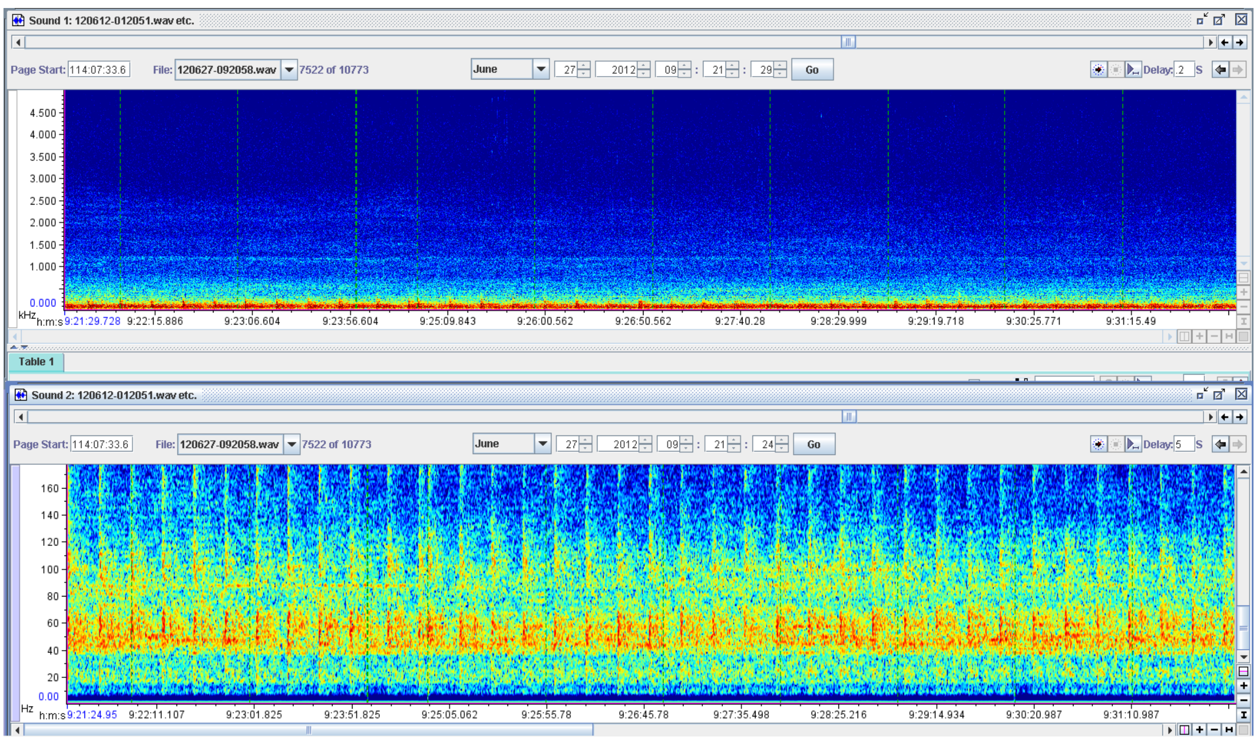

Figure 3: Example of time aligned spectra displayed in the software Raven Pro and showing seismic airgun signals. The upper spectrogram shows the 10-kHz down-sampled data and the lower spectrogram is the 1-kHz data.

The outer Washington coast study area provides habitat for numerous species of baleen whales that produce low-frequency vocalizations. Year-round acoustic monitoring (Širović et al. 2011) has confirmed the presence of blue whales (*Balaenoptera musculus*), fin whales (*B. physalus*), gray whales (*Eschritius robustus*), and humpback whales (*Megaptera novaeangliae*). In addition, minke whales (*B. acutorostrata*) have been identified in the area during visual surveys (Barlow and Forney 2007). Thus the glider recordings were also analyzed for the vocalizations of these species. The mid-frequency (10-kHz) data were analyzed for humpback whale song and social sounds (Payne and McVay 1971; Stimpert and Au 2008), and minke whale boings (Rankin and Barlow 2005), while the lower-frequency (1-kHz) data were examined for northeast Pacific blue whale A and B calls (Stafford et al. 1999, 2001), blue whale D calls (Oleson et al. 2007; Thompson, P., Findley, L., Cummings 1996), 20-Hz fin whale calls (Thompson et al. 1992; Watkins 1981), and low-frequency moans produced by gray whales (Crane and Lashkari 1996).

2.3.4 Seismic Airgun Sounds

An initial screening of the data revealed the sounds from seismic airguns in most days of the survey. These loud, broad-band sounds are created as air, pressurized within cylinders, is released suddenly into the water (Dragoset 2000; Parkes and Hatton 1986). Typically, the sounds associated with both commercial and research airguns occur repetitively every 10 to 20 seconds over a time span of days to weeks, with occasional interruptions for such actions as turning the ship that tows the airgun array. Time periods with airgun signals present were annotated using the Triton Software Package.

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3. Results

The glider conducted a total of 155 dives during the survey. The PAM system was active for only 56 of the dives, intermittently between 12 June and 02 July (**Figure 4**).

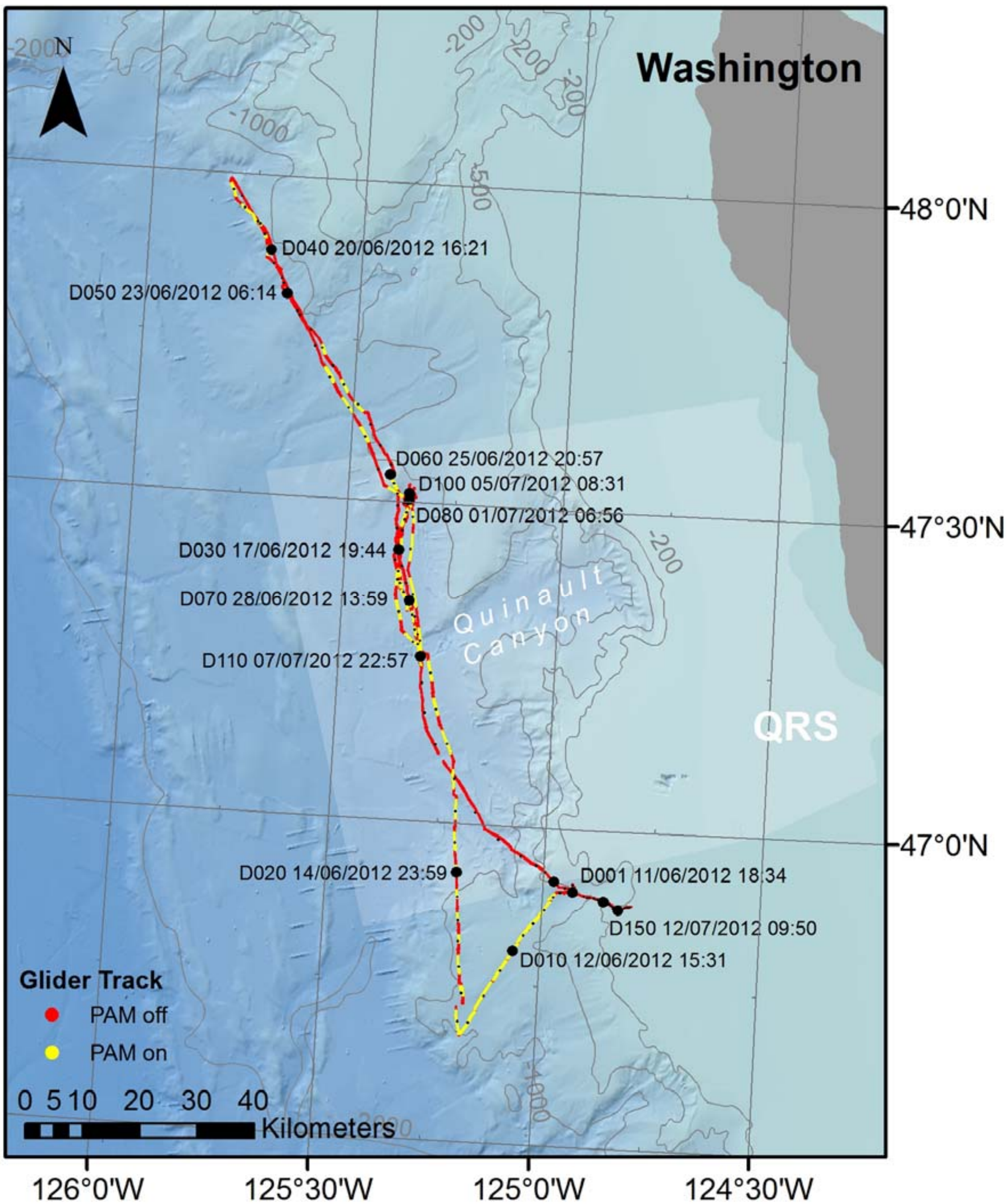

Figure 4: SG179 track line for the period 11 June and 12 July 2012. Each black dot on the track line indicates the midpoint location of a glider dive; every 10th dive is represented by a larger dot. Labels indicate dive number (e.g., D001 for dive no. 1) and date/time (format: dd/mm/yy hh:mm UTC). Red sections indicate that the PAM system was OFF. The yellow marks indicate that the PAM system was active.

The system recorded a total of 172 hours (approximately 7.2 days) of acoustic data, amounting to 212 gigabytes. An additional 87 megabytes of engineering/environmental data were collected.

3.1 Environmental Data

The results of the environmental data analysis are summarized in **Figures 5, 6, and 7**. The sea-surface temperature (**Figure 5**) varied little geographically and temporally and was around 12 degrees Celsius.

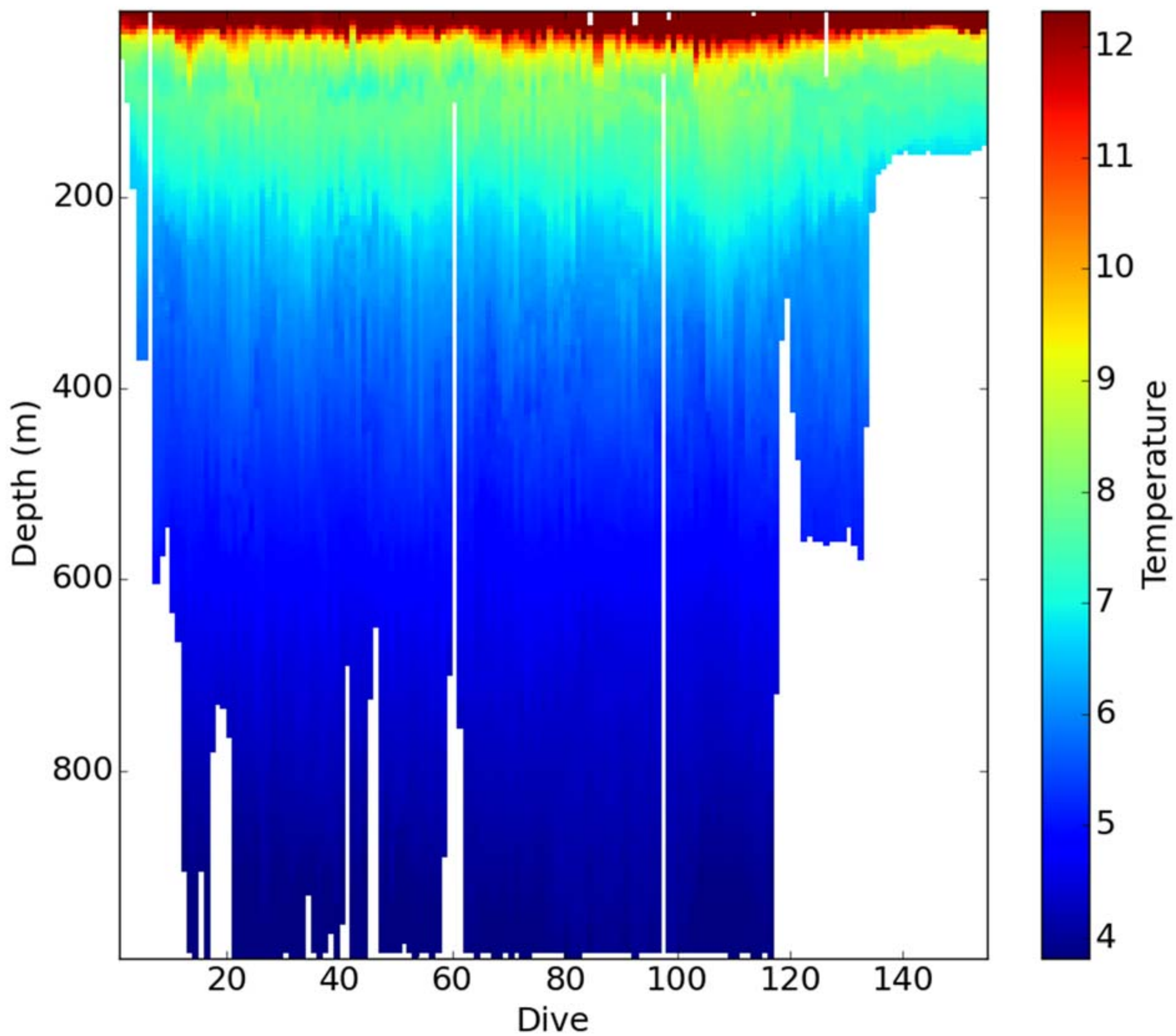

Figure 5: Temperature profiles recorded with SG179. White areas indicate no data, resulting from dives shallower than 1,000 m (e.g., bathymetry-limited dives).

