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Integrative onshore-offshore fault mapping and hazard assessment, Icy Bay, southeast Alaska

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Contents

Abstract

The St. Elias Mountains in southeastern Alaska represent the tallest coastal mountain range in the world. The tectonically active orogen is the result of the collision of the Yakutat Terrane, an anomalously thick piece of oceanic crust and microplate, with the North America Plate. Convergence between the Yakutat Terrane and the North America Plate is accommodated locally along several fault strands including the Malaspina Fault and Foreland Fault Zone, which mark the onshore/offshore deformation front between the two plates. The active tectonics and steep relief in the St. Elias Mountains poses landslide and tsunami hazards regionally. The Yakutat/North America subduction/collision zone last ruptured in a series of major earthquakes in September of 1899. The largest event in this series, a M_w 8.2 event on 10 September, likely ruptured onshore portions of the Malaspina system, causing over 14 m of coseismic uplift and a 6 m tsunami in Yakutat Bay, Alaska. The onshore-offshore connections of the Malaspina Fault and the potentially important Foreland Fault Zone likely traverse Icy Bay but have yet to be mapped there in detail despite the penultimate Mw 8.1 event on 4 September 1899 likely occurring near or within Icy Bay. The hazards associated with the structure and geology of the St. Elias Mountains and the Yakutat/North America plate boundary make the Icy Bay region an obvious target for first-order mapping and hazard assessment related to earthquakes, landslides, and tsunamis.

We aimed to find, quantify, and characterize offshore fault systems and landslide/tsunami deposits within Icy Bay and Taan Fjord in a multi-disciplinary, collaborative, and multifaceted approach. During an 18-day cruise aboard the R/V *Alaskan Gyre* in August 2016, in a joint effort between the U.S. Geological Survey (USGS), The University of Texas Institute for Geophysics (UTIG), and Texas A&M University (TAMU), a suite of high-resolution multi-channel seismic (MCS) data and multibeam bathymetry were collected in Icy Bay and Taan Fjord. The seismic system included TAMU's DuraSpark sparker source along with a dual-streamer system including UTIG's 24-channel, ~72 m active length streamer and TAMU's 24-channel, 150 m active length streamer. Highlights of data collection include a complete multibeam bathymetry map of the Taan Fjord seafloor and over 450 line-km of MCS data collected in Taan Fjord and Icy Bay. These new geophysical data will provide new information about active fault structures in Icy Bay.

Field Work Details

Dates: August 2 - August 19, 2016

Port of Origin: Homer, Alaska

Port of Termination: Seward, Alaska (DEMOB) and Homer, Alaska (ship)

Personnel:

Sean Gulick, co-chief scientist, University of Texas Institute for Geophysics (UTIG)
Peter Haeussler, co-chief scientist, United States Geological Survey (USGS)
Maureen Walton, co-chief scientist, USGS
Bobby Reece, geophysicist, Texas A&M University (TAMU)

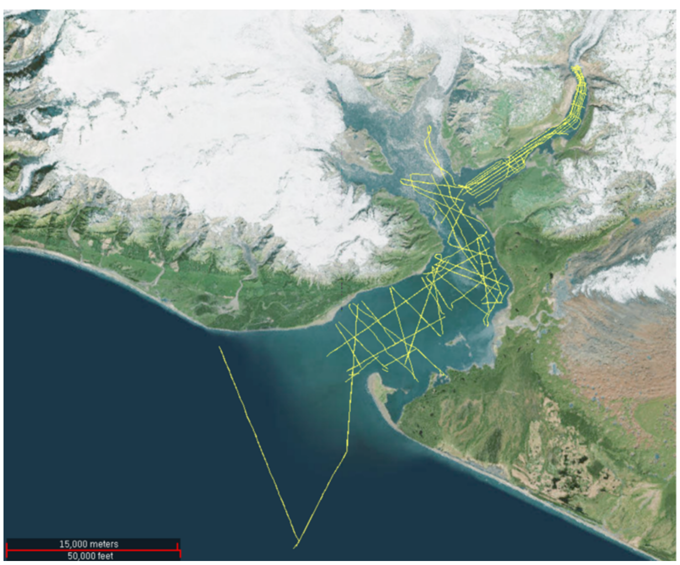
Steffen Saustrup, seismic technician, UTIG
Naoma McCall, graduate student watchstander, UTIG
Billy Choate, captain (first segment), USGS
Greg Snedgen, captain (second segment), USGS

