GEOLOGICAL SURVEY OF CANADA
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Cruise Report 2013001PGC

The Mw 7.7 Haida Gwaii Earthquake Ocean Bottom Seismometer Experiment
Instrument recovery and active-source seismic refraction experiment

CCG Vessel John P. Tully
7-14 January, 2013

M. Riedel, M.M. Côté, P.J. Neelands

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1. Introduction

1.1 General Information

Canada's second largest instrumentally recorded earthquake occurred at 8:05 p.m. (PDT) on October 27th, 2012, off the west coast of Moresby Island, Haida Gwaii (Figure 1). The earthquake occurred at the southern end of the rupture zone of the 1949 M 8.1 strike-slip earthquake, which was Canada's largest instrumentally recorded event. Analysis of seismic waveforms, coseismic global positioning system displacements, and the pattern of aftershocks indicate that it was a "thrust" earthquake, similar to the earthquake that hit Japan off Tohoku on March 11, 2011. The tectonic margin off Haida Gwaii, extending to southern Alaska, is the transform fault boundary between the Pacific and North America plates. Off Moresby Island where the M 7.7 event occurred, there is a 20 degree oblique convergence between the Pacific and North American plates, giving rise to a small accretionary prism, referred to as the Queen Charlotte terrace. This terrace is the main study area of this OBS experiment. Thrust earthquakes have the potential to generate large tsunamis, and models for this event predict wave heights in some bays and inlets along the coast of Moresby Island as large as 3-5 m. Results from a post-tsunami survey along select inlets along the west coast of Haida Gwaii confirmed significant wave heights. In the first month after the earthquake more than 20,000 aftershocks were recorded. The majority of these are less than magnitude 2. The initial locations of aftershocks from this earthquake (Figure 1) cover an area 150 km along the margin and at least 50 km wide, extending seaward from beneath the west coast of Moresby Island to more than 50 km offshore. The central zone on the aftershock sequence is the target of the OBS experiment.

1.2 Objectives of the OBS Experiment

To accurately locate earthquakes, recording stations need to be positioned such that they surround the epicenter and the speed at which seismic waves travel through the earth's crust must be known. The land stations on Haida Gwaii are all to the east of the aftershock sequence, thus making these offshore earthquake epicentre locations uncertain and making depths for those events almost impossible to calculate accurately. The OBS will improve hypocentre locations considerably, especially their depths. If even a few earthquakes are recorded on both the land and OBS instruments, the combined data will improve the hypocentres of aftershocks recorded only on the land stations. This will also improve the historic earthquake catalog and reduce previous biases in the earthquake locations.

The distribution of the OBS sites was chosen to cover a reasonable area of the aftershock sequence centered around the epicenter, covering mostly the Queen Charlotte terrace (Figure 2). The deployment occurred in December 2012 (Riedel et al., 2014) with a recovery mission in January, which restricts offshore operations due to expected heavy seas and high wind speeds. Thus, the study area had to be limited in areal extent to avoid large transit distances between stations. A total of nine instruments were available from the instrument pool at the NRCan office at the Bedford Institute of Oceanography (BIO) in Dartmouth, NS. An additional nine instruments were borrowed from Dalhousie University through collaboration with Dr. Keith Louden. However, due to logistical constraints related to recovery time in January, only five of the Dalhousie instruments were deployed as part of the regional grid.

1.3 Accomplishments and Results

The expedition accomplished several critical components for the Haida Gwaii response effort by NRCan. All 14 OBS instruments were recovered (Table 1). Though data were recorded on the OBS for a shorter period of time than anticipated due to unexpected short battery lifetimes (Table 2), the data themselves are of very high quality and cover (with the staggered start-time of the OBSs) a period of 16 days from December 15, 2012 to December 31, 2012. Early data analyses show multiple clear and easily identifiable earthquakes as well as other records that could be T-phase arrivals or tremor-like events. OBS clock-drifts were determined immediately upon recovery of the instruments (Table 3) (note that not all instruments had sufficient power remaining to perform this calibration). The OBS data from the regional grid were converted to a format suitable for use in Antelope (i.e. mini-SEED) and will be further processed for other applications (including conversion to SAC or SEGY format).

Two short active source seismic surveys were conducted using a 520 cubic inch airgun as seismic source (total number of shots: 7100, ~500 total line-kilometres, Figure 3). The first refraction survey was conducted at the beginning of the recovery expedition under the assumption that the regional grid of OBS may still be operational. However, upon recovery of the OBS instruments it was noticed that none of the instruments recorded the airgun shots, even though some instruments had sufficient power left to write digital files. The main power loss was identified as the amplifier board that reads the data from the geophone and hydrophone. Due to a higher than usual sampling rate (500 Hz for the NRCan instruments, 200 Hz for the Dalhousie instruments) power was consumed sooner than expected based on previous experiments using of these instruments at much lower sampling rates (~100 Hz). Therefore a second OBS refraction survey was conducted using all available spares batteries, which allowed for the redeployment of six OBS instruments (Table 4).

The second refraction survey was also successful as all six OBS were recovered with full data coverage. Again, clock-drifts were immediately determined upon recovery onboard (Table 5). Early data analyses show clear refractions with apparent velocities up to 6 km/s, which are believed to be from the upper crust. Despite the fact the first refraction experiment failed in that no data were recorded on the OBS instruments, the airgun shots were recorded on the land stations that were deployed during the survey. Unexpectedly, strong and clear arrivals were seen on multiple stations, including Barry Inlet and Hotspring Island, with observed distances between the stations and the shot locations exceeding 55 km. The results of the refraction data and the single-channel seismic data complement older data from the 1970s and 1980s (paper records). Clear images of the Queen-Charlotte Transform Fault were recorded and the airgun was strong enough to generate reflections from the upper crust, i.e. the top of the Pacific Plate. Additionally, across the Queen Charlotte Terrace region, bottom-simulating reflectors were seen and the coincident OBS refraction data indicate high-velocity sediment with P-wave velocities values of 2.0-2.5 km/s, indicative of the presence of gas hydrate. Additional 3.5 kHz data as well as echo sounder data using all available sounders installed on the CCGS John P. Tully (12 kHz, 18/38 kHz) were co-recorded on all lines.

Additional lines were acquired using only the 3.5 kHz and echo sounders between operational downtimes (Figure 3f).

2. Narrative of Events

All times listed here are local time, Pacific Standard Time (PST).

06/01 Sunday

08:00 Science crew to drive to Port Hardy
Equipment shipped with commercial shipping company to arrive on January 7th;
Equipment mobilized through IOS (compressor) arrived by 15:00

07/01 Monday

08:45 Commercial shipment of winch and power-pack arrived and installed on deck
09:15 Loading completed
10:30 The Haida Nations Observer George Wesley arrived
12:15 Safety briefing on board by Coast Guard personnel
13:00 Life-Boat drill
14:30 Moving rental vehicles to Budget outlet in Port Hardy
17:45 All deck-space clear, building of pressure/tow-lines for airgun completed
18:00 Test of solenoid completed successfully
19:20 Leaving for Haida Gwaii

08/01 Tuesday

07:30 Decided to change anticipated deployment station for airgun work to optimize time available given current favourable weather conditions, and pre-seismic marine mammal watch restrictions
13:00 Start pre-seismic marine mammal watch
14:30 Deploy airgun (wind: 10-15 knots; 5 m seas)
14:35 Airgun deployed and first shot at 14:40
15:25 Streamer deployed
15:30 Start recording streamer data digitally
16:50 Remove hull-protection system, improved signal on streamer
17:10 Start recording 3.5 kHz system

09/01 Wednesday

02:37 Start of central line across Queen Charlotte Terrace
08:08 Completed central line, start lines criss-crossing the Queen Charlotte Transform fault (QCTF) towards northern-most crossing line
15:07 End of transects across the QCTF
15:45 Problems with streamer cable, improve towing strength-cable; temporarily steer off main line; setting boat into a course straight into the wind to help set stopper; winds are increasing to 30 knots; decision is made to continue acquire data as weather prediction says winds will come down soon;
16:30 Work on streamer grip/stopper completed, back to main line
18:30 Heading SW on the northern crossing line

20:16 End of Northern line
Start to turn, but still 30 knot winds; Beaufort-Scale 7-8
21:15 Decision made to not risk a turn and keep going in more northerly direction until winds/seas more favourable for turning

<u>10/01 Thursday</u>

02:30 Wind and sea-state have improved (< 6 m wave height, < 30 knot wind), start turn
At this point, we have moved 16 nautical miles into the more northerly direction;
03:15 Revised the plan for remaining seismic program to end at OBS station #9
07:00 The vessel is being pushed now with the change in wind direction and we are making 6 knots speed over ground; therefore, we will be too early at OBS #9, seismic program continues;
10:23 End of seismic program;
10:30 Streamer on deck
10:45 Airgun on deck
11:20 Begin OBS recovery sequence at OBS Station #7, DAL-D
deploy pinger and hydrophone to send release code
All release codes and station locations are listed in Table 1;
11:25 Ship is rather noisy, go to Generator-mode (Gen-Mode) and release clutch; vessel much quieter and we can hear the pinger operate and return-signal from OBSs on hydrophone;
12:00 OBS #7 on surface
12:22 OBS #7 on deck
13:17 OBS #6, NRCan-F released
13:30 Upon inspection of data from OBS #7, DAL-D, we realized that recordings only lasted 8 days (start Dec 22, end Dec 31) due to too low battery levels in the amplifier board; the digitizer still generated data (of constant value) until Jan 10, when its power supply stopped upon recovery; All data recording parameters are listed in Table 2;
14:03 OBS #6, NRCan-F on deck
14:07 OBS #5, DAL-J released
15:03 OBS #5, DAL-J on deck
15:10 OBS #4, NRCan-N released
16:00 OBS #4, NRCan-N on deck
18:06 OBS #3, NRCan-H on deck
19:44 OBS #2, NRCan-J on deck
22:00 OBS #1, NRCan-K on deck
Decision was mode to interrupt OBS recovery to get technical staff time to recover/sleep and continue work in the morning; fill-in program by investigating plateau region, where gas plumes were found in December expedition
22:10 Transit to plateau region

<u>11/01 Friday</u>

00:04 Start of 1st line across plateau
12 kHz; 18/38 kHz system; 3.5 kHz system

04:28 End of lines across plateau, heading back to OBS stations for recovery after breakfast;
07:10 At OBS station #14
08:18 OBS #14, DAL-C on deck
10:12 OBS #8, NRCan-L on deck

As it has become apparent, that all OBS did not record the first two days of seismic airgun data, we decided to re-deploy the maximum amount of OBS for a second refraction experiment; weather has steadily improved to allow for a second airgun operation; we will utilize again the 520 cubic inch airgun
Discussions on backup release time (UTC 23:00 Jan 13) to ensure that recovery is possible within operational window available;

10:47 1st attempt to release OBS #9, DAL-B, appears to have failed, moving closer to OBS station and try again; recording on 12 kHz sounder system show finally that OBS is on its ascent, and was released in 1st attempt; echo from OBS is too weak to be heard on hydrophone
12:30 OBS #9, DAL-B on deck
14:16 OBS #10, DAL-A on deck
16:10 OBS #11, NRCan-E on deck
17:50 OBS #12, NRCan-D on deck
19:33 OBS #13, NRCan-A on deck

19:35 On way to start new deployment of OBS
Refurbishing six OBS for second deployment

22:22 D2 OBS #6, NRCan-D, deployed
23:23 D2 OBS #5, NRCan-E deployed
23:50 D2 OBS #4, DAL-A deployed

12/01 Saturday
00:15 D2 OBS #3, DAL-B deployed
00:55 D2 OBS #2, NRCan-H deployed
01:27 D2 OBS #1, DAL-C deployed

Making our way back to start refraction experiment in deep ocean over D2 OBD#6 by steaming 5 knots and recording 3.5 kHz data across QCTF and other structures;

07:00 Start preparing for seismic experiment
08:30 Run up on compressor showed problems with belts; stop operation and start repair
Marine mammal observations continue; However, thick fog is descending.
We are going slowly (2 knots) towards anticipated deployment of airgun, moving out of fog region; weather is otherwise optimal: 5 knot wind, 1 m swell.
10:30 Compressor successfully repaired.

Throughout repair, no mammals were sighted, thus we can begin airgun work right away without further delay.

10:40 Airgun deployed
10:50 Streamer deployed
Projected end of second refraction experiment is 03:00 am on Sunday to allow sufficient time to return to Port Hardy in the morning, disembark science team and equipment to turn around vessel back to SAR.

15:00 Past storm has released large kelp-beds that now float out to the ocean; may require slight course-deviation to not catch kelp in streamer and/or airgun.

16:05 End of main central refraction line

<u>13/01 Sunday</u>

Continue shooting seismic lines; data quality is amazing due to calm weather
01:20 Start of the last refraction line across western-most D2 OBS #6
02:45 reached EOL, stop firing
03:04 Streamer on deck
03:07 Airgun on deck
Start sequence of D2 OBS recovery
04:42 D2 OBS #6, NRCan-D on deck
06:19 D2 OBS #5, NRCan-E on deck
07:45 D2 OBS #3, DAL-B on deck
08:53 D2 OBS #4, DAL-A on deck
09:27 D2 OBS #2, NRCan-H on deck
10:30 D2 OBS #1, DAL-C on deck

All six OBS back on deck; all recorded the airgun data seen on hydrophone and all geophone components

11:00 Heading back to plateau for last survey line across feature exploiting unusual calm sea conditions for optimal 3.5 kHz and echo sounder data recordings
13:46 Start line across plateau
14:29 End of line; extreme high quality of data, observation of gas plumes in 12 kHz
Heading towards Port Hardy

<u>14/01 Monday</u>

09:00 At dock in Port Hardy
Science crew disembark
Offloading of equipment
Commercial shipment only possible on Tuesday
G. Middleton, D. Manning, B. Murphy stay in Port Hardy until Tuesday to ensure shipping of equipment completed
All other scientists drive home to IOS, Sidney

3. OBS Recovery Procedures

The OBS instruments forming the regional grid (Table 1) as well as those of the second refraction experiment (Table 4) have a build-in code to respond to an acoustic release signal sent out by an echo-sounder upon recovery. The echo-sounder as well as a hydrophone used to listen to the response echo from the OBS were hand-deployed on the starboard side of the vessel (Figure 4a). To maximize operation time, the release code was sent from a location about 2 to 3 nautical miles away from the assumed OBS location. The OBS is released from the anchor after about 6 min, which is the time required to burn the wire that keeps the OBS attached to the anchor. The instruments rise with a velocity of ~1m/s. The remaining time to steam to the assumed OBS location is then approximately 15 minutes at maximum speed of 10 knots. In total, we assume to have saved ~4 hours of operational time with this expedited sending of the release code.

The OBS instruments have a rope attached to the floatation bodies (Figure 4b) which makes recovery from the vessel very simple. First, a deck-hand grabs that rope either with an extension-pole or by using a grappling iron (Figure 4c), typically on the star-board side of the vessel. Once the rope is secured, the instrument is pulled towards the stern by hand. A second line is then attached and the instrument is finally pulled up using the A-Frame and centre-winch (Figure 4d). Once the instrument is on deck, it is dismantled and the pressure-housing case is brought inside the lab for analyses and data recovery (Figure 4e-f) while the remaining flotation bodies are secured on deck.