The sound-speed profiles (**Figure 6**) showed that signal propagation conditions in the study area were complex. Throughout the survey, there was a local sound speed minimum present at approximately 75 m. A second sound-speed minimum, the axis of the sound fixing and ranging (SOFAR) channel, was located at approximately the 500-m depth.

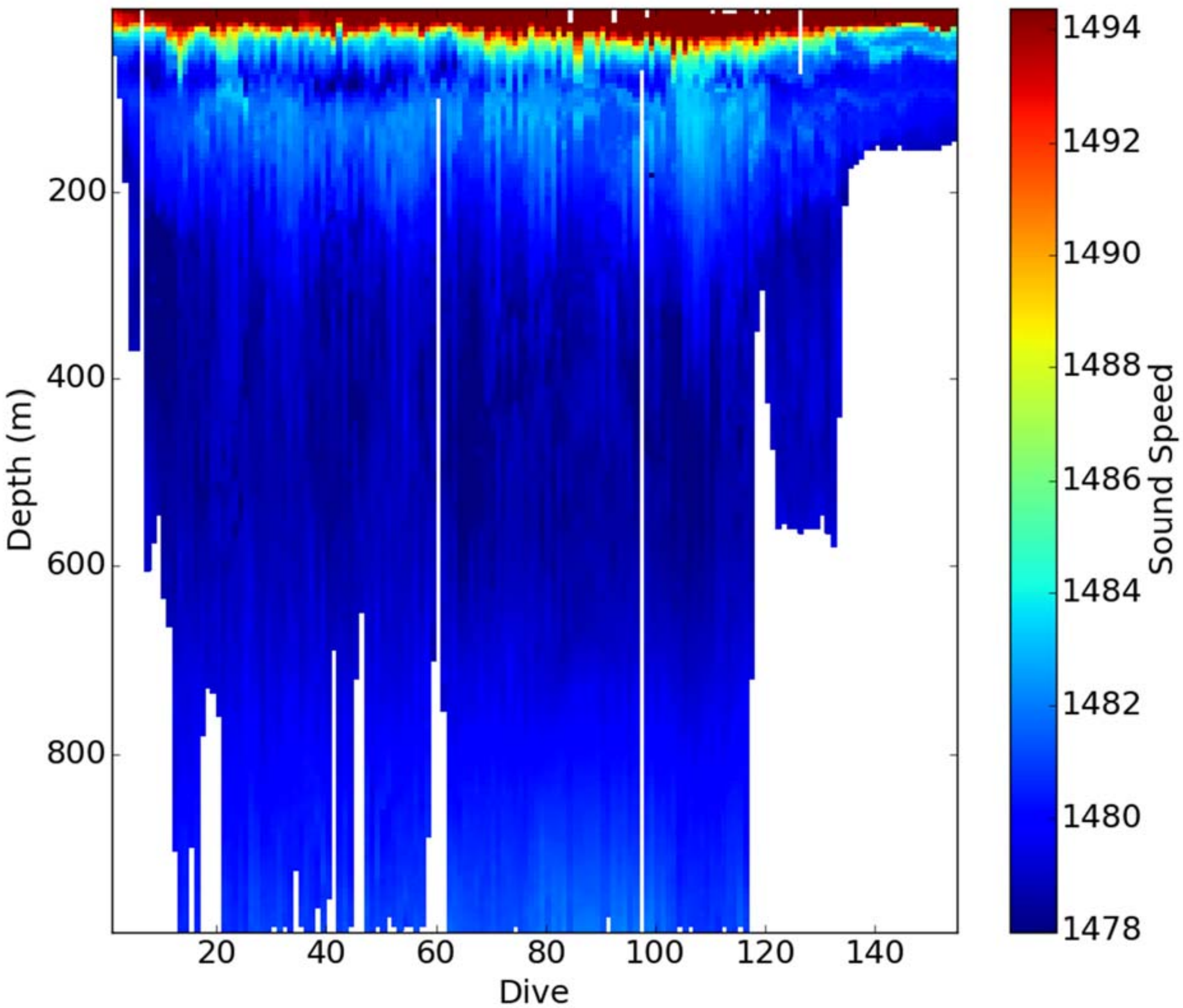

Figure 6: Sound-speed profiles [meters per second] recorded with SG179. White areas indicate no data, resulting from dives shallower than 1,000 m (e.g., bathymetry-limited dives).

SG179 reported a median depth-averaged current velocity of 8.3 centimeters per second. The direction of the current flow changed multiple times throughout the survey, which indicates complex oceanographic conditions within this region of the California Current System (**Figure 7**).

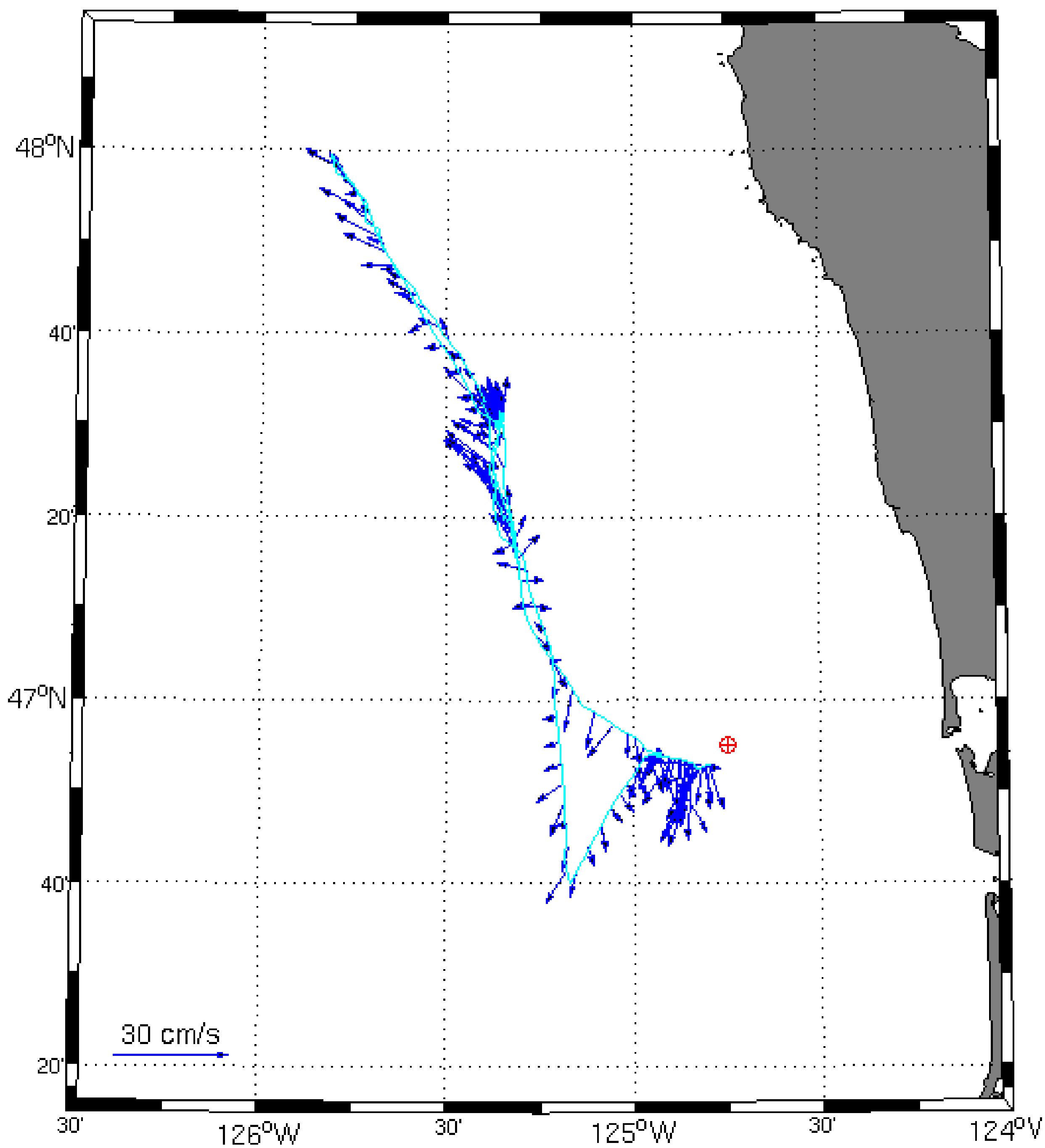

Figure 7: Depth-averaged currents measured with SG179.

3.2 Odontocetes

Beaked whales

Echolocation clicks from Stejneger's beaked whales (**Figure 8**) were the only beaked whale signals recorded during this deployment. The glider detected signals by this species during dive 56 on 24 June 2012 for 4 minutes in duration. The clicks were detected outside the boundary of QRS (**Figure 9**).

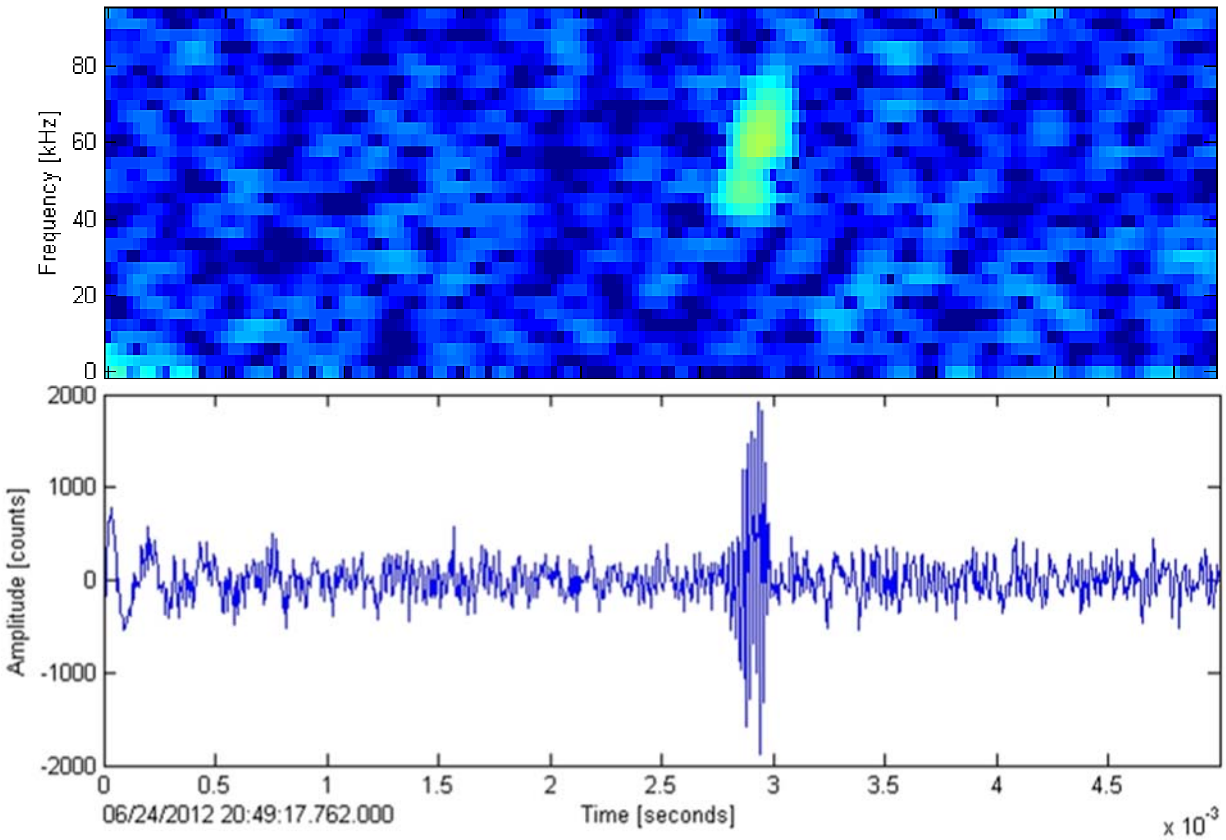

Figure 8: Stejneger's beaked whale echolocation click recorded with SG179 on 24 June 2012. The upper panel shows the characteristic upsweep signal with a center frequency of approximately 60 kHz. The corresponding waveform is shown in the lower panel.