4. Refraction Experiment 1 (January 8 - 10, 2013)

Under the assumption that the OBS instruments of the regional grid were still operational, a total of 5159 airgun shots were fired for a survey of a total of 43 hours along a total of 380 line kilometers (see Figure 3a for line-locations).

The airgun data were recorded on the single channel streamer and a first analysis shows penetration up to two seconds two-way travel time with clear reflections from the top of the Pacific plate (Figure 5).

Upon return to IOS/PGC an analysis of some land-stations was performed to identify evidence for the airgun data to be recorded on land stations. A preliminary analysis of land station data from Barry Inlet (BNB) and Hot Spring Island (H3GB) show clear arrivals of the airgun from the first refraction experiment. Although the 14 OBS of the regional grid did not record any of the airgun seismic data, it is hoped that the data from the land-stations will allow for some tomography analyses of the airgun data.

5. Refraction Experiment 2 (January 12 - 13, 2013)

After realizing that the OBS from the regional grid failed to record useful data beyond 7 - 8 days after recording started (but spanning a total of 16 days for the entire grid when combined as the OBS were staggered in their recording parameters) it was quickly decided to utilize all available spares and prepare for a second short-duration seismic refraction experiment. A total of six (6) instruments were refurbished at sea

(Table 4) and deployed in a T-pattern centered around the main shock epicenter location and the Queen Charlotte Terrace. The second refraction experiment was conducted for 16 hours and data were acquired along several lines crossing the OBS with a total length of 145 line kilometers. The six OBS recorded all airgun data and refraction were clearly recorded on all stations (see Figure 6 for an example from D2 OBS #6). Re-locating the OBS positioning for a more accurate velocity analyses will be performed post-cruise.

6. High Resolution Imaging of "Shelf-Plateau" Region

During the OBS deployment expedition in December 2012 (2012005PGC), the plateau-region was imaged with one seismic line where prominent gas plumes were identified in the 12 kHz echo sounder records mostly over small elevations/outcrops of the seafloor. The favourable weather conditions during this January expedition (2013001PGC) warranted further investigation of these gas plumes. We also used the 3.5 kHz sounder system to image the structure of the plateau. A total of six lines were acquired in an operational "break" period on January 11, 2013 that was required to allow for an appropriate rest-period of technical staff. A final line (Figure 7) was acquired on the way home to Port Hardy on January 13, 2103. The data again show clear gas plumes (Figure 8) right above small seafloor elevations or outcrops. The seafloor is overall extremely hard with no evidence of any major sediment cover whereas the outcrops themselves appear "softer" when compared to the regular seafloor returns (as previously observed by V. Barrie; pers. communication), which could also be a result of their roughness and associated scattering effects (Figure 7). Due to operational constraints and limited time remaining on the expedition, we were not able to collect a seafloor grab sample. This may be attempted during a planed upcoming expedition to the region in 2013 or 2014.

7. Reference

Riedel, M.; Côté, M.M.; Neelands, P.J., 2014. Cruise Report PGC2012005PGC, The Mw 7.7 Haida Gwaii Earthquake Ocean Bottom Seismometer Experiment, Instrument deployment, gas-plume acoustic imaging, and water sampling, CCG Vessel John P. Tully, 7-10 December, 2012. Geological Survey of Canada, Open File 7555.

8. Tables

Table 1. Final drop locations of OBS instruments in regional grid deployed in December 2012, release codes and radio frequencies for directional finder.

OBS Station	Latitude	Longitude	Water Depth (m)	OBS-identifier	Release code	Frequency (MHz), Channel
1	52.169717	-132.066037	2909	NRCan-K	70	160.725, C
2	52.298262	-131.908236	2128	NRCan-J	30	157.125, 82
3	52.385719	-131.811520	1518	NRCan-H	20	156.575, 71
4	52.557899	-132.097616	1937	NRCan-N	40	160.725, C
5	52.512418	-132.162605	1629	Dal-J	20	154.585, A
6	52.480116	-132.214632	2070	NRCan-F	50	160.725, C
7	52.441314	-132.277701	1965	Dal-D	60	159.480, B
8	52.369217	-132.376557	2917	NRCan-L	50	157.125, 82
9	52.465601	-132.519974	2901	Dal-B	00	154.585, A
10	52.565744	-132.646831	2923	Dal-A	50	159.480, B
11	52.660033	-132.808669	2908	NRCan-E	70	160.725, C
12	52.776967	-132.648549	1436	NRCan-D	80	156.575, 71
13	52.854984	-132.526614	1367	NRCan-A	30	160.725, C
14	52.281435	-132.238748	2908	Dal-C	80	154.585, A

Table 2. Data recording limits of regional OBS grid (14 stations) deployed in December 2012; *: approximated from Figure 9 to see end of recording. Despite the amplifier no longer able to pass useful seismic (i.e. amplitude) data to the digitizer, the digital data still got recorded until all battery power was drained.

OBS Station	Start digital data recording	End digital data recording	End of seismic data*	Last file-No. of digital data	Last file-No. of seismic data	Length of seismic data in last file*
#1; NRCan-K	Dec 15, 00:06	Jan 05, 05:34	Dec 22, 02:30	436	146	10.83 min
#2; NRCan-J	Dec 15, 00:05	Jan 06, 02:32	Dec 21, 16:24	454	137	35.82 min
#3; NRCan-H	Dec 15, 00:04	Jan 03, 05:25	Dec 21, 21:04	405	141	35.65 min
#4; NRCan-N	Dec 22, 00:06	Jan 11, 12:09	Dec 28, 07:59	411	130	18.32 min
#5; DAL-J	Dec 22, 00:00	Jan 10, 11:14	Dec 30, 23:17	164	73	151.22 min
#6; NRCan-F	Dec 15, 00:03	Jan 04, 05:02	Dec 21, 18:45	415	139	38.98 min
#7; DAL-D	Dec 22, 00:04	Jan 10, 08:43	Dec 31, 04:14	163	75	100.81 min
#8; NRCan-L	Dec 22, 00:02	Jan 09, 09:33	Dec 29, 07:19	388	150	24.00 min
#9; DAL-B	Dec 22, 00:01	Jan 11, 08:39	Dec 30, 10:45	171	69	101.65 min
#10; DAL-A	Dec 22, 00:00	Jan 11, 10:25	Dec 30, 09:36	172	69	34.10 min
#11; NRCan-E	Dec 15: 00:02	Jan 04, 07:21	Dec 21, 19:26	417	140	10.66 min
#12; NRCan-D	Dec 15: 00:01	Jan 06, 09:27	Dec 22, 12:50	460	155	6.66 min
#13; NRCan-A	Dec 15: 00:00	Jan 06, 02:06	Dec 22, 03:51	464	147	27.66 min
#14; DAL-C	Dec 22, 00:03	Jan 11, 04:28	Dec 30, 20:22	170	72	153.30 min

Table 3. Calculation of instrument clock drift, and other notes on data for the 14 OBS instruments of regional grid deployed in 2012 [n.d. = not determined].

OBS Station	Comments	Drift calibration		Total drift (sec)
		Prior to drop	After drop	
#1; NRCan-K	No post-drop calibration; battery dead	Set: Dec 8, 20:55	Calibration: n.d.	n.d.
		Behind by 0.000004 sec	n.d.	
#2; NRCan-J	Noisy hydrophone No post-drop calibration, battery dead	Set: Dec 8, 20:18	Calibration: n.d.	n.d.
		Behind by 0.000035 sec	n.d.	
#3; NRCan-H	No post-drop calibration, battery dead	Set: Dec 8, 17:51	Calibration: n.d.	n.d.
		Behind by 0.00000 sec	n.d.	
#4; NRCan-N	Channel 2 dead (vertical)	Set: Dec 9, 16:08	Calibration: Jan 11, 00:14	0.012071
		Behind by 0.000033 sec	Behind by 0.012104 sec	
#5; DAL-J		Set: Dec 8, 23:55	Calibration: an 10, 23:30	0.007361
		Behind by 0.000008 sec	Ahead by 0.007353	
#6; NRCan-F	No post-drop calibration, battery dead	Set: Dec 8, 19:31	Calibration: n.d.	n.d.
		Behind by 0.000032 sec	n.d.	
#7; DAL-D		Set: Dec 8, 23:34	Calibration: Jan 10, 20:13	0.002751
		Behind by 0.000019 sec	Behind by 0.00277	
#8; NRCan-L	Channel 3 dead (horizontal) No post-drop calibration, battery dead	Set: Dec 8, 21:37	Calibration: n.d.	n.d.
		Behind by 0.000002 sec	n.d.	
#9; DAL-B		Set: Dec 8, 22:46	Calibration: Jan 11, 20:39	0.062136
		Behind by 0.000030 sec	Ahead by 0.062166 sec	
#10; DAL-A		Set: Dec 8, 22:26	Calibration: Jan 11, 22:25	0.019649
		Behind by 0.000007 sec	Ahead by 0.019642 sec	
#11; NRCan-E	No post-drop calibration, battery dead Hydrophone dead	Set: Dec 8, 16:34	Calibration: n.d.	n.d.
		Behind by 0.000002 sec	n.d.	
#12; NRCan-D	No post-drop calibration, battery dead	Set: Dec 9, 21:54	Calibration: n.d.	n.d.
		Behind by 0.000036 sec	n.d.	
#13; NRCan-A	No post-drop calibration, battery dead	Set: Dec 8, 18:09	Calibration: n.d.	n.d.
		Behind by 0.000033 sec	n.d.	
#14; DAL-C	All channels very noisy	Set: Dec 8, 23:10	Calibration: Jan 11, 16:28	0.016299
		Behind by 0.000040 sec	Ahead by 0.016259 sec	

Table 4. Locations of the OBS instruments used in second refraction experiment, release codes and radio frequencies for directional finder.

OBS Station	Latitude	Longitude	Water Depth (m)	OBS-identifier	Release code	Frequency (MHz), Channel
D2-1	52.560844	-132.101515	1939	Dal-C	80	154.585, A
D2-2	52.514843	-132.171782	1845	NRCan-H	50	157.125, 82
D2-3	52.512417	-132.278231	2060	Dal-B	00	154.585, A
D2-4	52.479424	-132.223832	2065	Dal-A	50	159.480, B
D2-5	52.446256	-132.169197	1857	NRCan-E	70	160.725, C
D2-6	52.395885	-132.351070	2909	NRCan-D	80	157.125, 82

Table 5. Calculation of instrument clock drift, and other notes on data for the six OBS instruments of second refraction experiment.

OBS Station	Drift calibration		Total drift (sec)
	Prior to drop	After drop	
D2-11; Dal-C	Set: Jan 11, 17:28	Calibration: Jan 13, 18:47	0.009580
	Behind by 0.000035 sec	Ahead by 0.000923 sec	
D2-2; NRCan-H	Set: Jan 11, 19:35	Calibration: Jan 13, 17:35	0.004944
	Behind by 0.000007 sec	Ahead by 0.004937 sec	
D2-3; Dal-B	Set: Jan 11, 20:57	Calibration: Jan 13, 15:56	0.003431
	Behind by 0.000030 sec	Ahead by 0.003401 sec	
D2-4; Dal-A	Set: Jan 11, 22:48	Calibration: Jan 13, 17:00	0.000721
	Behind by 0.000011 sec	Ahead by 0.000732 sec	
D2-5; NRCan-E	Set: Jan 12, 00:43	Calibration: Jan 13, 14:27	0.000383
	Behind by 0.00007 sec	Behind by 0.000376 sec	
D2-6; NRCan-D	Set: Jan 12, 02:30	Calibration: Jan 13, 12:50	0.007647
	Behind by 0.000052 sec	Behind by 0.007699 sec	

Table 6. Science crew.

Name	Affiliation	Function onboard
Michael Riedel	GSC-Pacific	Chief scientist
Greg Middleton	GSC-Pacific	Deck supervision
Peter Neelands	GSC-Pacific	Lab supervision
Graham Standen	Geoforce	OBS technician
Robert (Bob) Iuliucci	Dalhousie-U.	OBS technician
Desmond Manning	GSC-Atlantic	Airgun technician
Robert Murphy	GSC-Atlantic	Airgun technician
Michelle Côté	GSC-Pacific	Navigation
Malaika Ulmi	GSC-Pacific	Watch keeper
Cooper Stacey	GSC-Pacific	Watch keeper
Rhonda Reidy	Contractor	Marine Mammal observer
Jacklyn Barrs	Contractor	Marine Mammal observer
George Wesley	Haida Nation	Observer

9. Figures

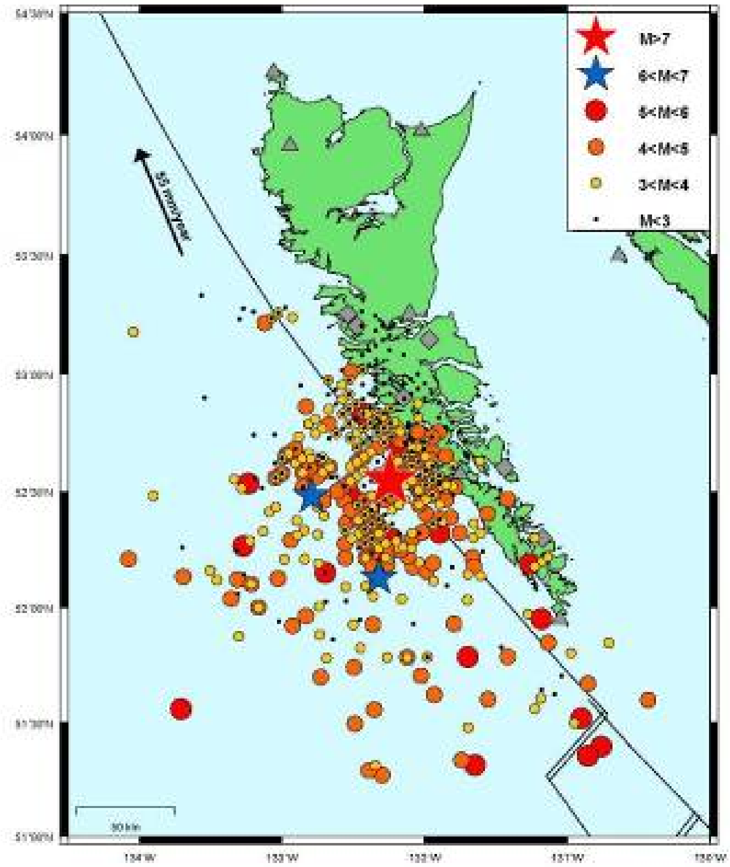

Figure 1. Preliminary locations of aftershocks with magnitude 3.0 and above for the first 30 days after the M 7.7 Haida Gwaii earthquake. The epicentre of the main event is shown by the red star and the two largest aftershocks of magnitude 6.0 and above are shown as blue stars (from Cassidy et al., 2012+).

+J. Cassidy, T. James, R. Hyndman, M. Riedel, G. Rogers, M. Schmidt, K. Wang, and T. Mulder, 2012. The M 7.7 Haida Gwaii Earthquake of October 27, 2012, Simon Fraser University Newsletter December 2012

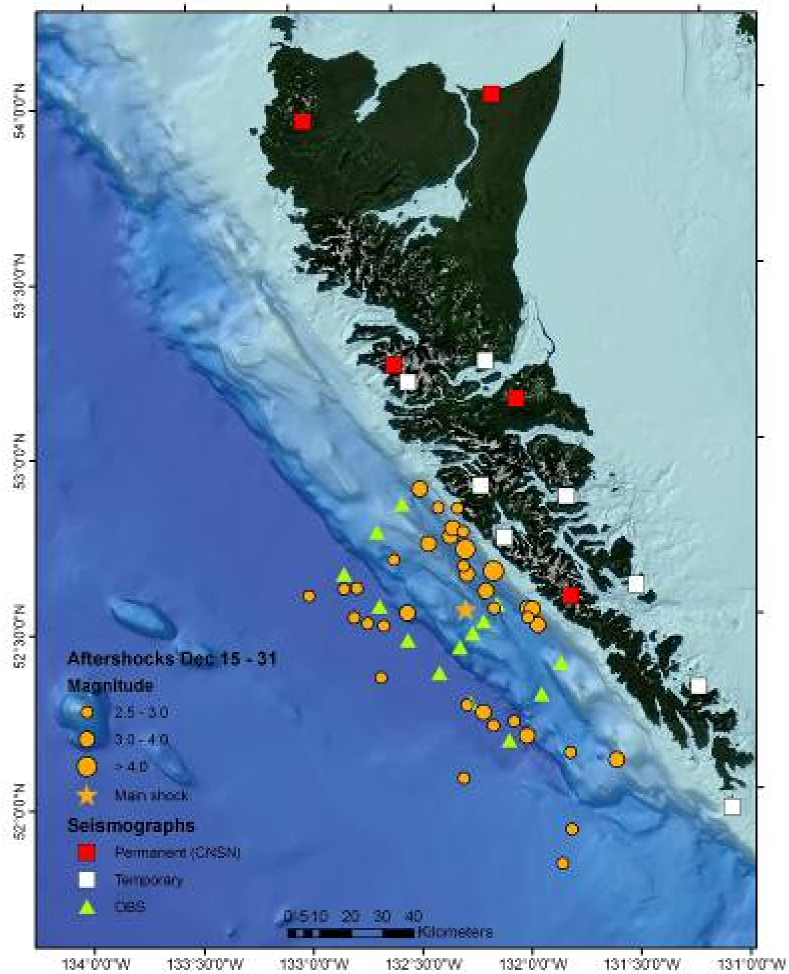

Figure 2. Map of OBS stations deployed during cruise 2012005PGC and location of land seismometers. Locations with magnitude of aftershocks recorded only using the land stations during the actual active recording period of the 14 OBS are shown in orange dots (for magnitude scale, see legend).

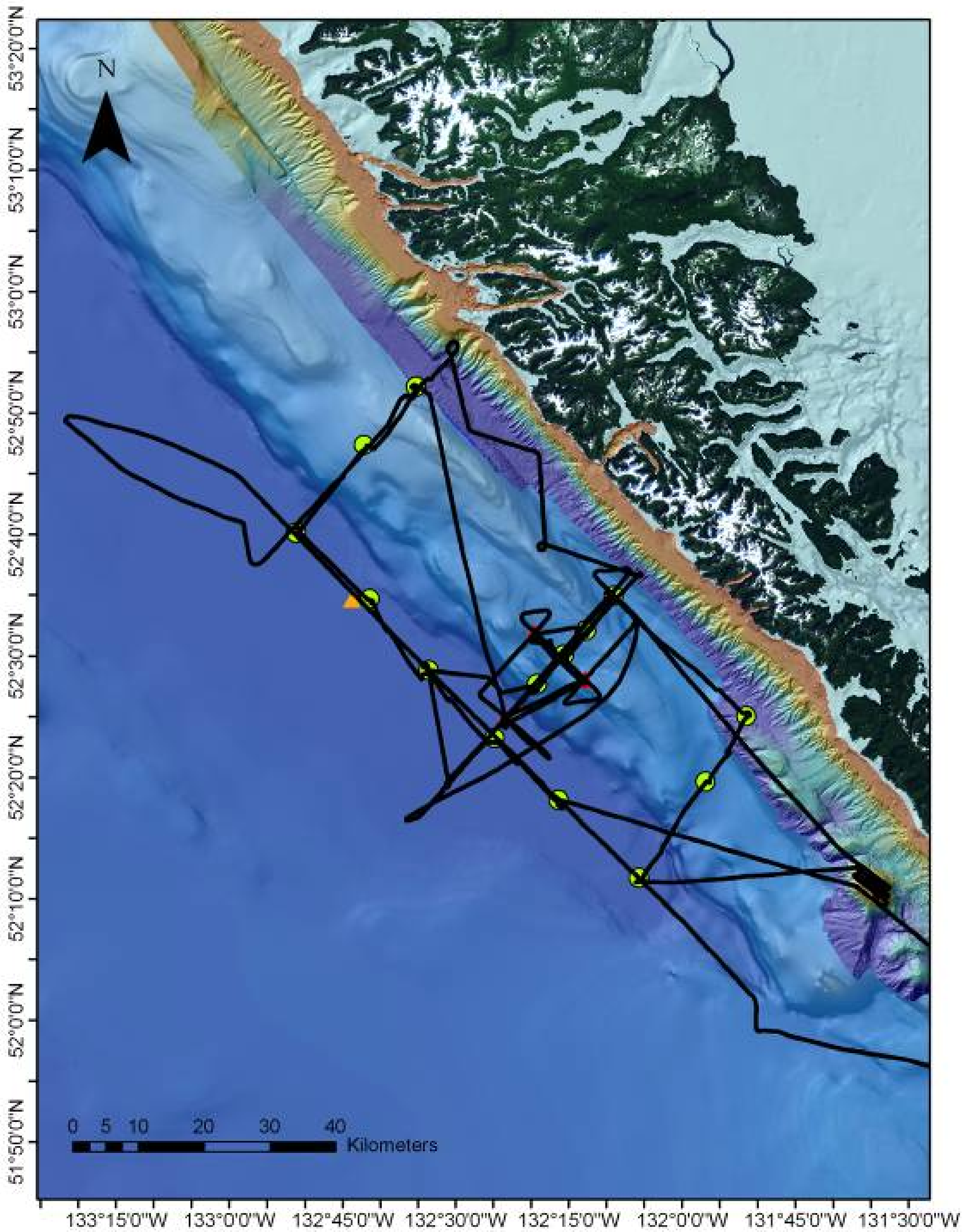

Figure 3a. All lines run during expedition. OBS locations from regional grid (green circles) and 2nd refraction experiment (red triangles) are shown, as well as the ODAS mooring site (orange triangle).

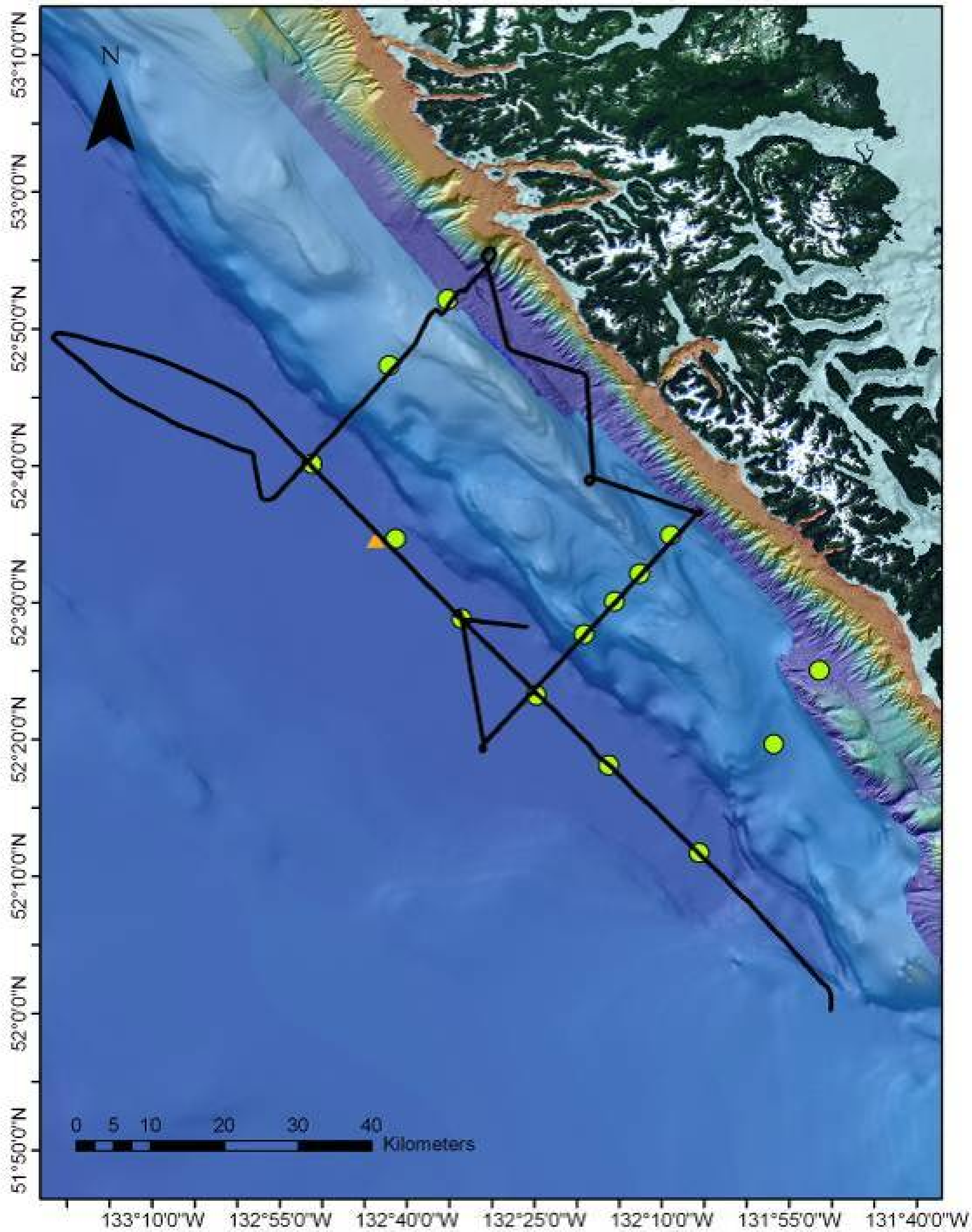

Figure 3b. Map of all seismic lines acquired during first refraction experiment. OBS locations from regional grid (green circles) are shown, as well as the ODAS mooring site (orange triangle).

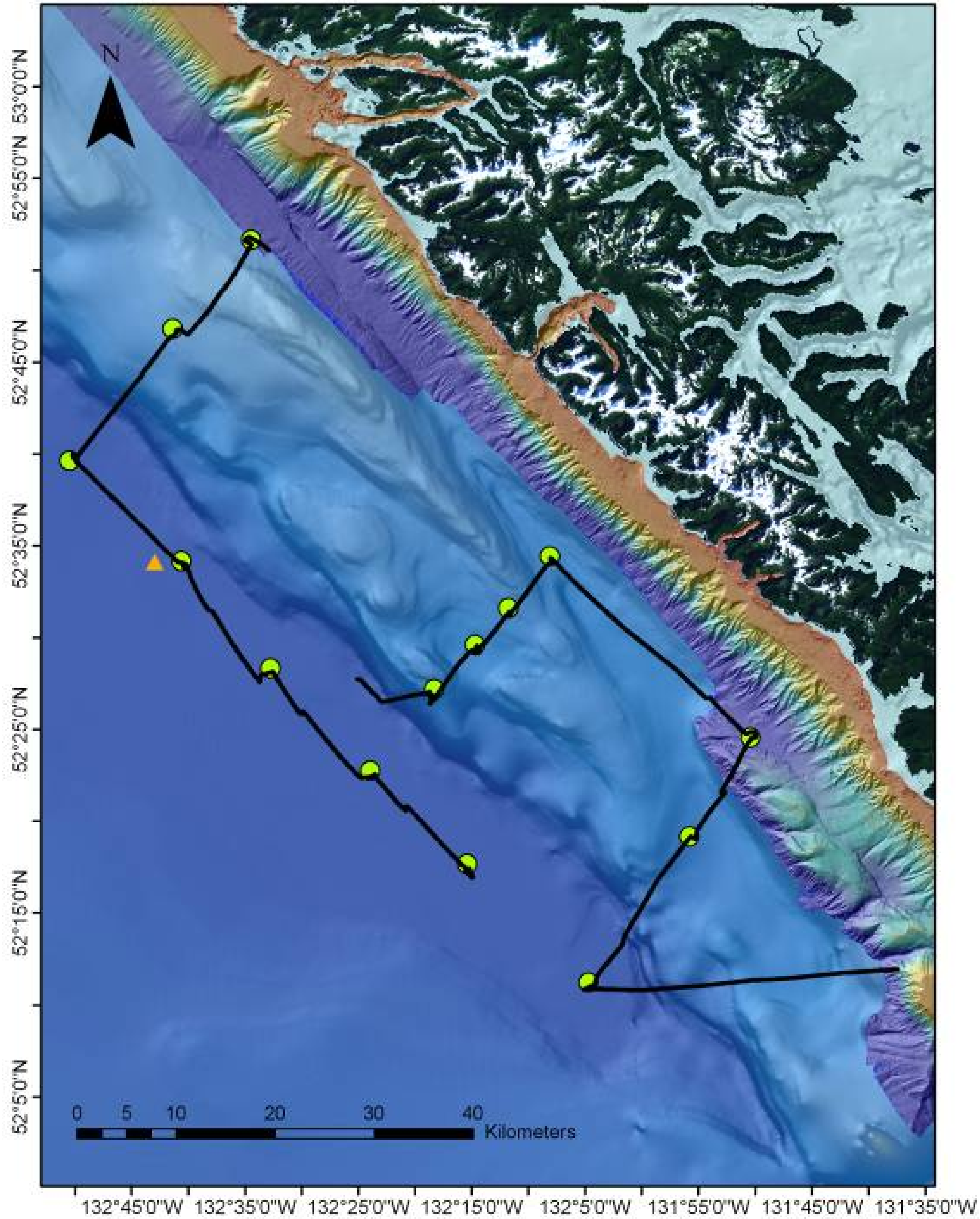

Figure 3c. Map of lines for recovery of the regional grid of 14 OBS. OBS locations from regional grid (green circles) are shown as well as the ODAS mooring site (orange triangle).