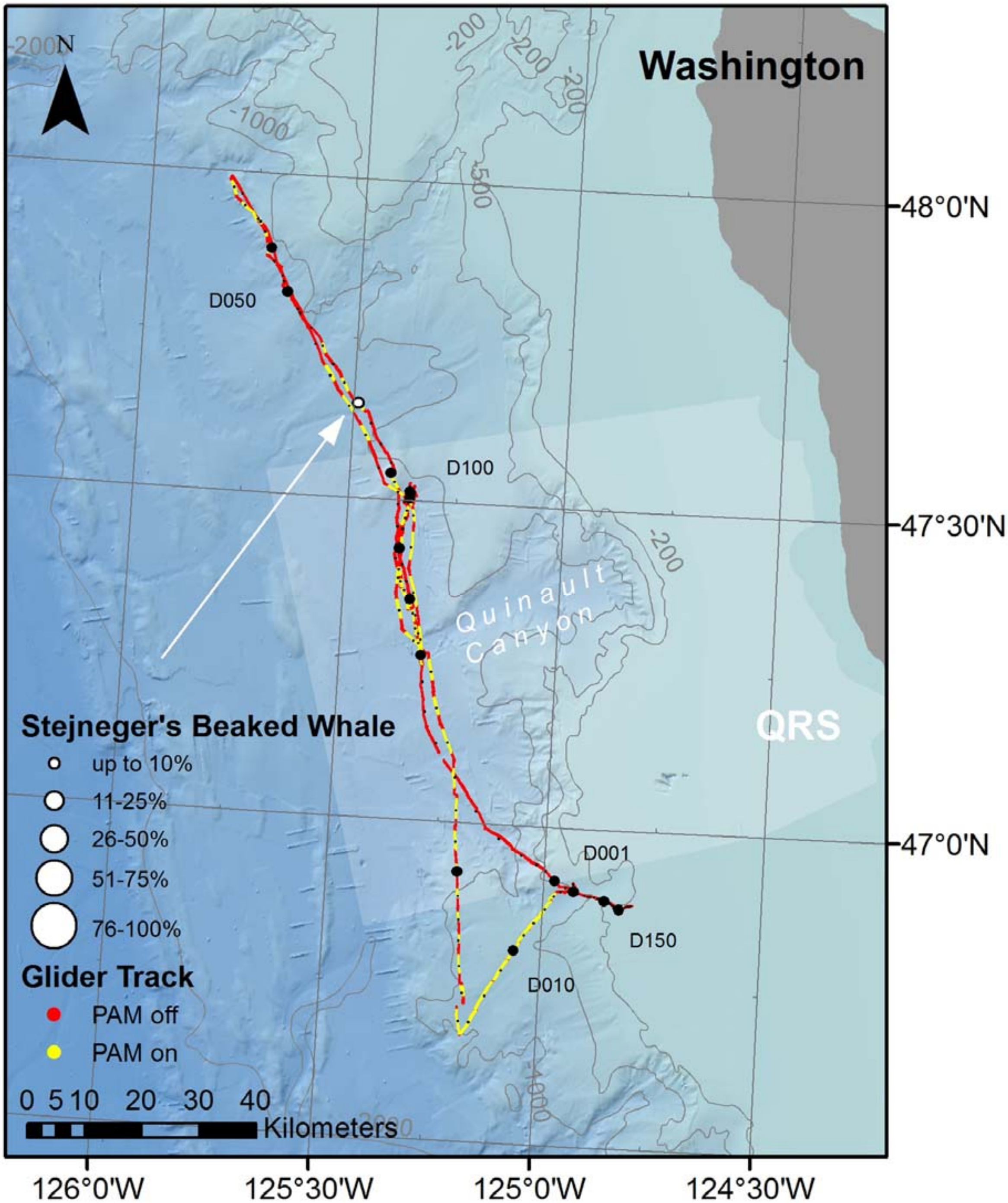

Figure 9: White arrow points to single SG179 Stejneger's beaked whale encounter. The circle size indicates the percentage of recording time per dive with target signals.

Sperm whales

Sperm whale clicks (**Figure 10**) were recorded throughout the survey during 18 dives between 12 June 2012 and 01 July 2012. Detection events were primarily located in the vicinity of the Quinault Canyon (on the QRS; **Figure 11**). No detections occurred on the northernmost part of the glider track (north of 47.5°N).

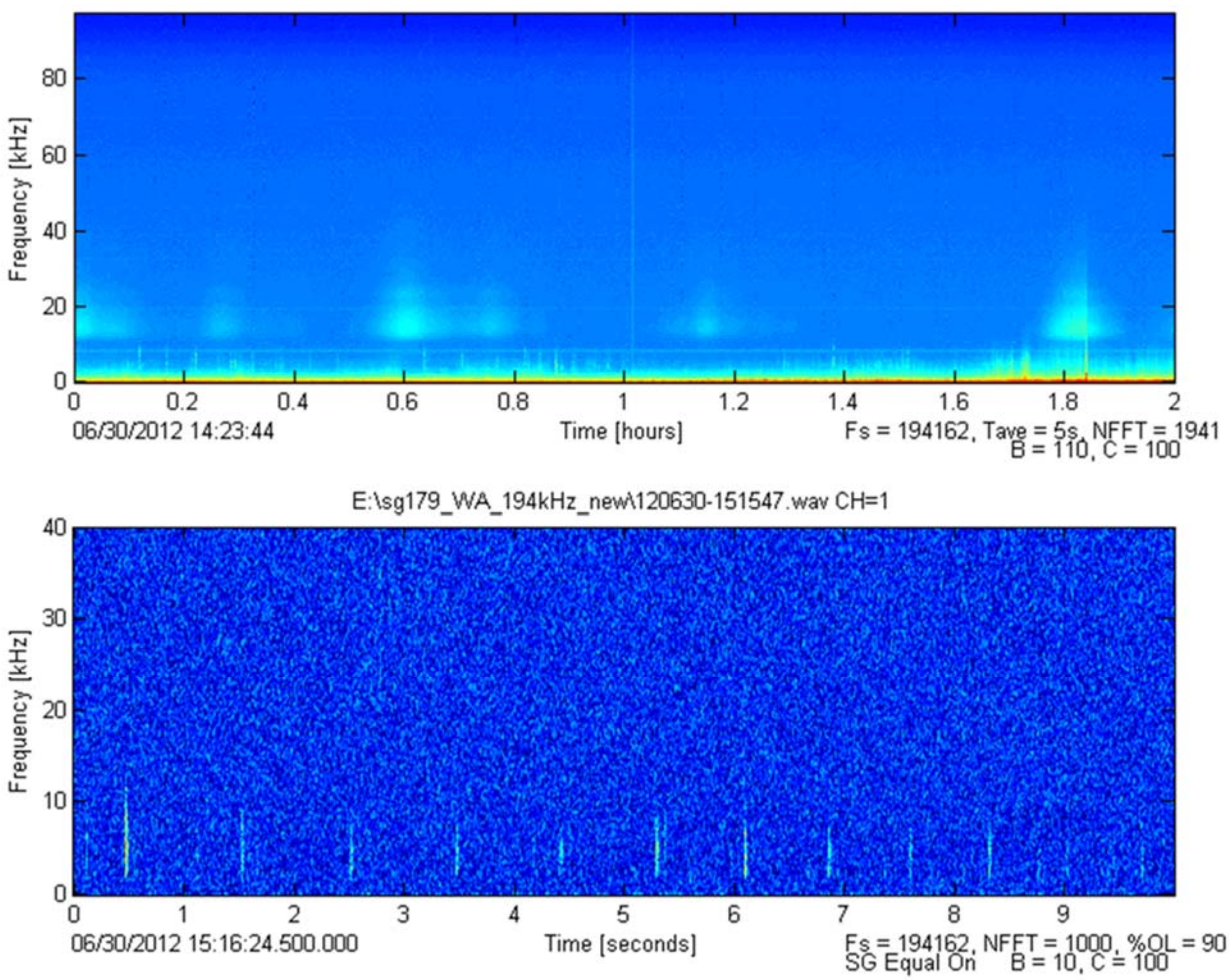

Figure 10: Sperm whale vocalizations recorded with SG179 on 30 June 2012.

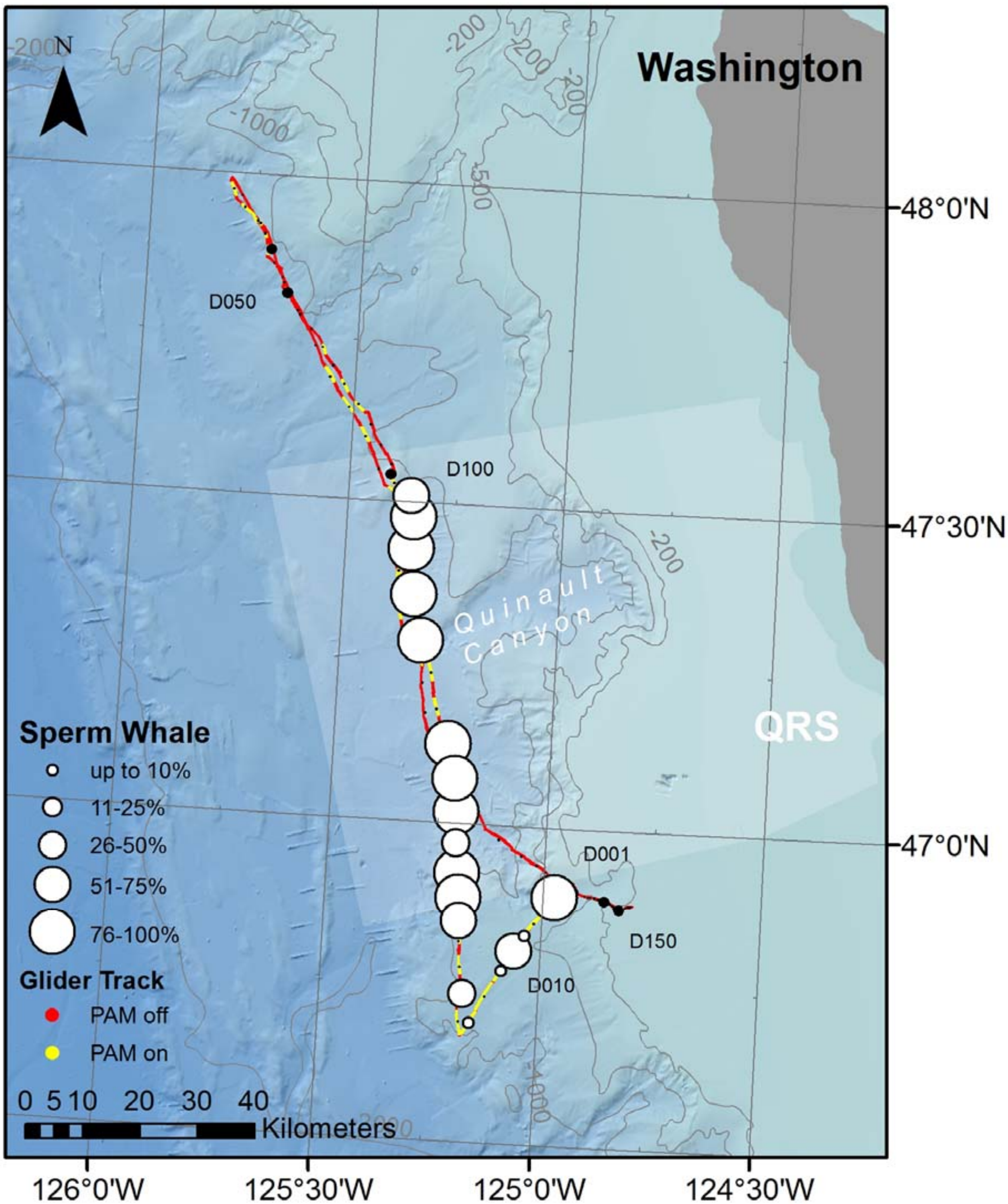

Figure 11: SG179 sperm whale encounters. The circle size indicates the percentage of recording time per dive with target signals.