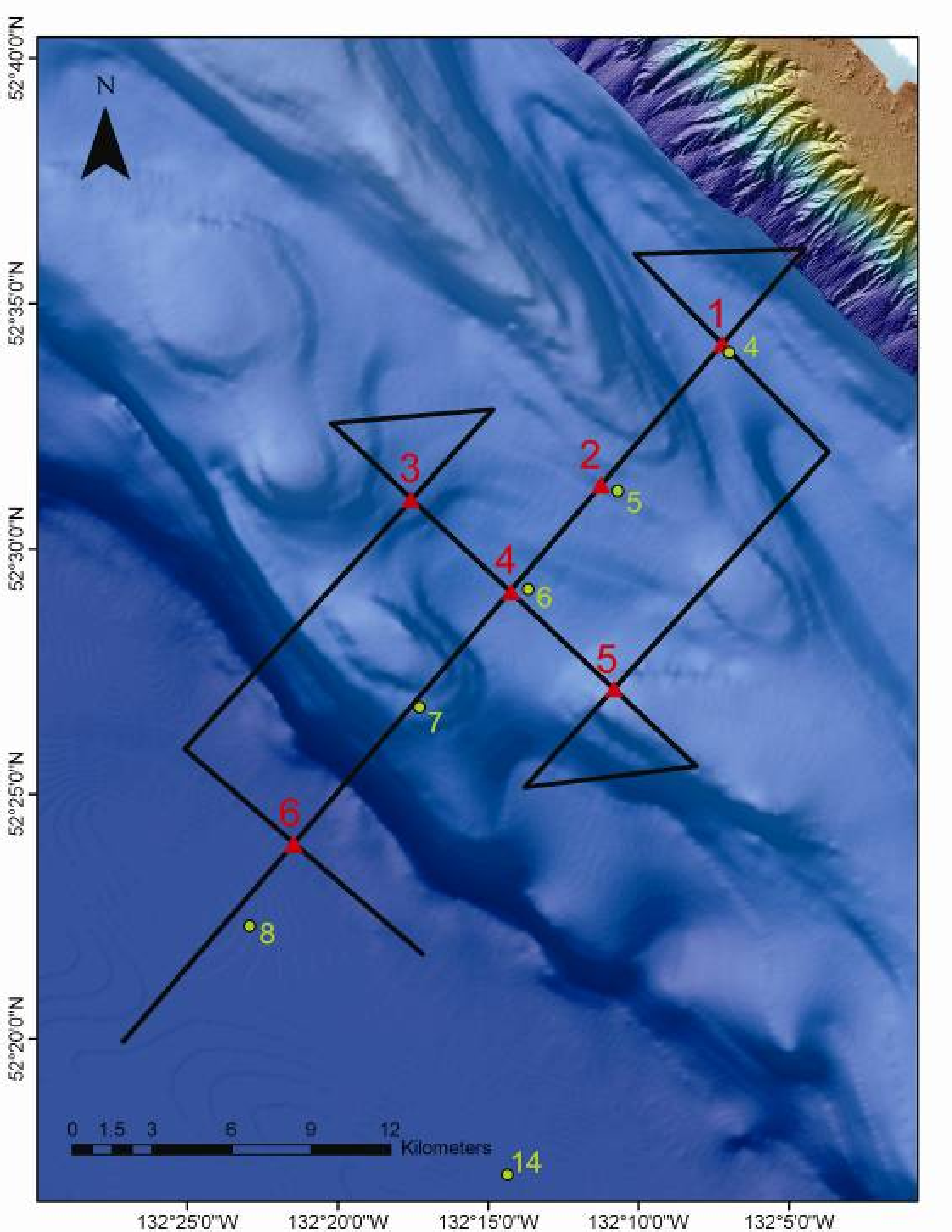

Figure 3d. Map of seismic lines acquired during second refraction experiment. OBS locations from regional grid (green circles) and 2nd refraction experiment (red triangles) are shown and label represents station numbers as listed in Tables 1 and 4.

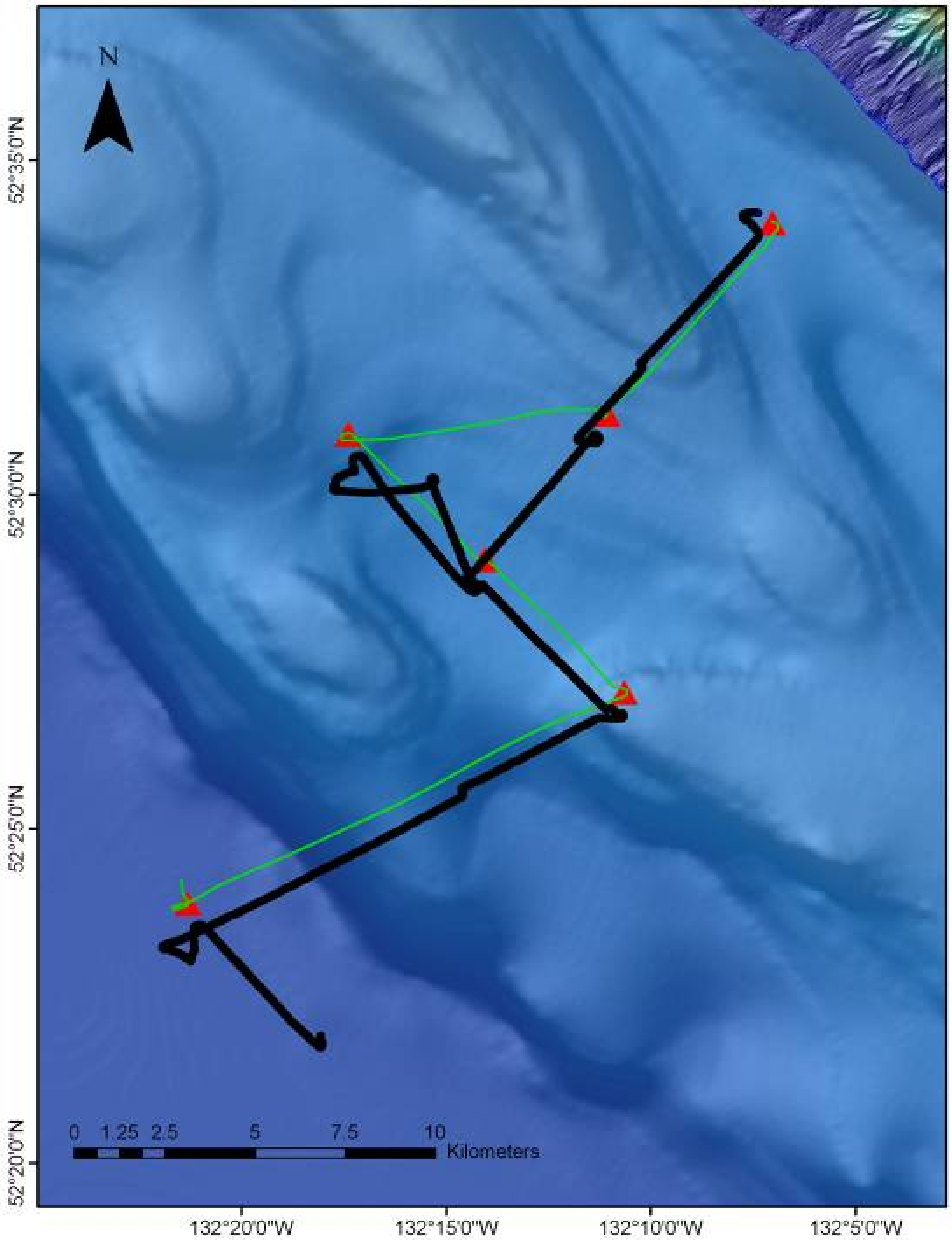

Figure 3e. Map of lines during deployment (green) and recovery (black) of the six OBS of second refraction experiment. OBS locations from second refraction experiment are shown as red triangles.

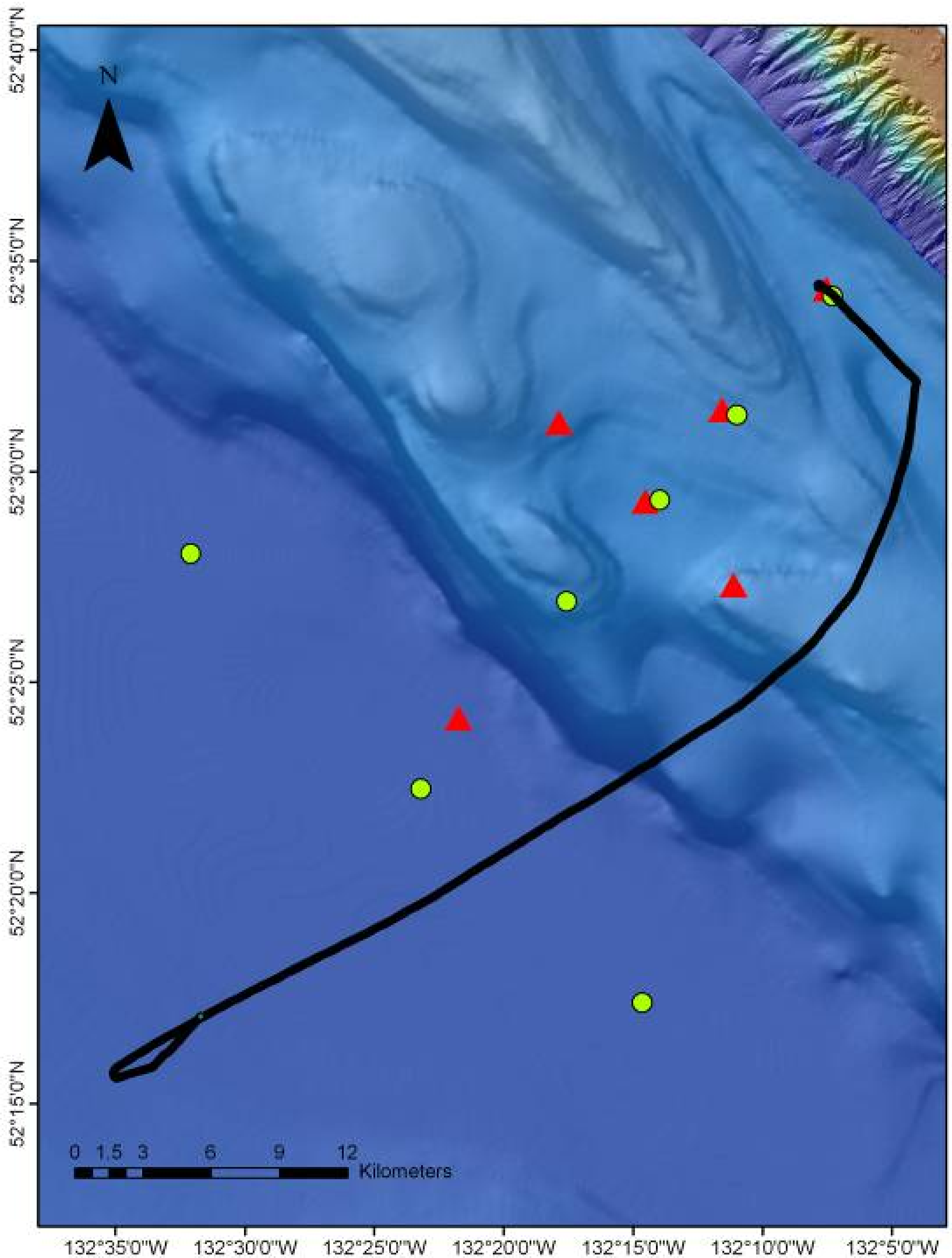

Figure 3f. Map of line where only 3.5 kHz data were acquired during operational downtimes between 2nd refraction experiment OBS deployment and start of airgun work. OBS locations from regional grid are shown in green circles, OBS locations from second refraction experiment are shown as red triangles.

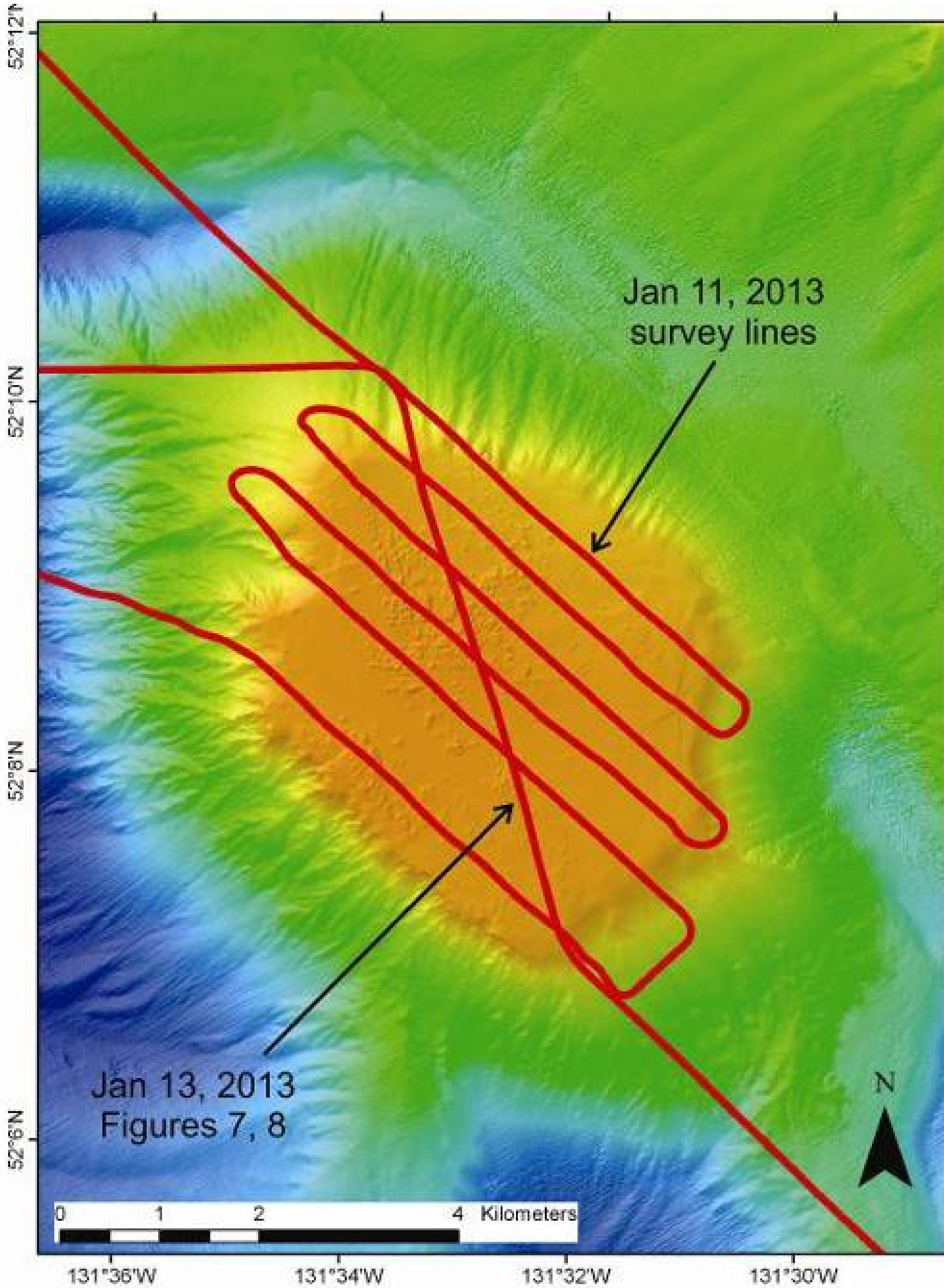

Figure 3g. Map of lines acquired across the "plateau"-feature using 3.5 kHz and using the 12 kHz and 18/38 kHz echo sounders.

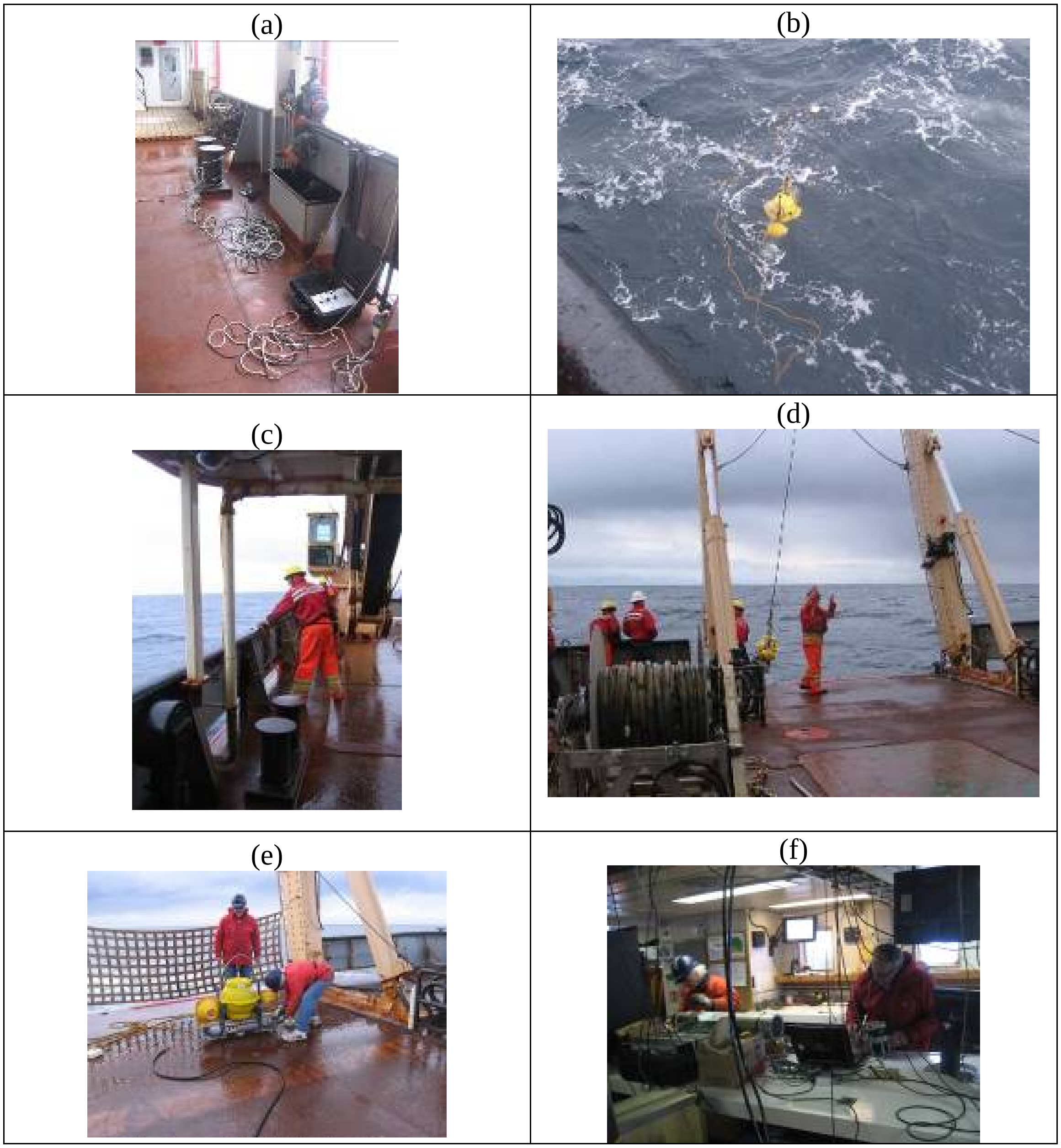

Figure 4. Sequence of OBS recovery: (a) installation of acoustic pinger and hydrophone for OBS release operation on starboard breezeway of the *CGGS John P. Tully,* (b) Floating OBS with rope attached, (c) Coast Guard personnel ready to through grappling iron to catch rope, (d) OBS secured with second rope, lifted onboard with A-frame and central winch, (e) OBS secured on deck, ready to be dismantled by scientists, (f) OBS pressure case inside dry-lab for data recovery.

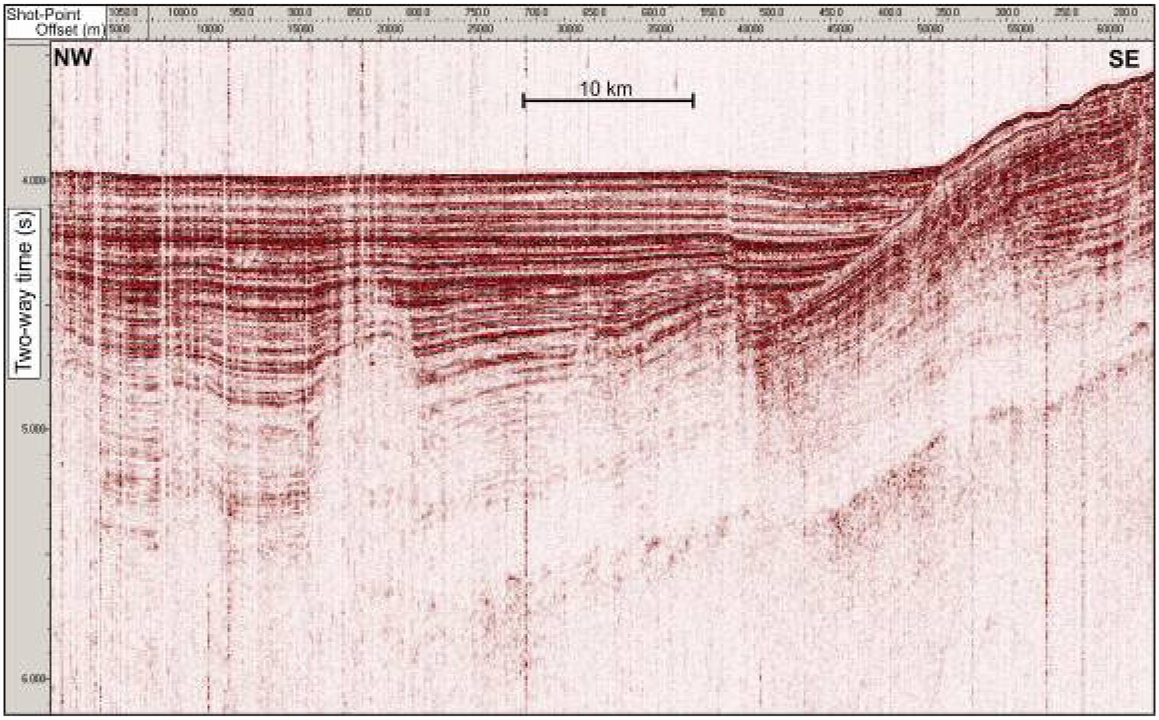

Figure 5. Example of airgun data recorded on single-channel streamer.

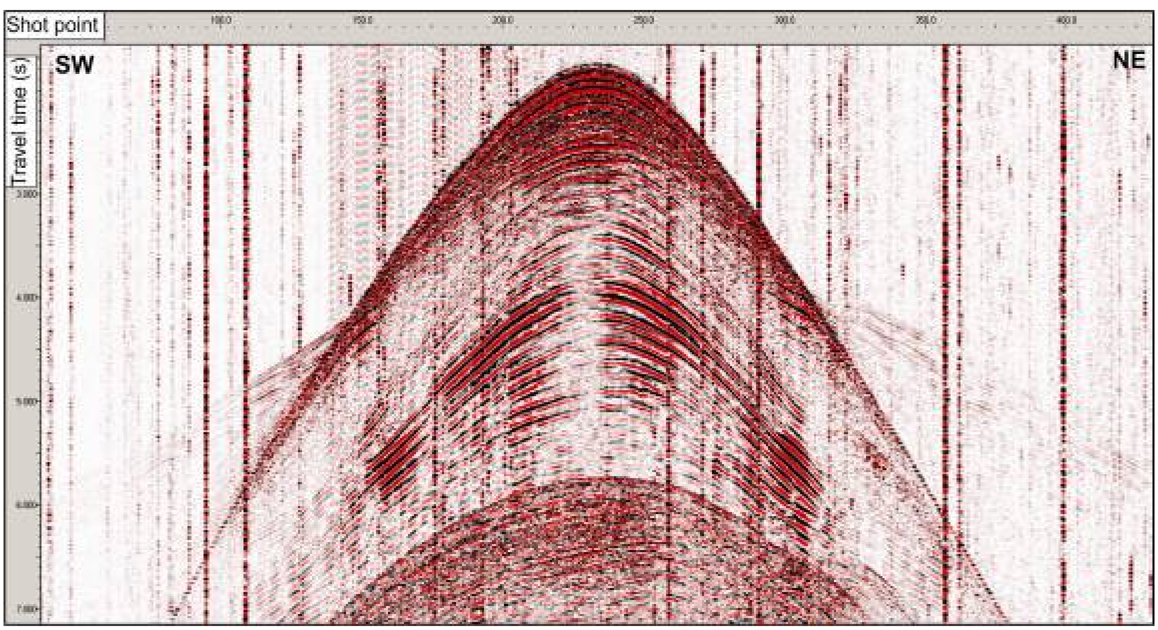

Figure 6. Example of airgun data recorded on D2 OBS #6 (western-most station of second refraction experiment) showing portion of SW-NE-trending main central line shot upslope across the terrace region. Clear refractions can be seen on both side of the shot-record.

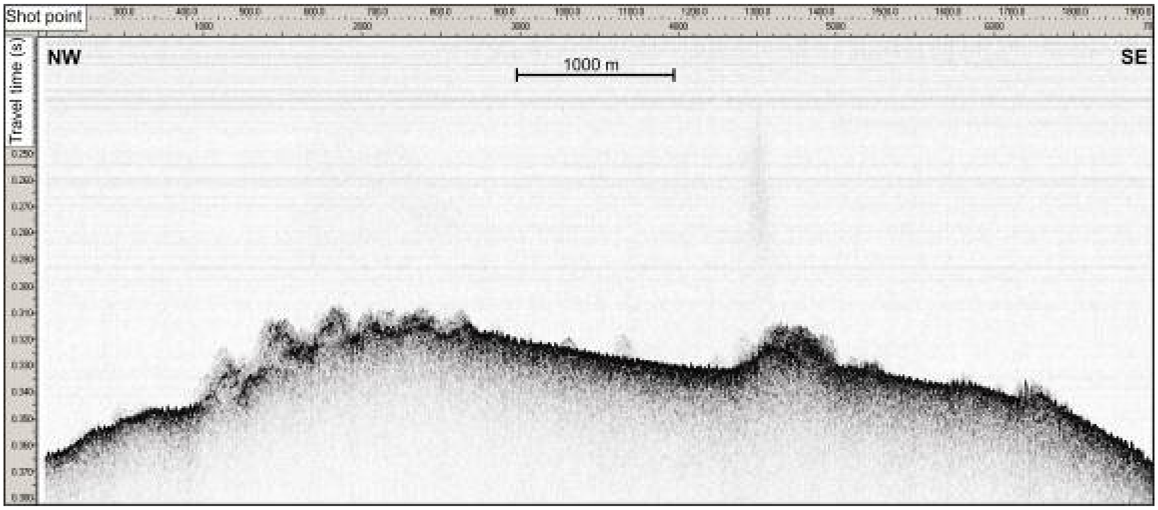

Figure 7. Example of the 3.5 kHz data recorded across plateau-feature on the last day returning to Port Hardy. Individual knoll-features produce chaotic signal from surface roughness. Note the hint of the gas plume at the largest knoll feature, near shot point 1300.

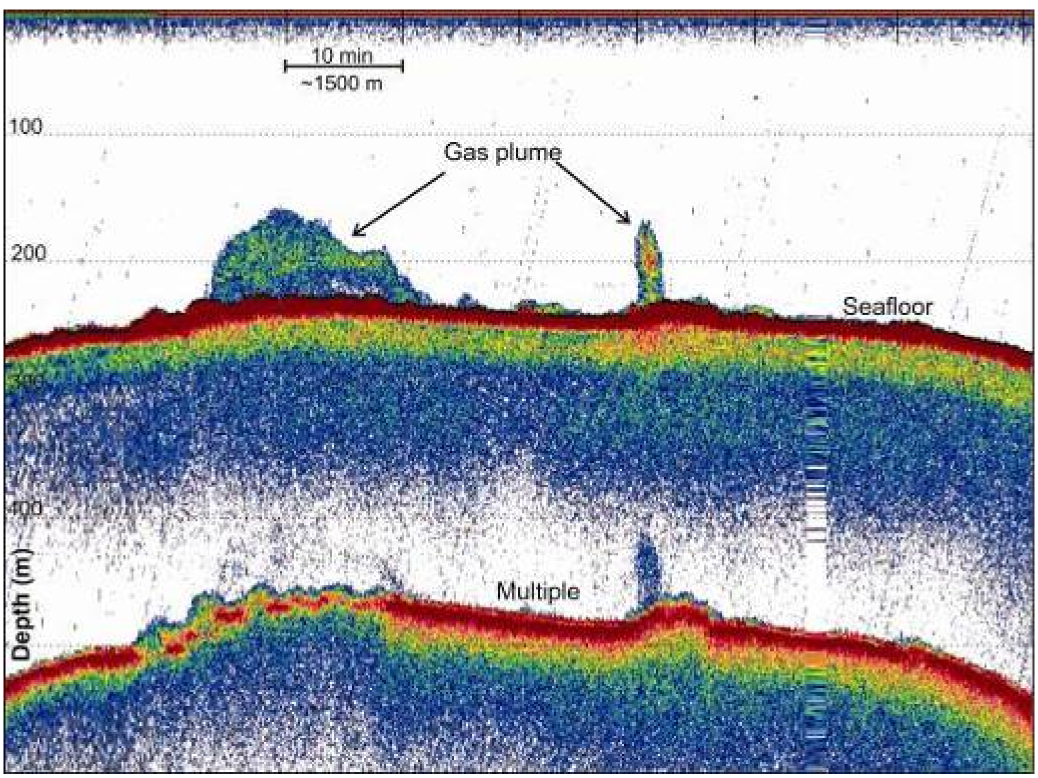

Figure 8. Example of the 12 kHz data recorded across plateau-feature on the last day returning to Port Hardy. Two large gas plumes are evident in the record.