Killer whales

No killer whale vocalizations were detected during this deployment.

Risso's dolphins

Risso's dolphin echolocation clicks (**Figure 12**) were detected on six dives (**Figure 13**). On two of these, the clicks overlapped with Pacific white-sided dolphin calls; however, they were easily distinguished by the different "banding pattern" of the clicks in the LTSA (peaks at ~22, 25, 30, and 38 kHz, notches at 24, 27, and 36 kHz; Soldevilla et al. 2008).

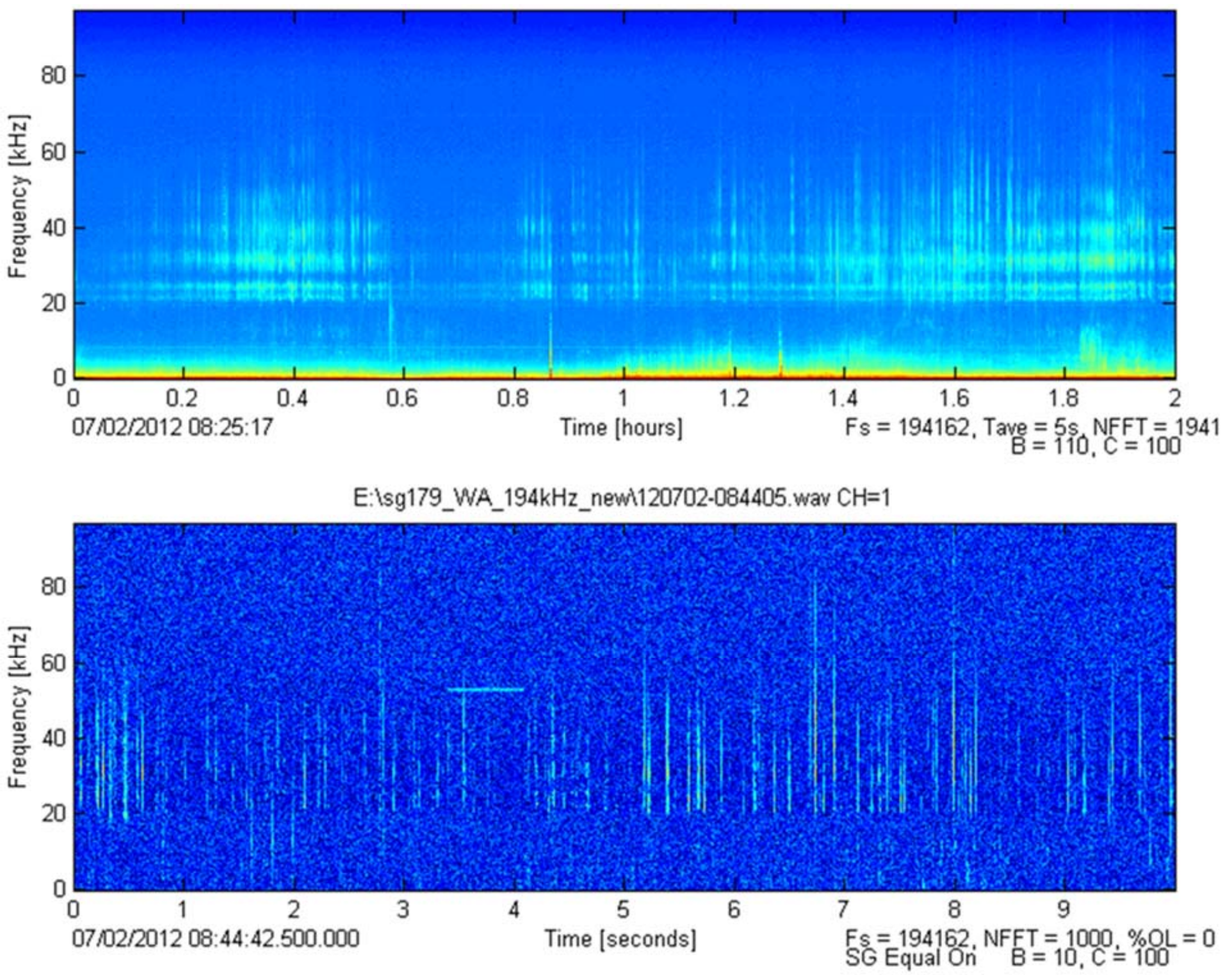

Figure 12: Risso's dolphin vocalizations recorded with SG179 on 02 July 2012. The ~55 kHz tonal sound starting at 3.3 s is electronics noise by the glider.

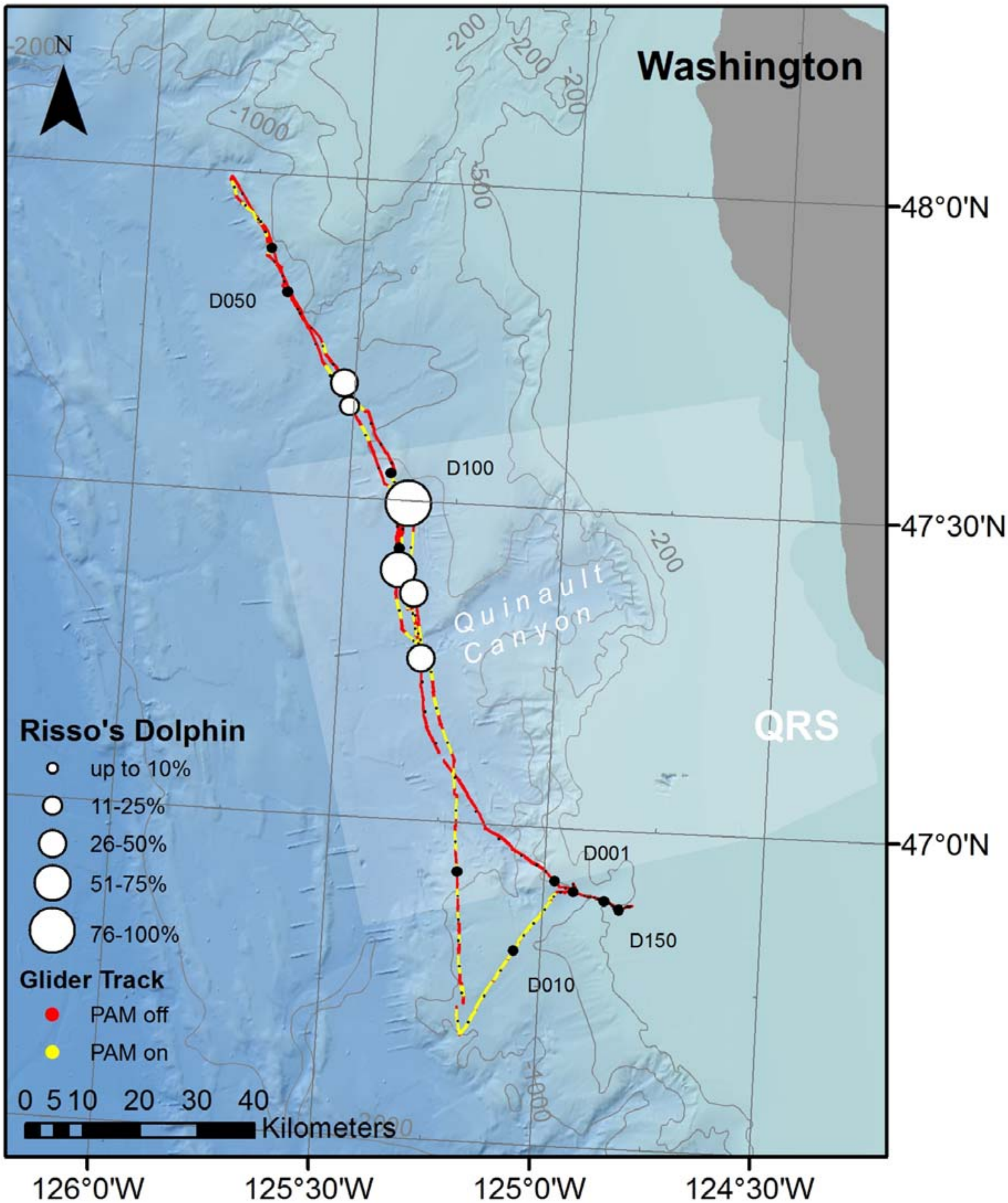

Figure 13: SG179 Risso's dolphin encounters. The circle size indicates the percentage of recording time per dive with target signals.

Pacific white-sided dolphins

Pacific white-sided dolphins were the most commonly detected species, with recordings of echolocation clicks (**Figure 14**) made during 38 dives between 12 June and 01 July 2012. Detections occurred in all regions of the survey area (**Figure 15**), with longer duration recordings in the northern part of the track. Pacific white-sided dolphin clicks often overlapped with broad-band burst pulse sounds produced by northern right whale dolphins (see below).

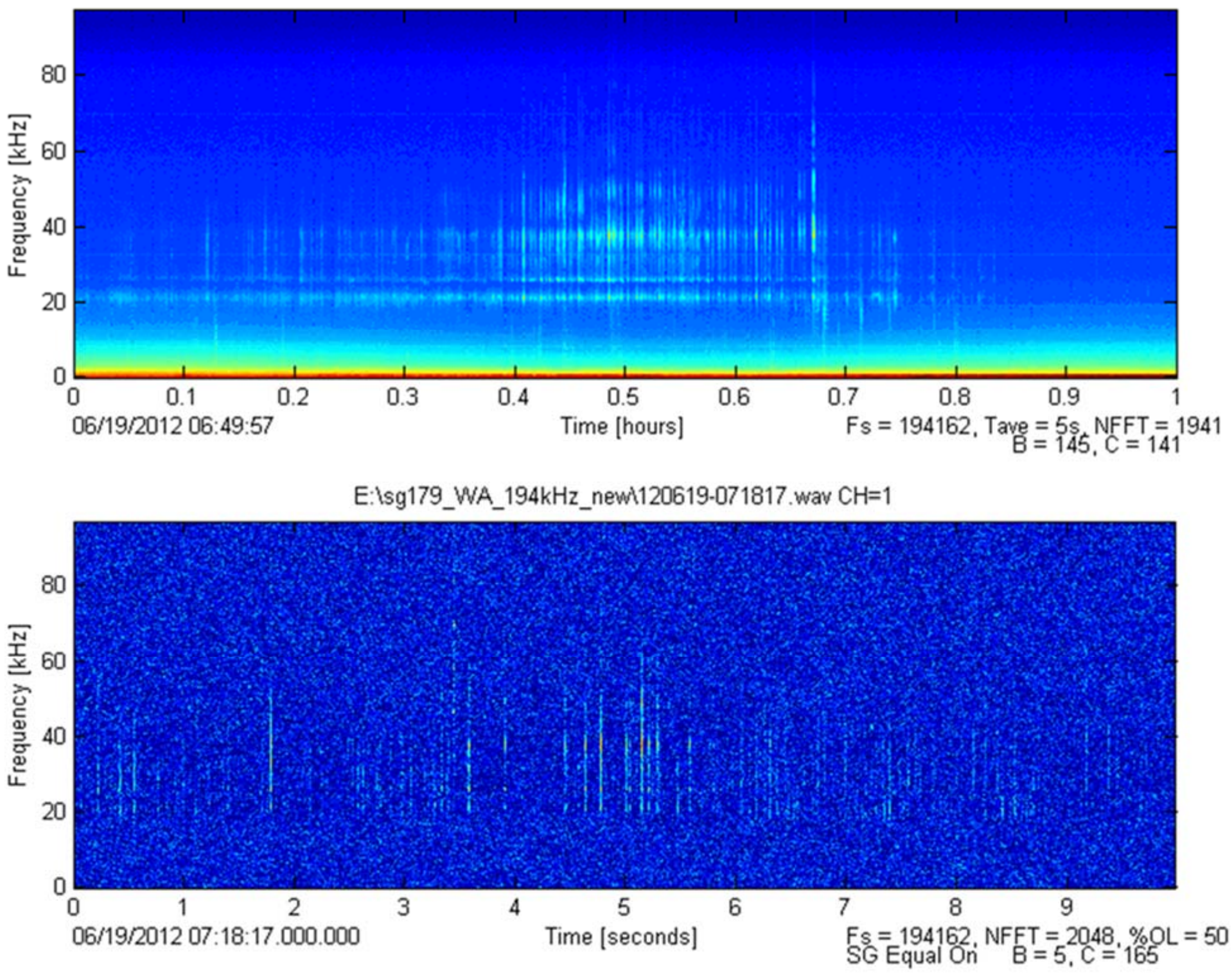

Figure 14: Pacific white-sided dolphin vocalizations recorded with SG179 on 19 June 2012.

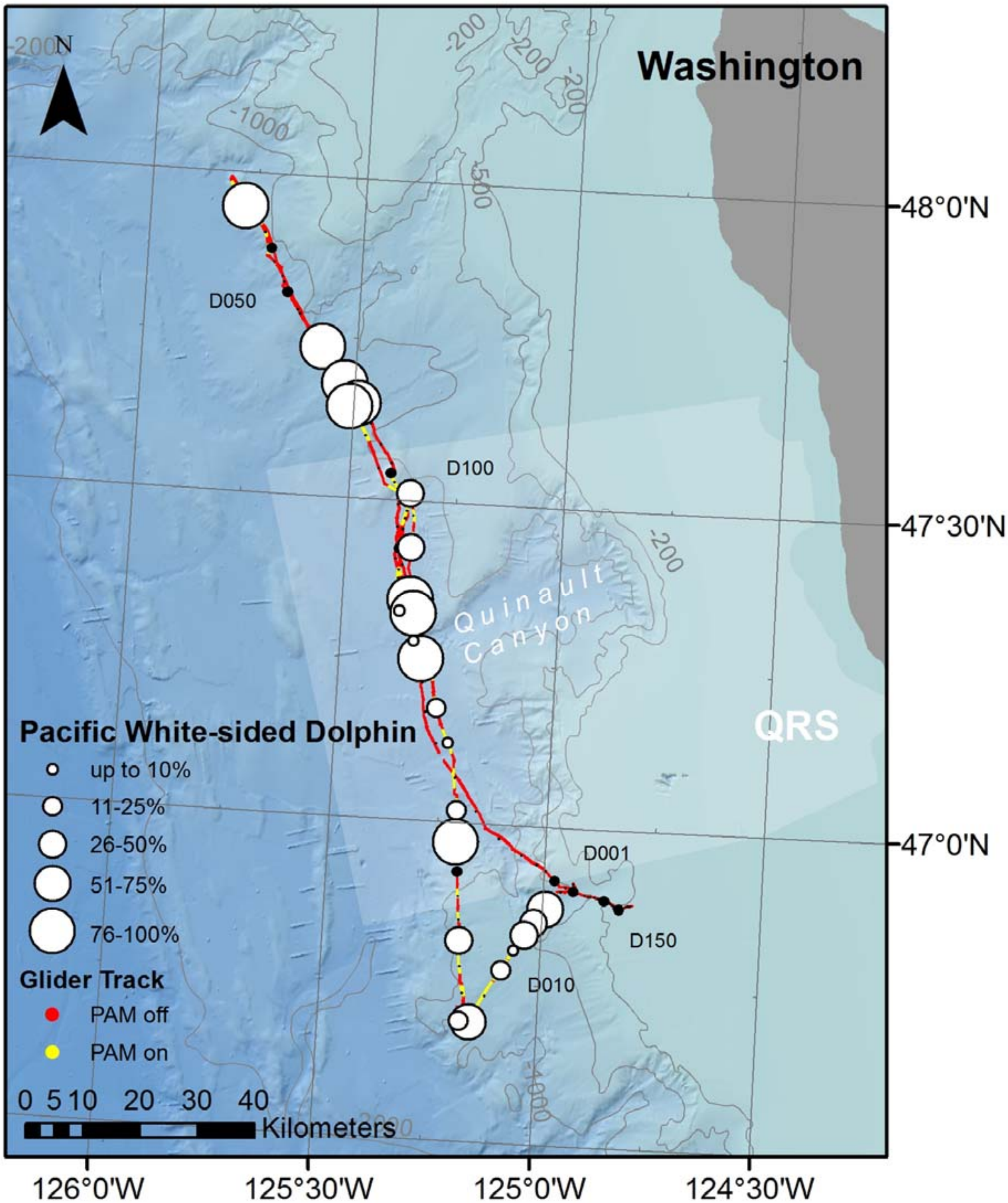

Figure 15: SG179 Pacific white-sided dolphin encounters. The circle size indicates the percentage of recording time per dive with target signals.

Northern right whale dolphins

Burst-pulse vocalizations from northern right whale dolphins (**Figure 16**) were recorded during 26 dives between 12 and 30 June 2012. Eight of the detected events partially overlapped with Pacific white-sided dolphin vocalizations. Detections were widely distributed throughout the study site (**Figure 17**).

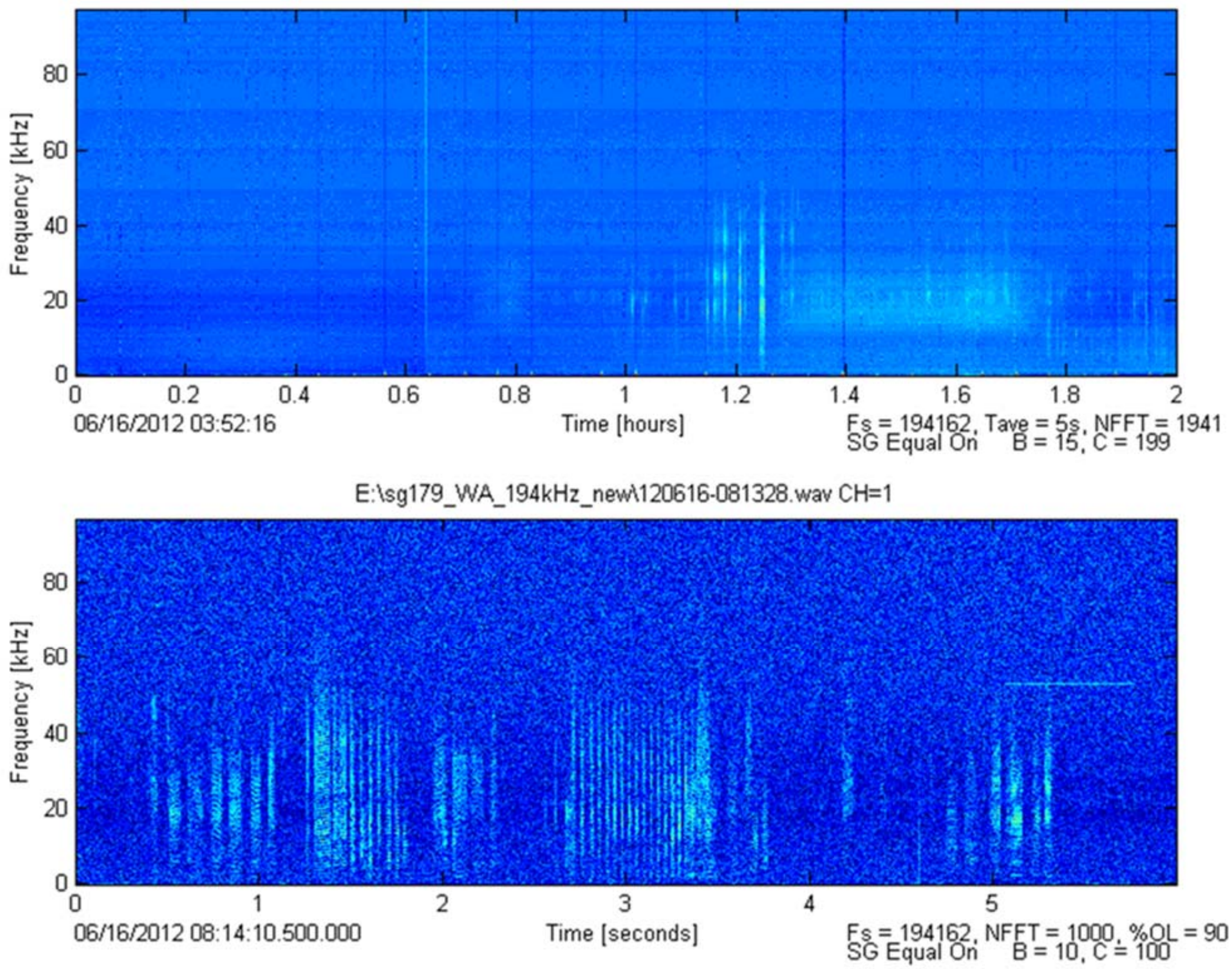

Figure 16: Northern right whale dolphin vocalizations recorded with SG179 on 16 June 2012.