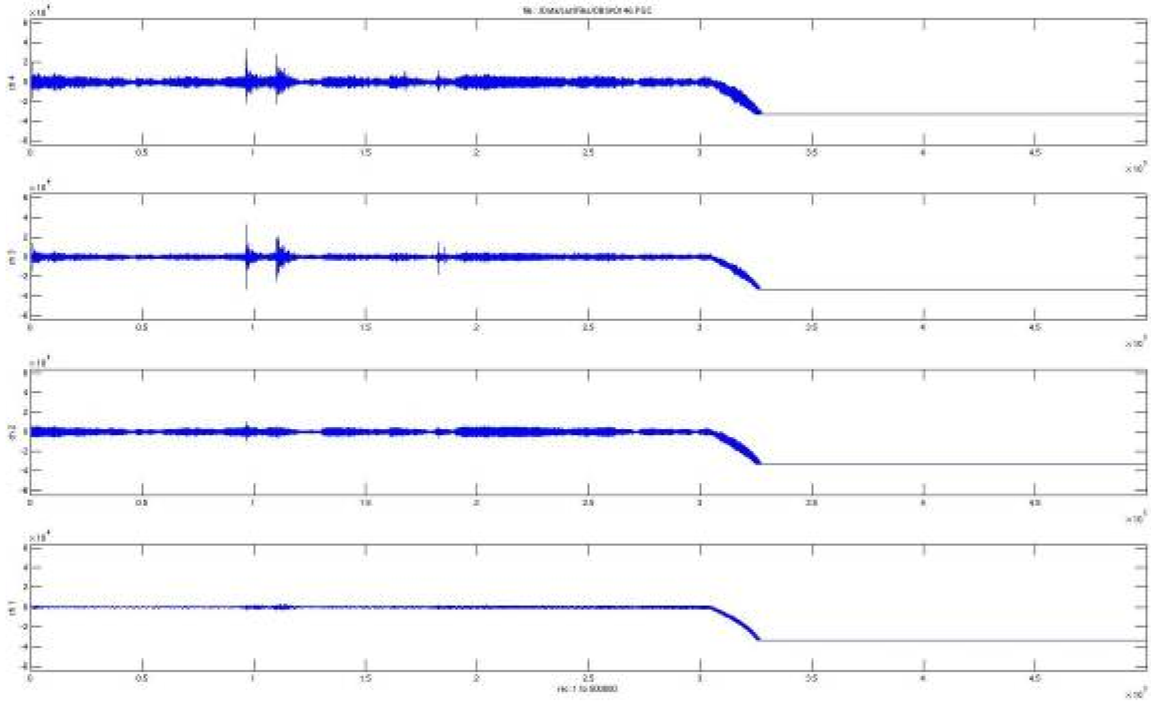

Figure 9a. End of recording cycle on OBS #1, NRCan-K, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

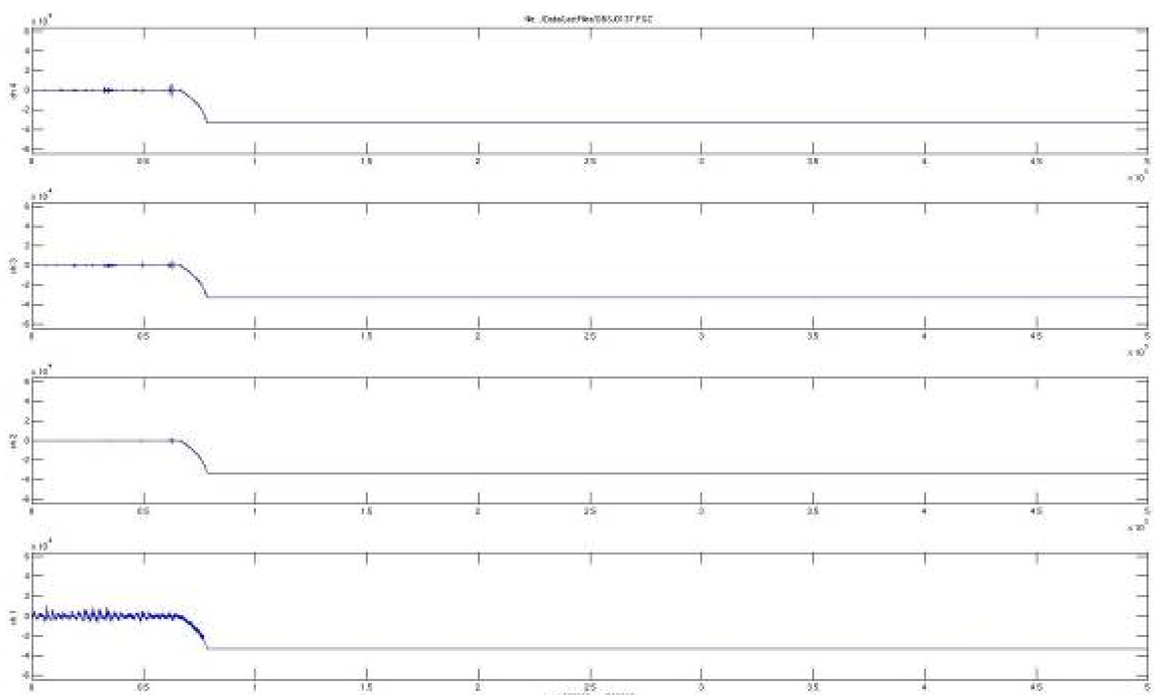

Figure 9b. End of recording cycle on OBS #2, NRCan-J, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

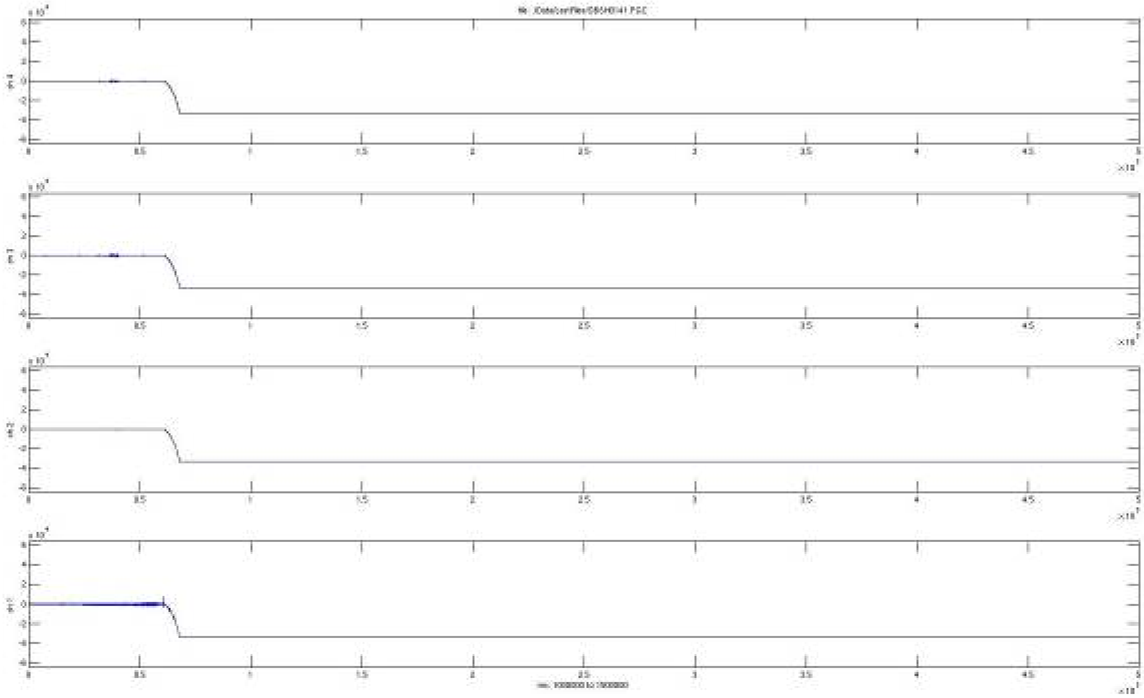

Figure 9c. End of recording cycle on OBS #3, NRCan-H, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

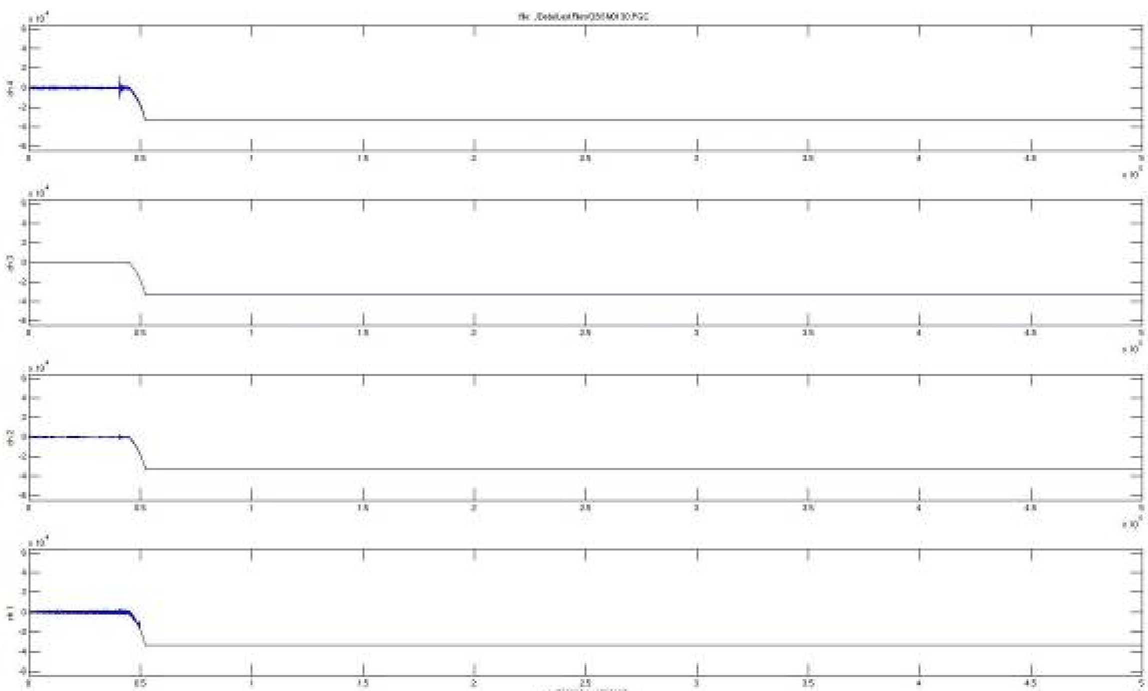

Figure 9d. End of recording cycle on OBS #4, NRCan-N, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

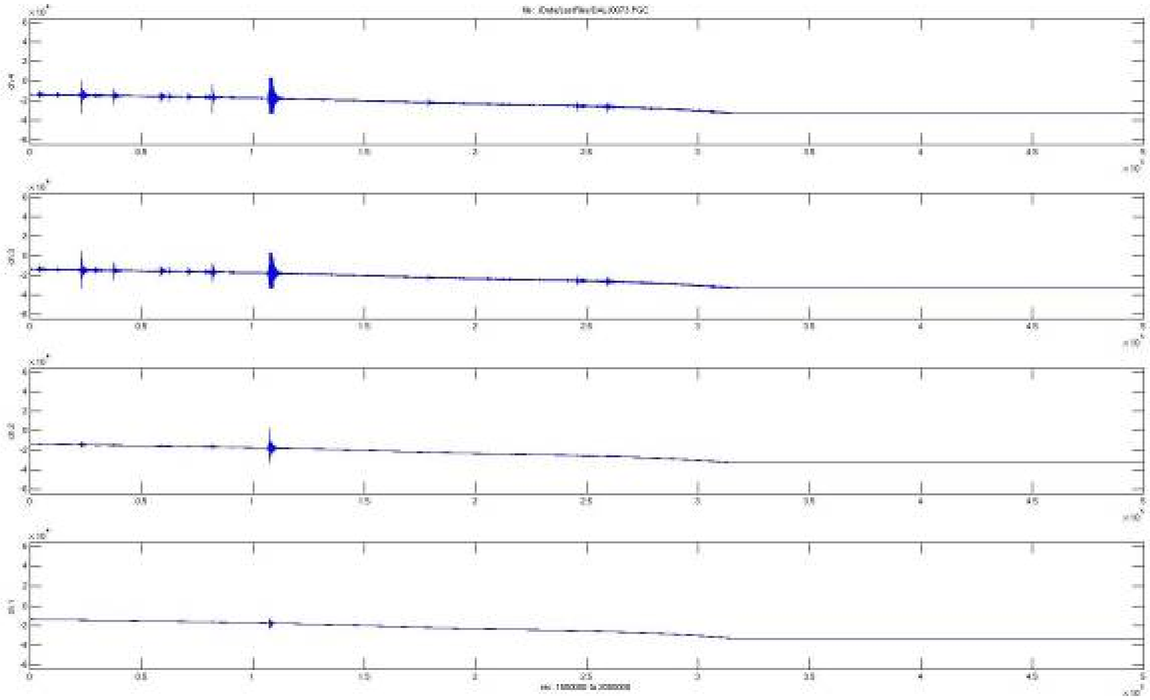

Figure 9e. End of recording cycle on OBS #5, Dal-J, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

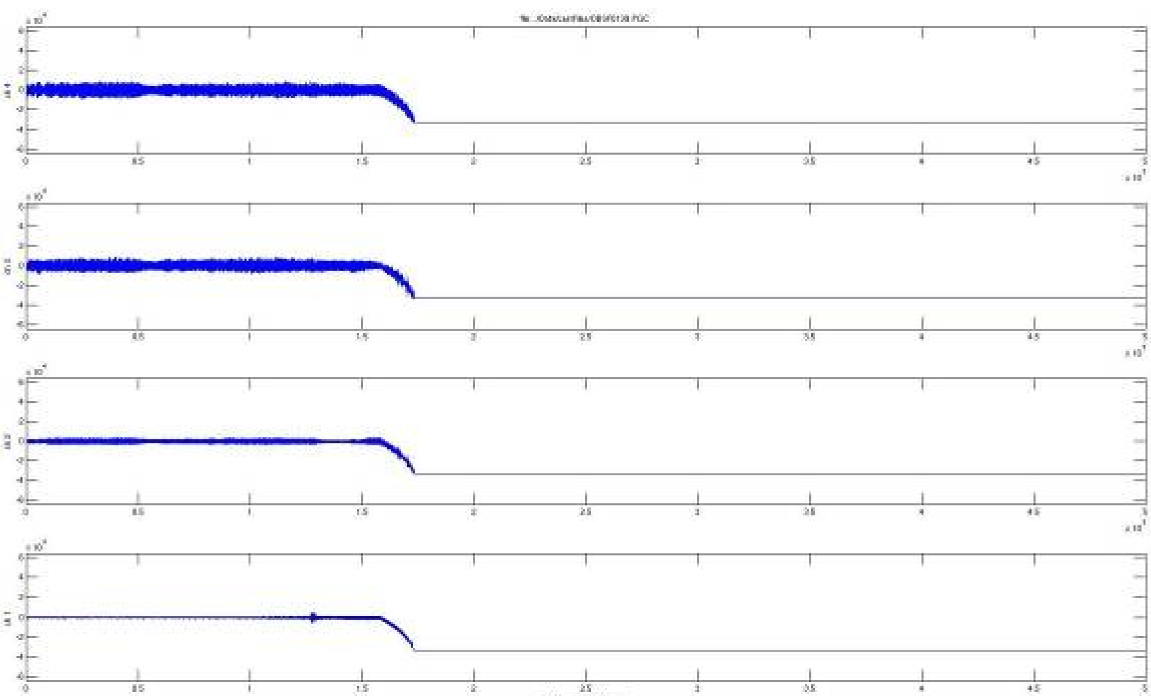

Figure 9f. End of recording cycle on OBS #6, NRCan-F, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