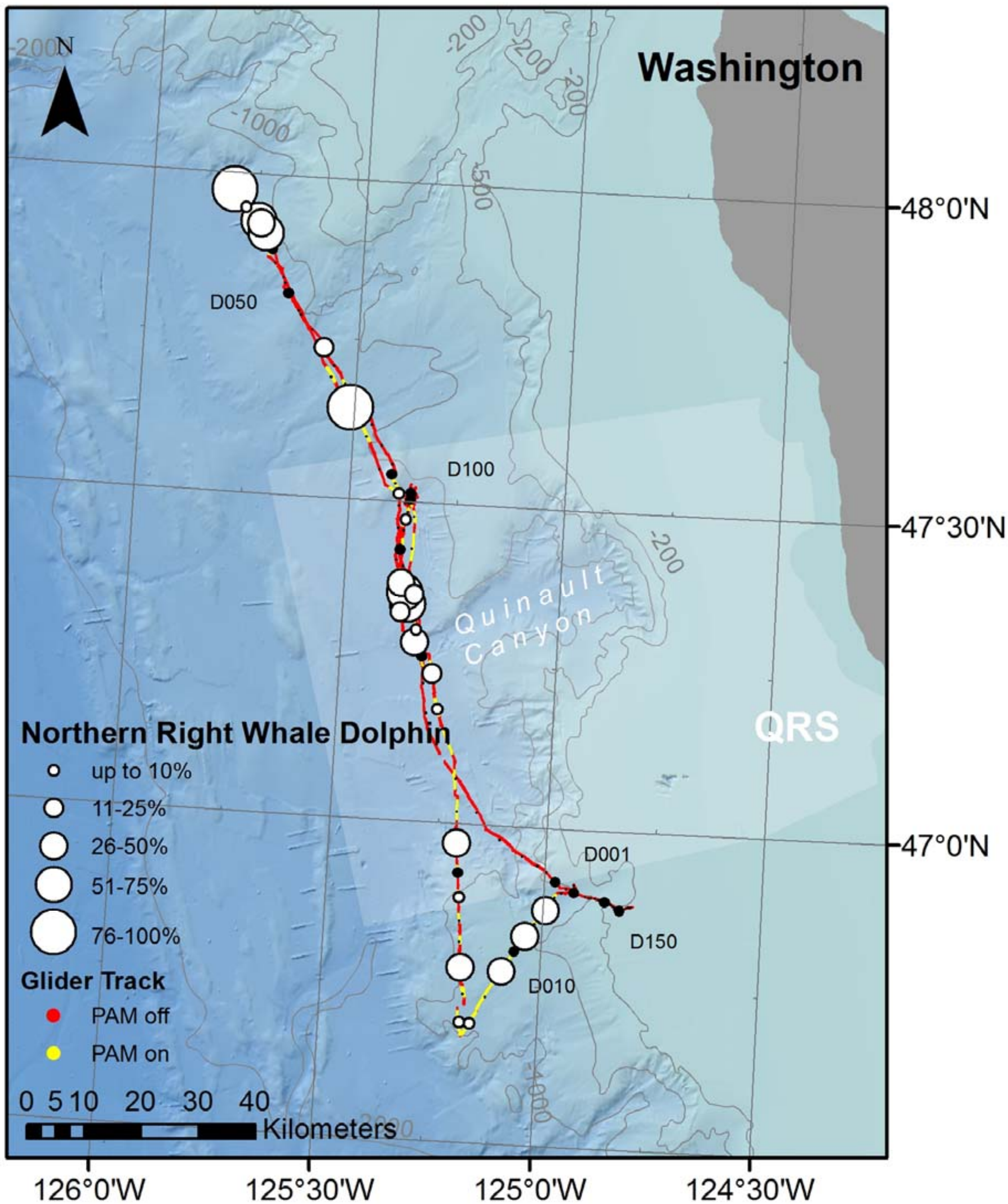

Figure 17: SG179 Northern right whale dolphin encounters. The circle size indicates the percentage of recording time per dive with target signals.

Unidentified delphinids

On three dives, recordings were made of unidentified delphinids (**Figure 18**). The recorded clicks (no whistles) did not feature acoustic characteristics that would have allowed a species identification. All three encounters occurred on the QRS (**Figure 19**).

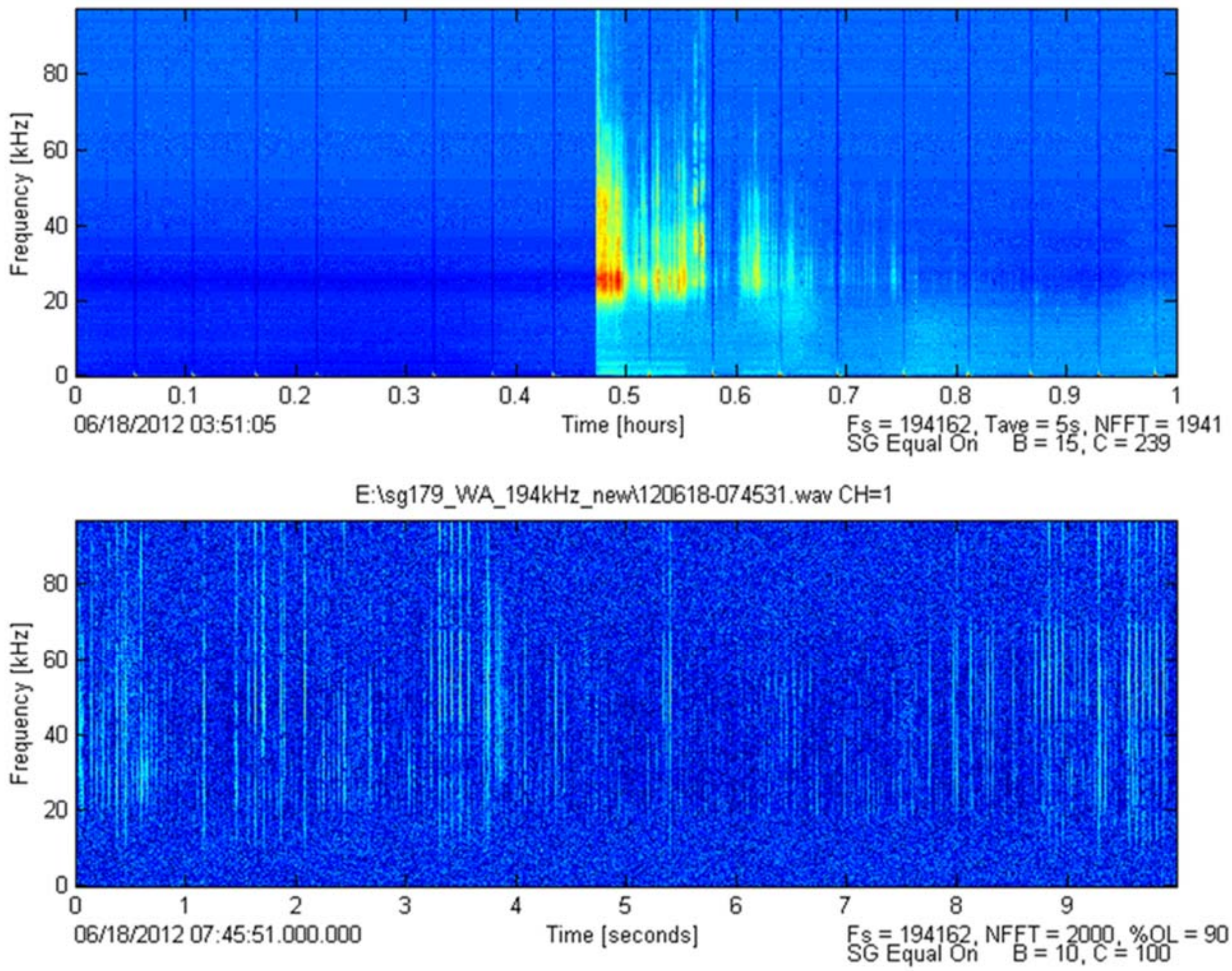

Figure 18: Unidentified delphinid vocalizations recorded with SG179 on 18 June 2012.

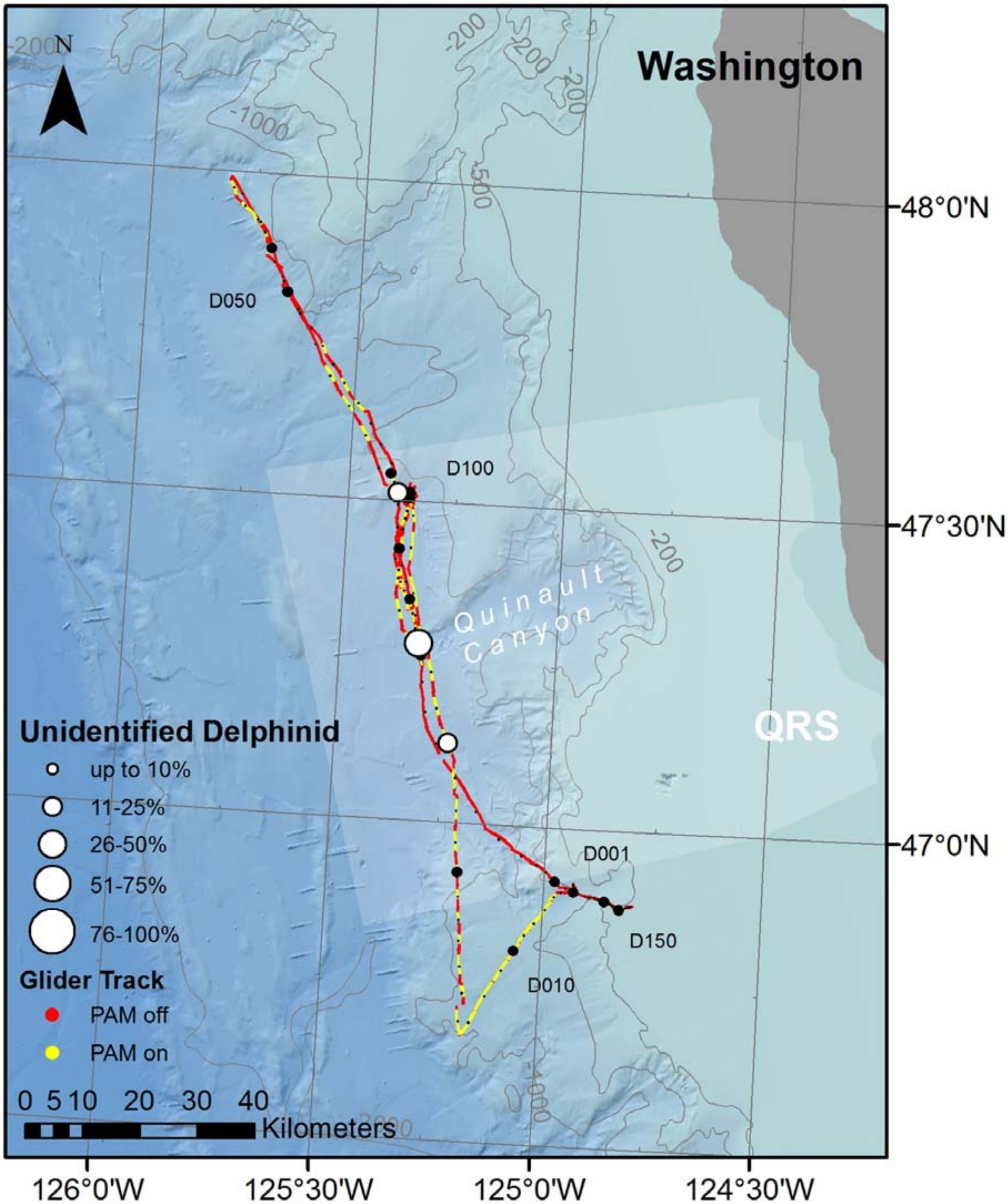

Figure 19: SG179 unidentified delphinid encounters. The circle size indicates the percentage of recording time per dive with target signals.

3.3 Mysticetes

No mysticete vocalizations were recorded during this survey.

3.4 Seismic Airgun Sounds

Seismic airgun sounds (**Figure 20**) were recorded during 52 dives between 12 June and 01 July 2012. As is typical for seismic surveys, these sounds occurred for hours at a time with brief interruptions (**Figure 21**). The time between airgun shots varied between 12 and 20 seconds.

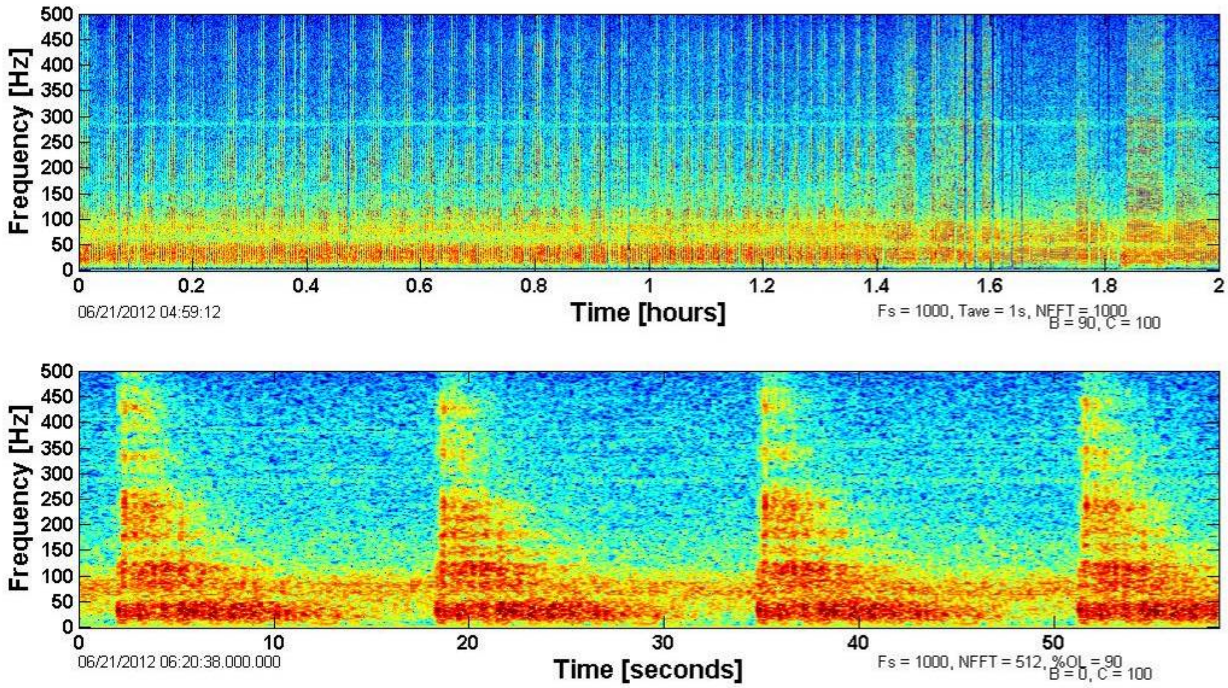

Figure 20. Airgun signals recorded with SG179 on 21 June 2012.

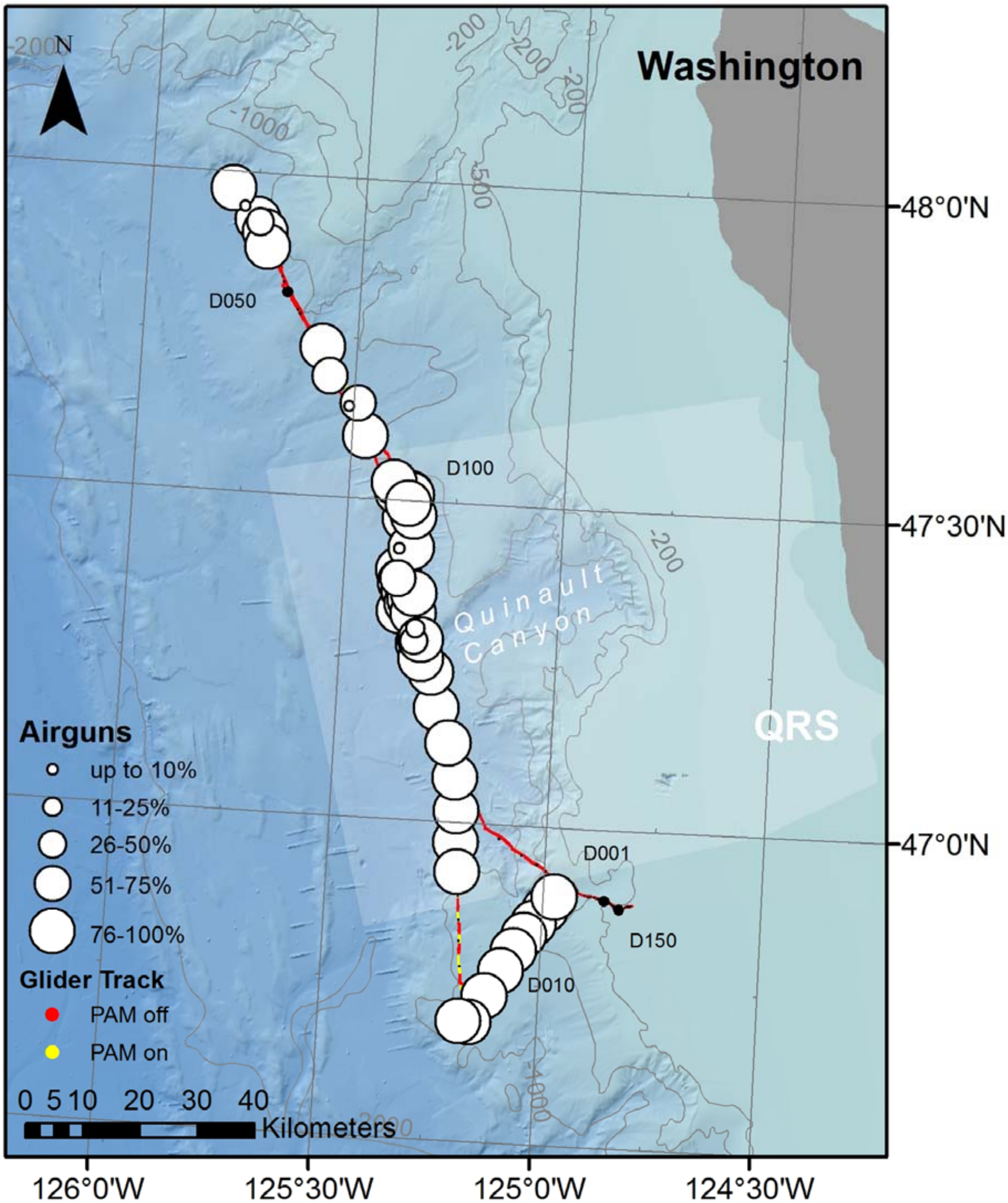

Figure 21: SG179 airgun encounters. The circle size indicates the percentage of recording time per dive with target signals.

4. Discussion

Glider Performance

The Seaglider worked well as an underwater vehicle and was able to navigate successfully on its programmed track. The vehicle did not experience any flight problems. Unfortunately, the glider only collected a limited amount of acoustic data.

During the survey SG179 experienced problems with its data-management system. The PAM electronics are controlled by a single-board ARM-9 computer running Linux. The system was configured to run with one microSD card as the system disk and another microSD card as the primary data disk. Two additional USB sticks were added to the system to increase the data-storage capacity. The idea was to initially record onto the primary data disk and then, at a later stage in the survey, transfer it over to the USB sticks. About 1 week into the mission, the system began to have trouble mounting the USB sticks. It often became stuck in a cycle of repeatedly trying to check the integrity of the file system on the USB stick. This effectively blocked use of that USB sticks until the pilot held the Seaglider at the surface and manually managed the process. There were dives where the PAM system was powered on, but spent its entire time trying to check the integrity of its various file systems, and was unable to record any data.

Environmental Data

An additional benefit of using gliders for marine mammal surveys is the collection of environmental data. The measured depth-averaged currents indicated that the glider can be safely operated in the vicinity of the QRS. The current information as well as the temperature profiles are useful for additional future analysis efforts on occurrence patterns of cetacean species in the study area. The in-situ measured sound-speed profiles can be used to describe the sound propagation conditions in the study area in detail. These data will be used in an ongoing project funded by ONR to develop and evaluate a framework for density estimation of cetacean species using slow-moving underwater vehicles including gliders and floats.

The Seaglider can be equipped with a suite of additional environmental sensors. For example, active acoustic sensors would provide information on prey fields, which would be helpful for more comprehensive ecosystem studies (e.g., how the occurrence of cetaceans relates to the availability of prey and oceanographic conditions).

Odontocetes

Pacific white-sided dolphins were the most commonly recorded species off the Washington coast in June and July 2012. This matches results of previous studies in the region during the summer (Oleson et al. 2009; Širović et al. 2011). The glider documented the occurrence of mixed (acoustic) odontocete encounters on numerous occasions. Mixed-species groups of odontocetes are not uncommon for the reported species (Black 1994; Rankin et al. 2007). Risso’s dolphins, Pacific white-sided dolphins, and northern right whale dolphins were detected concurrently, with Pacific white-sided and northern right whale dolphins acoustically overlapping the most (eight encounters). There was a single detection of a Stejneger’s beaked whales, exhibiting the ability of gliders to monitor beaked whales in this region.

Mysticetes

As stated earlier, there were no mysticete sounds recorded by the glider during this survey. This agrees with other passive acoustic surveys in the area; June/July is a time when very few baleen whale vocalizations are recorded off Washington (Oleson and Hildebrand 2012). In addition, the low-frequency band was dominated by seismic airgun signals (see **Figure 20**). It is therefore possible that mysticete calls were present but masked by the high energy airgun signals.

Seismic Airgun Sounds

Seismic airgun sounds were a prominent feature of the low-frequency acoustic dataset. During the glider survey, scientists from Lamont-Doherty Earth Observatory ran a scientific seismic survey with the *R/V Langseth* (cruise #1211, 13 June to 8 July 2012) in the study area[1]. The purpose of the survey was to collect “active source seismic data (Multi-Channel Seismic (MCS) and Ocean Bottom Seismometer (OBS) data) along 3 transects of the Juan de Fuca plate: [1] offshore Washington state to the Endeavour Ridge, [2] offshore Oregon to Axial Volcano, and [3] along the Cascadia trench ~100 km offshore.” Unfortunately, the PAM system was not calibrated and received levels of airgun signals could not be provided.

4.1 Conclusions

This QRS survey was part of the original ONR-funded (awards # N00014-10-1-0515 and # N00014-08-1-1082) development effort of the passive-acoustic Seaglider. This sea-trial was the initial step for demonstration and validation of the technology. Even though this was primarily an engineering test, the glider collected valuable acoustic data to document the presence of cetaceans in this area of QRS. The results of this data analysis (funded by the U.S. Pacific Fleet) will be especially useful for the ongoing ONR effort “Cetacean density estimation using slow-moving underwater vehicles,” led by the University of St. Andrews, Scotland.

The QRS trial focused on testing the proper functionality and robustness of the PAM system. Some technical issues as described below were expected. Identification of such problems during at-sea tests were a crucial part of the development effort funded by ONR.

A lesson learned from the Washington coast field deployment in summer 2012 was that the PAM electronics board storage management system needed to be modified for enhanced reliability. Therefore, Revision B of the PAM electronics board was developed - switching from USB-based data storage to high-capacity microSD cards. The move made the PAM data-storage/management system simpler and more reliable, as the cards only need to be mounted once, written until full, and then unmounted. Eight microSD cards are available for data storage on the Revision B PAM electronics boards. Current microSD maximum capacity is 128 GB, approximately 1 TB of total storage. Revision B of the PAM electronics board is currently being used for the operational monitoring phase of the Seaglider PAM project.

This survey exemplified how crucial long-duration field tests are to thoroughly evaluate the performance of newly developed ocean-going instruments and to identify potential issues with their operations.