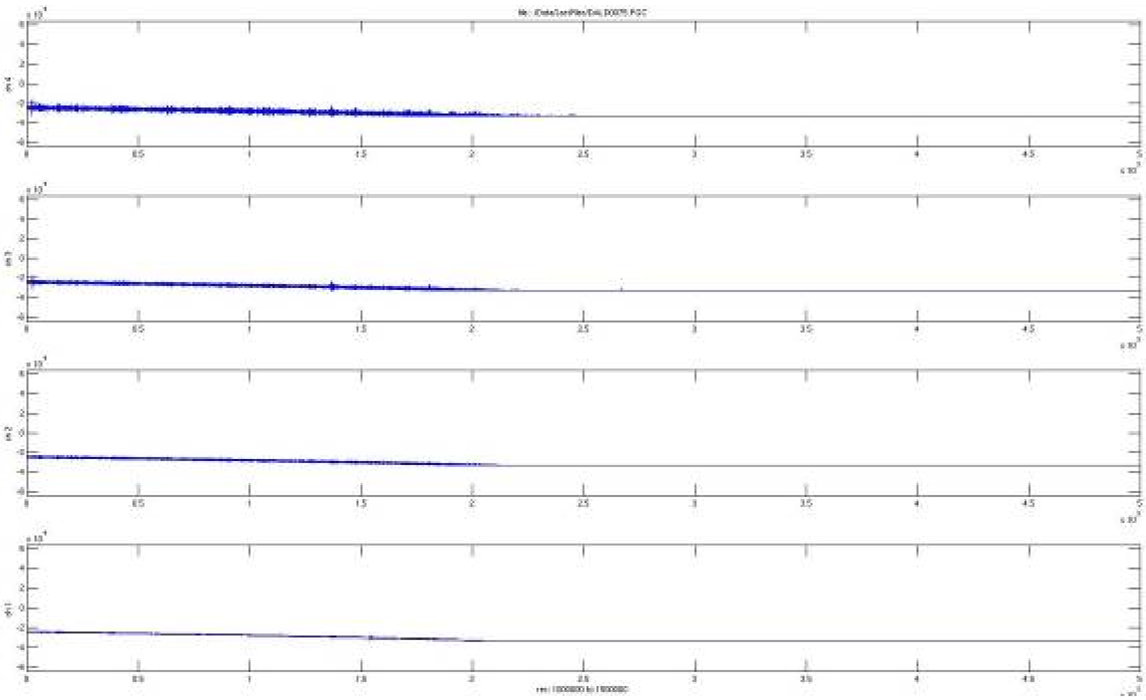

Figure 9g. End of recording cycle on OBS #7, Dal-D, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

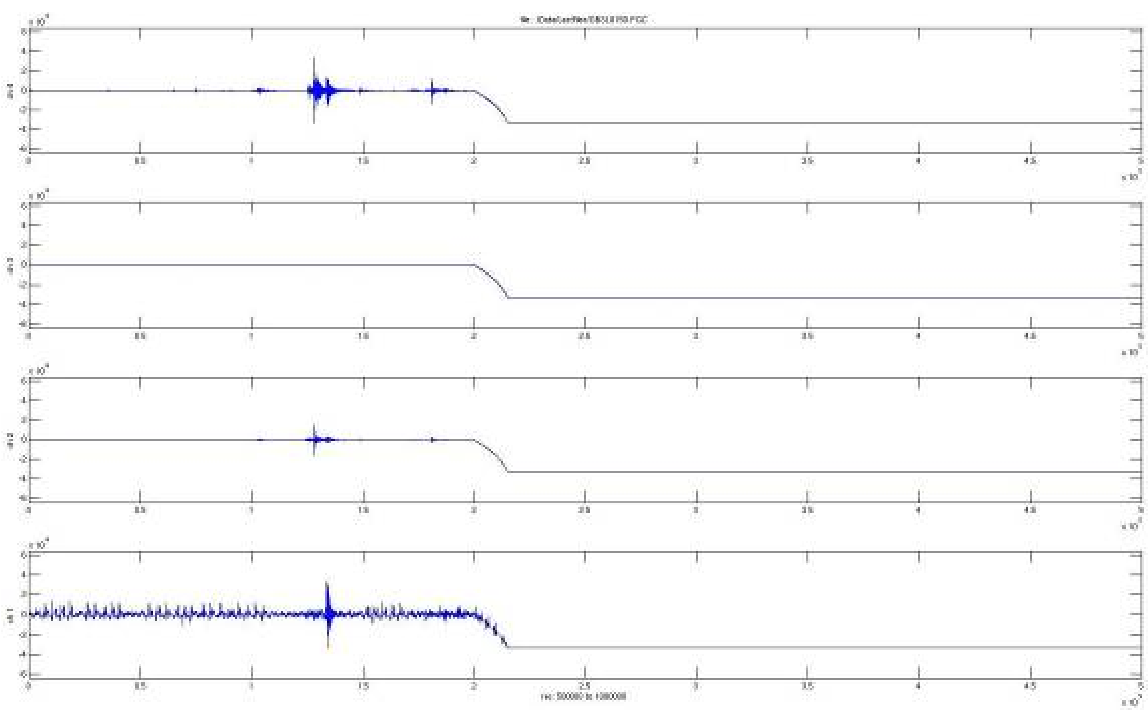

Figure 9h. End of recording cycle on OBS #8, NRCan-L, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

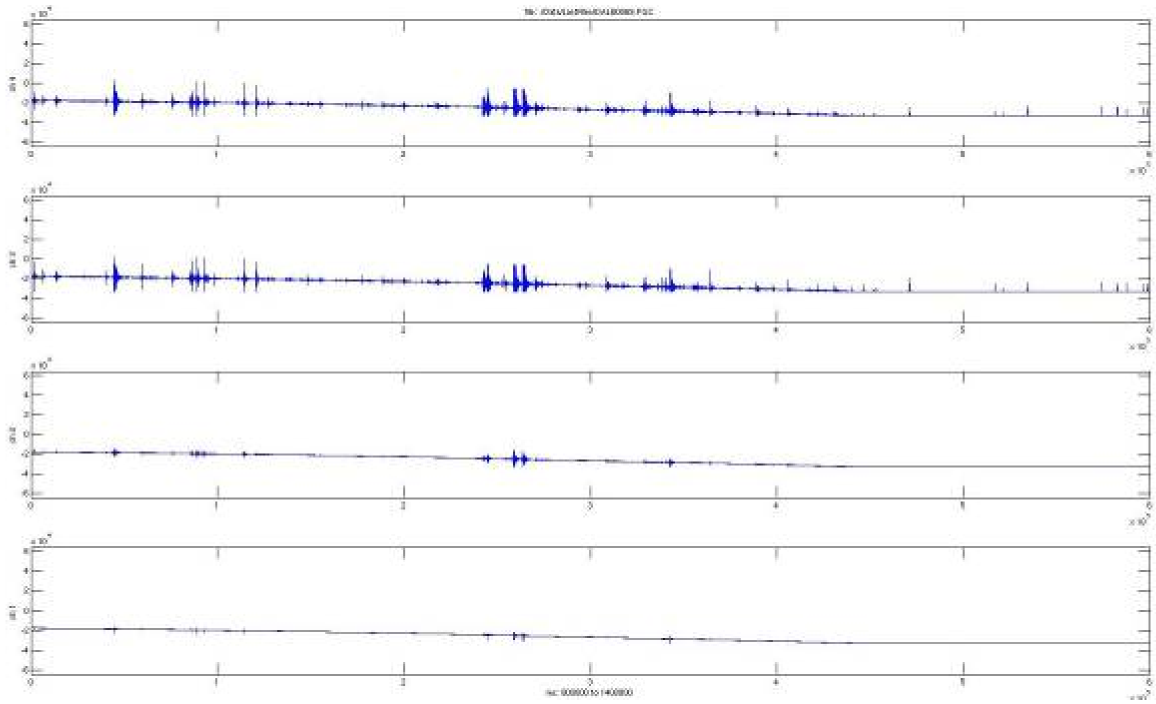

Figure 9i. End of recording cycle on OBS #9, Dal-B, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

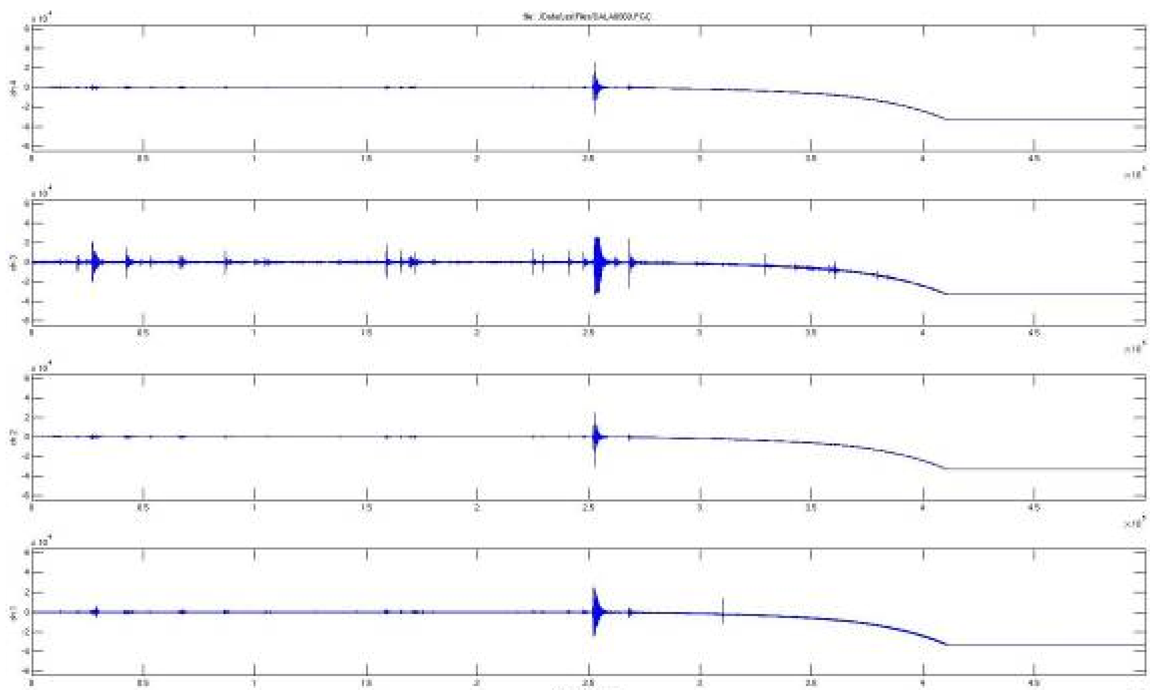

Figure 9j. End of recording cycle on OBS #10, Dal-A, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

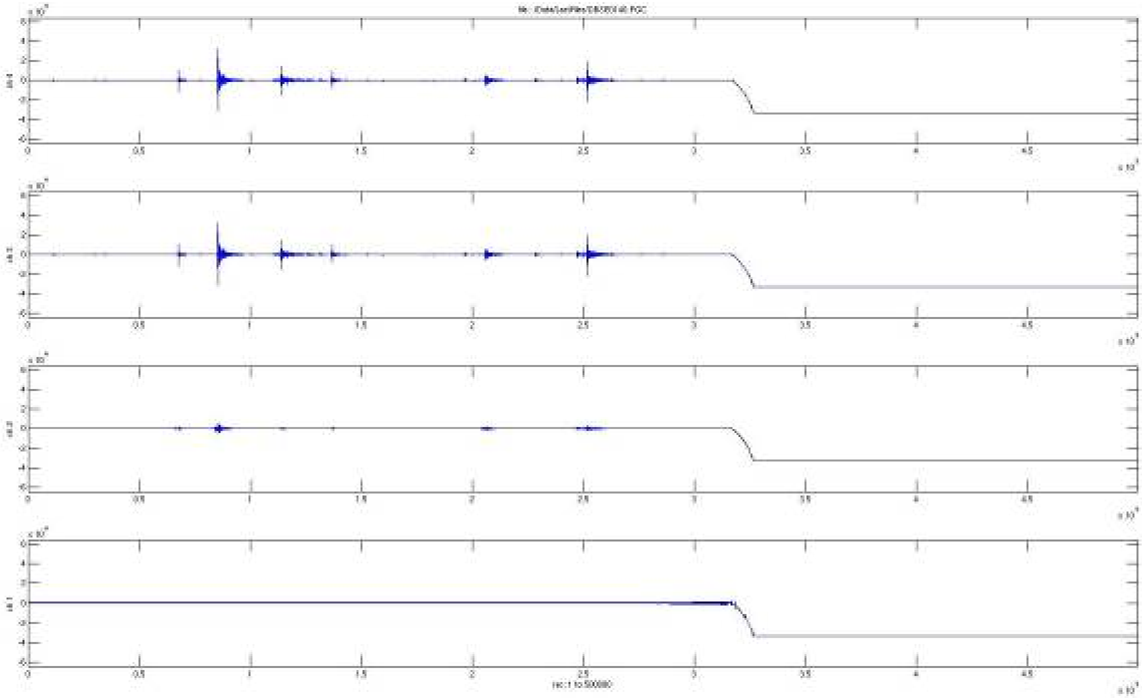

Figure 9k. End of recording cycle on OBS #11, NRCan-E, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