[1] http://www.ldeo.columbia.edu/research/blogs/cascadia-in-motion

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A

Details of All Acoustic Encounters Recorded by Glider SG179

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A.1 ODONTOCETES

Beaked whale encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	56	24/06/2012 20:46:00	24/06/2012 20:50:00	Ms	47.6484	-125.4900

*Ms = Stejneger's beaked whale

Sperm whale encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	6	12/06/2012 01:20:00	12/06/2012 03:50:00	Pm	46.8919	-124.9742
2	7	12/06/2012 04:49:00	12/06/2012 04:49:00	Pm	46.8718	-124.9929
3	9	12/06/2012 12:52:00	12/06/2012 13:00:00	Pm	46.8288	-125.0384
4	10	12/06/2012 14:04:00	12/06/2012 14:07:00	Pm	46.8038	-125.0601
5	10	12/06/2012 14:42:00	12/06/2012 16:30:00	Pm	46.8038	-125.0601
6	11	12/06/2012 17:43:00	12/06/2012 18:00:00	Pm	46.7713	-125.0874
7	13	13/06/2012 04:34:00	13/06/2012 04:38:00	Pm	46.6878	-125.1546
8	15	13/06/2012 20:50:00	13/06/2012 21:33:00	Pm	46.7337	-125.1731
9	18	14/06/2012 13:30:00	14/06/2012 14:40:00	Pm	46.8480	-125.1890
10	19	14/06/2012 18:08:00	14/06/2012 19:47:00	Pm	46.8846	-125.1937
11	20	14/06/2012 23:07:00	15/06/2012 00:52:00	Pm	46.9230	-125.1995
12	21	15/06/2012 04:19:00	15/06/2012 06:00:00	Pm	46.9693	-125.2057
13	22	15/06/2012 11:10:00	15/06/2012 14:45:00	Pm	47.0189	-125.2090
14	23	15/06/2012 18:00:00	15/06/2012 21:00:00	Pm	47.0705	-125.2163
15	24	16/06/2012 00:22:00	16/06/2012 04:21:00	Pm	47.1244	-125.2365
16	69	28/06/2012 03:10:00	28/06/2012 04:30:00	Pm	47.3402	-125.3493
17	75	29/06/2012 22:23:00	30/06/2012 01:10:00	Pm	47.2831	-125.3130
18	76	30/06/2012 04:48:00	30/06/2012 08:37:00	Pm	47.3557	-125.3360

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
19	77	30/06/2012 11:23:00	30/06/2012 15:22:00	Pm	47.4265	-125.3472
20	78	30/06/2012 17:40:00	30/06/2012 19:57:00	Pm	47.4771	-125.3463
21	79	30/06/2012 23:01:00	01/07/2012 00:51:00	Pm	47.5092	-125.3543

*Pm = Sperm whale

Risso's dolphin encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	35	19/06/2012 05:30:00	19/06/2012 06:21:00	Gg	47.6427	-125.5101
2	55	24/06/2012 13:42:00	24/06/2012 14:40:00	Gg	47.6787	-125.5237
3	66	27/06/2012 07:30:00	27/06/2012 10:04:00	Gg	47.3906	-125.3734
4	74	29/06/2012 17:58:00	29/06/2012 19:02:00	Gg	47.2537	-125.3098
5	76	30/06/2012 04:44:00	30/06/2012 04:50:00	Gg	47.3557	-125.3360
6	76	30/06/2012 05:38:00	30/06/2012 06:55:00	Gg	47.3557	-125.3360
7	85	02/07/2012 08:25:00	02/07/2012 10:53:00	Gg	47.4965	-125.3606

*Gg = Risso's dolphin

Pacific white-sided dolphin encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	7	12/06/2012 05:11:00	12/06/2012 07:15:00	Lo	46.87181	-124.99289
2	8	12/06/2012 07:58:00	12/06/2012 08:57:00	Lo	46.84898	-125.01752
3	9	12/06/2012 11:25:00	12/06/2012 12:10:00	Lo	46.82882	-125.03843
4	10	12/06/2012 16:25:00	12/06/2012 16:36:00	Lo	46.80377	-125.06013
5	11	12/06/2012 19:41:00	12/06/2012 20:20:00	Lo	46.77127	-125.08743
6	13	13/06/2012 04:23:00	13/06/2012 04:43:00	Lo	46.68777	-125.15455
7	13	13/06/2012 05:30:00	13/06/2012 06:32:00	Lo	46.68777	-125.15455
8	13	13/06/2012 07:13:00	13/06/2012 08:55:00	Lo	46.68777	-125.15455
9	14	13/06/2012 10:04:00	13/06/2012 10:43:00	Lo	46.68905	-125.1775
10	17	14/06/2012 07:59:00	14/06/2012 08:15:00	Lo	46.81535	-125.18641
11	17	14/06/2012 09:13:00	14/06/2012 09:40:00	Lo	46.81535	-125.18641
12	21	15/06/2012 04:26:00	15/06/2012 07:36:00	Lo	46.96928	-125.20565
13	22	15/06/2012 14:21:00	15/06/2012 14:46:00	Lo	47.01893	-125.20896
14	24	16/06/2012 03:25:00	16/06/2012 03:43:00	Lo	47.12443	-125.23654
15	25	16/06/2012 08:56:00	16/06/2012 09:22:00	Lo	47.17752	-125.2672
16	25	16/06/2012 10:41:00	16/06/2012 10:58:00	Lo	47.17752	-125.2672
17	27	17/06/2012 00:42:00	17/06/2012 00:43:00	Lo	47.28063	-125.32876
18	28	17/06/2012 04:13:00	17/06/2012 04:14:00	Lo	47.32691	-125.36703
19	1	17/06/2012 06:28:00	01/01/2012 07:37:00	Lo	46.91254	-124.93156
20	35	19/06/2012 04:49:00	19/06/2012 07:34:00	Lo	47.64272	-125.51009
21	41	20/06/2012 11:23:00	21/06/2012 06:27:00	Lo	47.92293	-125.74299
22	43	21/06/2012 09:55:00	21/06/2012 11:00:00	Lo	47.97459	-125.809

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
23	43	21/06/2012 13:00:00	21/06/2012 13:13:00	Lo	47.97459	-125.809
24	45	21/06/2012 23:58:00	22/06/2012 00:31:00	Lo	47.92712	-125.74868
25	46	22/06/2012 04:36:00	22/06/2012 05:36:00	Lo	47.90792	-125.73018
26	47	22/06/2012 10:23:00	22/06/2012 11:31:00	Lo	47.88424	-125.72213
27	61	25/06/2012 23:22:00	25/06/2012 23:44:00	Lo	47.52793	-125.39542
28	66	27/06/2012 06:45:00	27/06/2012 08:12:00	Lo	47.39061	-125.37343
29	66	27/06/2012 10:18:00	27/06/2012 10:43:00	Lo	47.39061	-125.37343
30	67	27/06/2012 16:18:00	27/06/2012 16:50:00	Lo	47.37276	-125.36693
31	68	27/06/2012 21:01:00	28/06/2012 00:25:00	Lo	47.35826	-125.35859
32	69	28/06/2012 02:58:00	28/06/2012 03:24:00	Lo	47.34021	-125.34931
33	69	28/06/2012 05:18:00	28/06/2012 07:02:00	Lo	47.34021	-125.34931
34	72	29/06/2012 04:25:00	29/06/2012 04:36:00	Lo	47.30038	-125.3262
35	72	29/06/2012 05:33:00	29/06/2012 05:34:00	Lo	47.30038	-125.3262
36	73	29/06/2012 08:15:00	29/06/2012 09:07:00	Lo	47.27698	-125.31766
37	73	29/06/2012 11:09:00	29/06/2012 11:43:00	Lo	47.27698	-125.31766
38	75	30/06/2012 00:06:00	30/06/2012 00:32:00	Lo	47.28313	-125.31304
39	76	30/06/2012 04:34:00	30/06/2012 04:39:00	Lo	47.35567	-125.33601
40	76	30/06/2012 06:56:00	30/06/2012 08:39:00	Lo	47.35567	-125.33601
41	80	01/07/2012 05:14:00	01/07/2012 05:25:00	Lo	47.51119	-125.35543

*Lo = Pacific white-sided dolphin

Northern right whale dolphin encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	7	12/06/2012 06:07:00	12/06/2012 07:19:00	Lb	46.8718	-124.9929
2	9	12/06/2012 11:50:00	12/06/2012 12:37:00	Lb	46.8288	-125.0384
3	11	12/06/2012 18:35:00	12/06/2012 19:55:00	Lb	46.7713	-125.0874
4	13	13/06/2012 04:32:00	13/06/2012 04:48:00	Lb	46.6878	-125.1546
5	14	13/06/2012 13:34:00	13/06/2012 13:39:00	Lb	46.6891	-125.1775
6	16	14/06/2012 02:09:00	14/06/2012 03:03:00	Lb	46.7748	-125.1815
7	19	14/06/2012 18:13:00	14/06/2012 18:17:00	Lb	46.8846	-125.1937
8	21	15/06/2012 06:00:00	15/06/2012 07:39:00	Lb	46.9693	-125.2057
9	25	16/06/2012 07:59:00	16/06/2012 08:14:00	Lb	47.1775	-125.2672
10	26	16/06/2012 15:48:00	16/06/2012 16:15:00	Lb	47.2336	-125.2853
11	27	16/06/2012 23:28:00	17/06/2012 00:48:00	Lb	47.2806	-125.3288
12	28	17/06/2012 04:15:00	17/06/2012 04:41:00	Lb	47.3269	-125.3670
13	28	17/06/2012 05:57:00	17/06/2012 06:17:00	Lb	47.3269	-125.3670
14	31	18/06/2012 02:11:00	18/06/2012 02:16:00	Lb	47.4725	-125.3658
15	31	18/06/2012 03:36:00	18/06/2012 03:45:00	Lb	47.4725	-125.3658
16	32	18/06/2012 10:12:00	18/06/2012 10:22:00	Lb	47.5119	-125.3854
17	35	19/06/2012 04:57:00	19/06/2012 07:37:00	Lb	47.6427	-125.5101
18	42	21/06/2012 03:11:00	21/06/2012 06:27:00	Lb	47.9647	-125.7881
19	43	21/06/2012 09:55:00	21/06/2012 13:15:00	Lb	47.9746	-125.8090
20	45	21/06/2012 20:09:00	22/06/2012 00:41:00	Lb	47.9271	-125.7487
21	46	22/06/2012 04:33:00	22/06/2012 05:15:00	Lb	47.9079	-125.7302
22	53	24/06/2012 02:58:00	24/06/2012 03:28:00	Lb	47.7340	-125.5794

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
23	67	27/06/2012 14:10:00	27/06/2012 14:12:00	Lb	47.3728	-125.3669
24	67	27/06/2012 15:15:00	27/06/2012 15:19:00	Lb	47.3728	-125.3669
25	67	27/06/2012 16:18:00	27/06/2012 17:35:00	Lb	47.3728	-125.3669
26	68	27/06/2012 21:32:00	28/06/2012 00:25:00	Lb	47.3583	-125.3586
27	69	28/06/2012 02:59:00	28/06/2012 06:04:00	Lb	47.3402	-125.3493
28	72	29/06/2012 04:29:00	29/06/2012 04:36:00	Lb	47.3004	-125.3262
29	76	30/06/2012 07:16:00	30/06/2012 08:06:00	Lb	47.3557	-125.3360

*Lb = Northern right whale dolphin

Unidentified delphinid encounters*

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	24	16/06/2012 02:57:00	16/06/2012 03:29:00	UnD	47.1244	-125.2365
2	32	18/06/2012 07:45:00	18/06/2012 08:09:00	UnD	47.5119	-125.3854
3	73	29/06/2012 08:58:00	29/06/2012 10:40:00	UnD	47.2770	-125.3177

*UnD = Unidentified delphinid

A.2 MYSTICETES

No mysticete encounters were registered during this survey.

A.3 SEISMIC AIRGUN SIGNALS

Encounter [no.]	Dive [no.]	Start date [UTC] [dd/mm/yyyy hh:mm:ss]	End date [UTC] [dd/mm/yyyy hh:mm:ss]	Species ID/Label	Latitude [degrees N]	Longitude [degrees W]
1	11	12/06/2012 01:24:02	13/06/2012 15:02:49	Airgun	46.7713	-125.0874
2	23	14/06/2012 23:07:35	16/06/2012 22:16:33	Airgun	47.0705	-125.2163
3	28	17/06/2012 00:07:34	17/06/2012 13:03:21	Airgun	47.3269	-125.3670
4	33	17/06/2012 21:25:45	19/06/2012 04:47:07	Airgun	47.5492	-125.4330
5	38	19/06/2012 12:45:00	20/06/2012 22:47:04	Airgun	47.7839	-125.6367
6	42	21/06/2012 03:29:35	21/06/2012 12:49:23	Airgun	47.9647	-125.7881
7	51	21/06/2012 20:08:42	24/06/2012 23:02:51	Airgun	47.7899	-125.6438
8	67	25/06/2012 22:48:49	29/06/2012 01:44:50	Airgun	47.3728	-125.3669
9	78	29/06/2012 04:49:52	02/07/2012 10:50:59	Airgun	47.4771	-125.3463

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