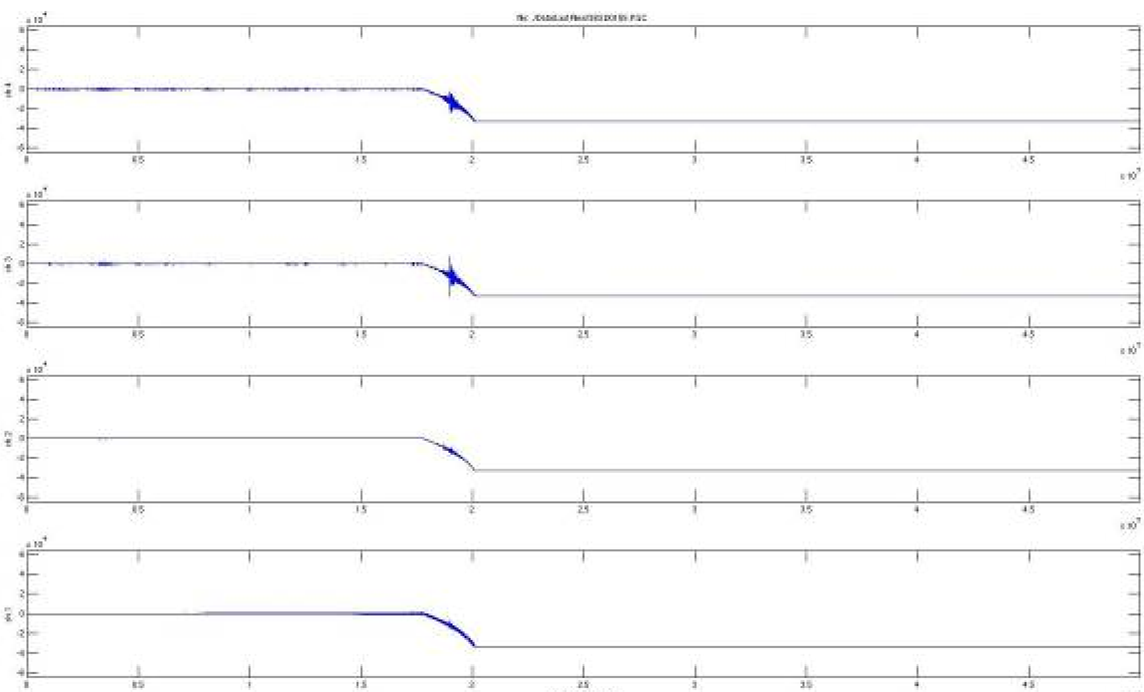

Figure 9l. End of recording cycle on OBS #12, NRCan-D, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

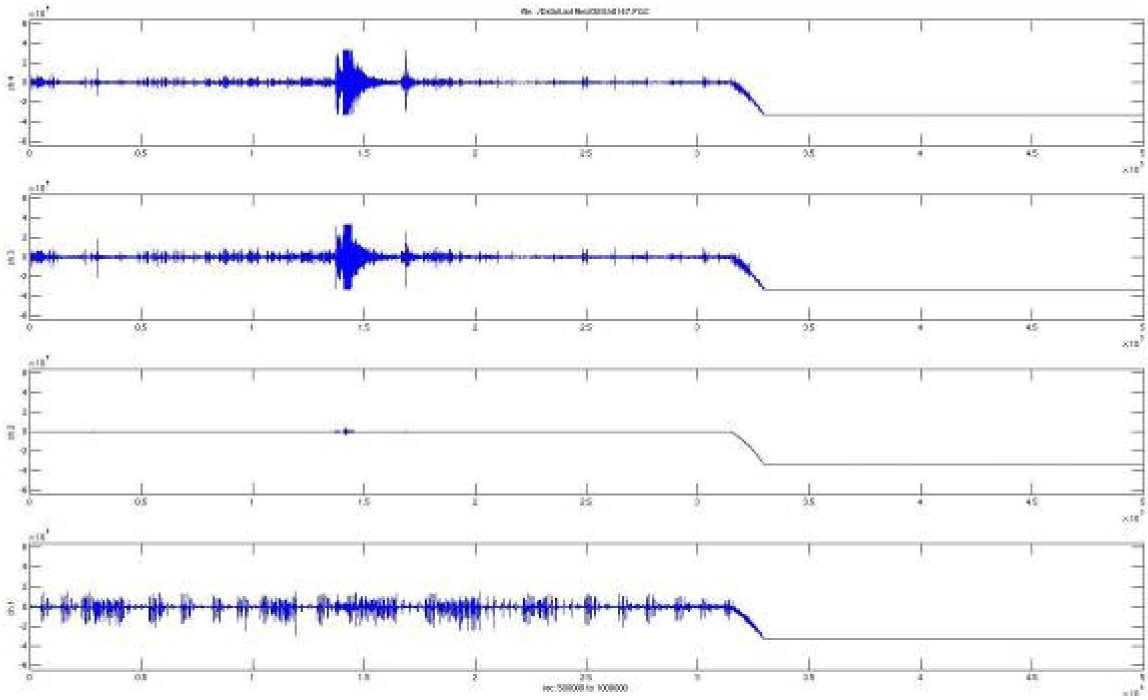

Figure 9m. End of recording cycle on OBS #13, NRCan-A, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

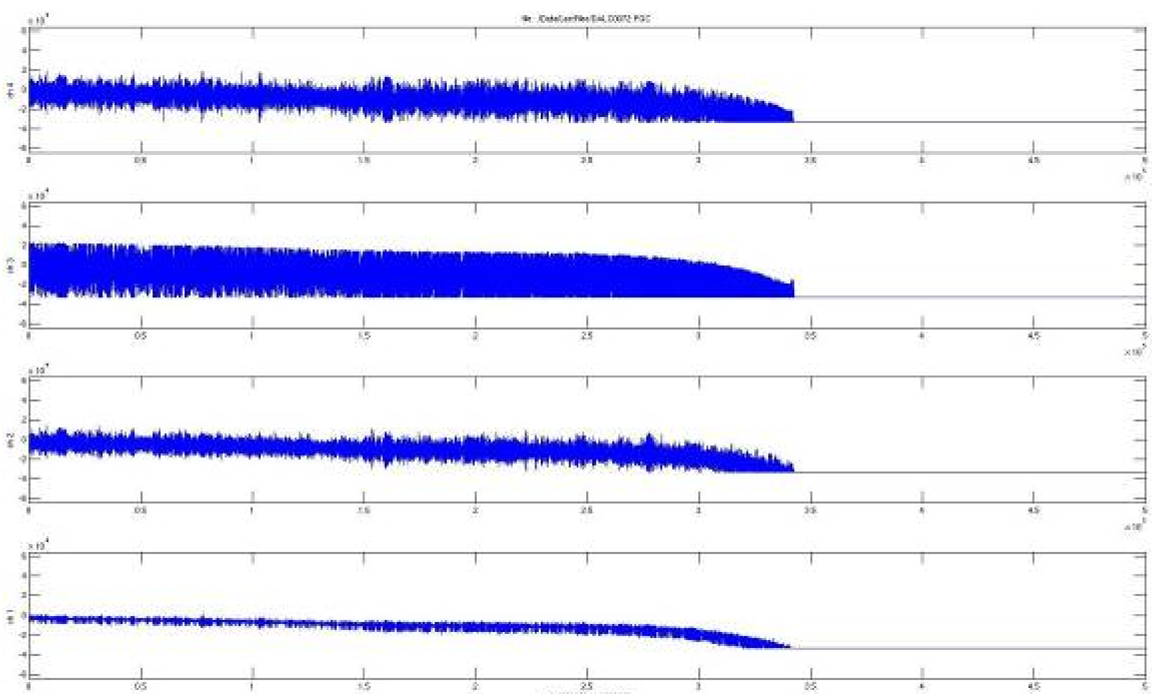

Figure 9n. End of recording cycle on OBS #14, Dal-C, from regional grid. Horizontal axis is sample-number (sampling rate is 500 Hz, total record length shown is 1000 seconds). All four channels are shown (ch1: hydrophone; ch2: vertical; ch3=horizontal 1; ch4: horizontal 2).

Appendix-A

COUNCIL OF THE HAIDA NATION

December 6, 2012

Dr. Michael Riedel
Natural Resources Canada
Geological Survey of Canada - Pacific
9860 West Saanich Road
Sidney, BC
V8L 4B2 Canada

Email: mriedel@nrcan.gc.ca

Dear Sir,

We have reviewed the project proposal "Haida Gwaii Earthquake Response – Ocean Bottom Seismometer and Refraction/reflection Seismic Experiment" that we received from Ernie Gladstone, the Gwaii Haanas Superintendent. We understand that the Archipelago Management Board (that includes Council of the Haida Nation representatives) has supported the project within Gwaii Haanas. The Council of the Haida Nation supports the project in the area outside the Gwaii Haanas marine area boundary and gives our permission for the project to proceed.

You have proposed to do surveys on the west coast of Haida Gwaii in the vicinity of the recent 7.7 magnitude earthquake. The surveys will take place both within the Gwaii Haanas marine area and in deeper water to the west of Gwaii Haanas during two cruises on December 7-12, 2012 and January 4-12, 2013 (tentative). The second cruise will involve experiments involving air guns and measures are proposed to avoid encounters with marine mammals.

We understand that you have invited us to place an observer on the vessel to work with two marine mammal observers. We accept the invitation. Brad Setso, the Haida Fisheries Program Manager, can work with you to identify a suitable observer and make the necessary arrangements. He can be contacted at 250 626-3302 or by email at brad.setso@haidanation.ca.

Sincerely

April Churchill

April Churchill
Vice President of the Haida Nation

cc: Ernie Gladstone
Brad Setso

☑ Box 98 Queen Charlotte City, Haida Gwaii, BC V0T 1S0 • Phone (250)559-4468 • Fax (250)559-8951
Toll Free Queen Charlotte City 1-877-559-4468

☐ Box 589 Massett, Haida Gwaii, BC V0T 1M0 • Phone (250)626-5252 • Fax (250)626-3403
Toll Free Massett 1-888-638-7778

Appendix-B

Fisheries and Oceans

Pêches et Océans

Pacific Region
Suite 200 - 401 Burrard Street
Vancouver, B.C.
V6C 3S4

November 29, 2012

Dr. Michael Riedel
Natural Resources Canada
Geological Survey of Canada - Pacific
9860 W. Saanich Road
Sidney, BC V8L 4B2

Dear Dr. Riedel:

RE: January 7 - 18, 2013
Natural Resources Canada Seismic Survey

The Fisheries Management Branch of Fisheries and Oceans Canada has a legal obligation to protect marine mammals under the *Fisheries Act* for any project that could disturb or harm marine mammals under the Marine Mammal Regulations and/or the *Species at Risk Act* (SARA).

We have reviewed the proposal and understand that a vessel cruise is proposed from January 7 – 18, 2013 to undertake active source seismic experiments and to retrieve 9 ocean bottom seismometers.

There are two separate components to the proposed active source seismic airgun experiments:

(a) A refraction seismic experiment using a single 520 cubic inch airgun (G-gun).

(b) A high-resolution reflection seismic experiment using a single 210 cubic inch GI-gun.

Estimated sound pressure levels of these air guns are equivalent to 215 dB re 1μPa-m_{rms} and 217 dB re 1μPa-m_{rms}, respectively. These are above the sound pressure level considered to cause temporary threshold shifts and behavioural disturbance in marine mammals.

Due to the likely presence of marine mammals including long diving species such as sperm and beaked whales, enhanced mitigation measures are required to prevent disturbance or harm.

Canadä

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Marine Mammal Mitigations Measures:

All participants should be reminded of their obligation to comply at all times with Section 7 of the *Marine Mammal Regulations*, which specifically prohibits the disturbance of marine mammals.

1. Marine Mammal Observers:

   Two trained DFO-approved marine mammal observers dedicated to maintaining constant observations for marine mammals during daytime operations in the ship's vicinity prior to and during seismic array operations. The marine mammal observers shall submit a written report containing the following information within 90 days of research completion to the Marine Mammal Coordinator:

   a. Date, time and position of seismic operations of each seismic array at start-up and shut down;
   b. Date, time, position, species and numbers of all marine mammal sightings;
   c. Date, time, and position of all seismic array shut-downs or start-up delays required because of marine mammals in the area of study; and the species and numbers of marine mammals causing the shut-down or start-up delay.
   d. In the unlikely event that a marine mammal is impacted, detailed description(s) of any observations of marine mammal impacts in the area of study should be recorded.

2. Exclusion Zone:

   A marine mammal exclusion zone having a radius of 1,500 m will be established and monitored to ensure under water sound pressure levels are less than 160 dB re 1µPa outside of this radius.

3. Pre-Operations Monitoring:

   The marine mammal exclusion zone must be visible to the marine mammal observer and is to be monitored for 60 minutes prior to initial start-up of the airgun or upon resumption of operations following a shut-down due to a marine mammal sighting within the exclusion zone.

4. Power-down and Shut-down Triggers:

   The air gun will be shut down should a marine mammal be observed within or about to enter the 1,500 m exclusion zone.

5. Start-up Procedures following Shut-downs and Power-downs:

   Airgun operations are not to start unless the zone is visible to the marine mammal observers and has been monitored for 60 minutes immediately prior to start-up. Procedures for ramp up to full power should occur over a 30-minute period as stated in the proposal. Should a shut-down be required for maintenance or other operational reasons when the exclusion zone is not visible (e.g., in thick fog or at night), no start-up will be initiated until the zone is visible.

6. These mitigation measures are valid for this survey as proposed. After this time, if the subject works have not been completed, this letter will be void. This will ensure that the proposed project will conform to current management policy, guidelines, and legislation.

7. It is understood that by proceeding with the proposed seismic activities, you, your contractors, agents or partners have indicated you understand and have agreed to the foregoing mitigation measures. In addition, a copy of this letter is to be available on board the vessel for the duration of the project.

8. All materials and equipment used for the purpose of project completion shall be operated in a manner that prevents any deleterious substances (e.g. petroleum products, etc.) from entering the water.

9. Any variances must be submitted to the DFO Marine Mammal Coordinator's office for review and approval, prior to any changes being implemented.

Please note that this Letter of Advice does not absolve the proponent from the responsibility of securing any other permits as may be required by federal or provincial legislation. If a disturbance occurs as a result of a change in the plans for the proposed activity, or failure to implement the mitigation measures specified above, contravention of Subsection (7) of the *Marine Mammal Regulations* or SARA could occur.

If you wish to discuss the mitigation measures, or you have any other questions, please contact the undersigned at 604-666-9965. If you propose to undertake the above marine mammal mitigation measures, please confirm by signing and returning a copy of the Letter of Advice attached to this letter.

Sincerely,

Paul Cottrell
A/Marine Mammal Coordinator
Fisheries and Aquaculture Management
Fisheries and Oceans Canada – Pacific Region

cc: J. Ford, L. Nichol DFO

Please sign this page and fax or scan a copy to: Annely.Greene@dfo-mpo.gc.ca

Fisheries and Aquaculture Management – Pacific Region
Marine Mammal Program
Suite 1420 - 401 Burrard Street
Vancouver, BC V6C 3S4

Attention: Paul Cottrell

RE: **January 7 - 18, 2013**
Natural Resources Canada Seismic Survey

LETTER OF ADVICE

I, Carmel Lowe, having authority to commit funds and activities on behalf of **Natural Resources Canada** have read and understood correspondence from DFO dated November 29, 12, outlining recommended marine mammal mitigation measures for the proposed seismic research.

Response:

(✓) I agree to the recommended mitigation measures in the above-referenced correspondence and commit to apply them during the proposed work or undertaking.

Signed Carmel Lowe
Title Director, GSC-Pacific
Dated Dec. 3rd 2012

Note: Failure to show due diligence in the protection of Marine Mammals could result in violation(s) of the *Fisheries Act* or *the Species at Risk Act*. In addition, this correspondence addresses only the concerns of DFO-FAM. It is the obligation of the proponent to meet any other regulatory requirements.