Primary equipment:
R/V *Alaskan Gyre* (USGS)
Applied Acoustics DuraSpark sparker source (TAMU)
Geometrics MicroEel 24-channel, ~144 m streamer (TAMU)
Beam Systems 24-channel, ~75 m streamer (UTIG)
Teledyne Reson SeaBat T50-P multibeam sonar (UTIG)
CastAway Conductivity-Temperature-Depth (CTD) profiler (UTIG)

Objectives

The primary goal of the UTIG-USGS-TAMU Taan Fjord/Icy Bay cruise in 2016 was to map and characterize offshore fault structures in Icy Bay associated with the Yakutat/North America deformation front. The USGS Earthquake Hazards Program (EHP) originally funded the MCS survey of Icy Bay in order map active and/or seismogenic faults offshore; namely, the Malaspina Fault and the Foreland Fault Zone and how they connect to the offshore faults in the Pamplona Zone. Secondary scientific objectives potentially include characterizing the 2015 Taan landslide failure and modeling the resultant tsunami, mapping Icy Bay glacial deposits, examining tectonic controls on Taan Fjord, researching the geomorphology and slope processes in Taan Fjord, and identifying paleohazards (MTDs, paleoseismic events, etc.) within the region. A four day extension (from 2 weeks to 18 days) was funded by the National Science Foundation to aimed at understand landslide hazards specifically. We summarize here the full data set collected by the USGS and the add-on program from the NSF.

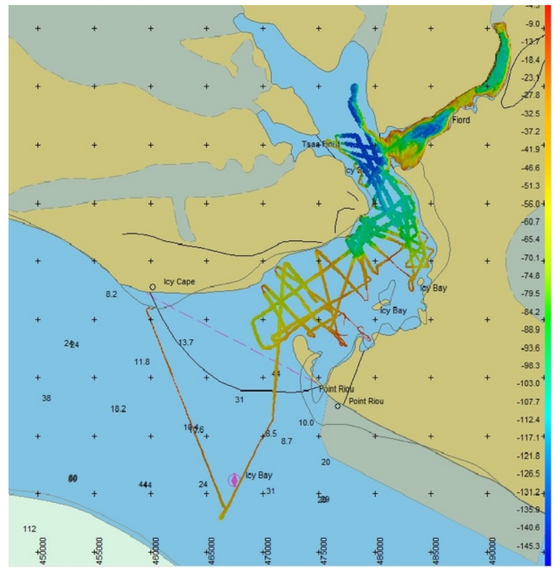
Synopsis of Survey



We acquired over 450 km (~466 km assuming constant 4 kt survey speed) of 2D MCS data (Fig. 1, Appendix A), a complete ~25 km^2 bathymetry grid of Taan Fjord (Fig. 2), and multibeam bathymetry data coincident with 102 seismic profiles in both Taan Fjord and in Icy Bay (Fig. 2).

Figure 1 (left). MCS survey trackline map in Icy Bay and Taan Fjord after loading data into Halliburton’s Landmark DecisionSpace Desktop interpretation software (www.landmark.solutions). Data are projected in UTM (zone 7N), with north straight up in this image, basemap is from ArcMap world imagery (www.ersi.com). See Fig. 3 for bathymetry coverage of the same area

Figure 2 (Right). Full raw bathymetry coverage in Icy Bay and Taan Fjord, a screenshot from the Teledyne PDS interpretation software (www.teledyne-pds.com). Projection and coordinates are UTM (Zone 7N). Background map shows Alaska ENCs (www.charts.noaa.gov).



Daily Log of Operations

31 July 2016: Scientists Walton, Gulick, Reece, Saustrup, and McCall arrive in Anchorage.

1 August 2016: Scientists meet at USGS Anchorage in the morning to retrieve USGS box truck that Haeussler loaded with shipped seismic and multibeam gear from TAMU and UTIG, respectively. Purchase some remaining supplies at hardware store in Anchorage. Travel to Homer with all personnel, seismic, and multibeam equipment in USGS suburban and box truck. Begin MOB aboard R/V *Alaskan Gyre* upon arrival in Homer.

2 August 2016: Continue MOB in Homer in the morning. Purchase supplies at grocery and hardware stores in Homer. Depart Homer for Icy Bay in the afternoon aboard the R/V *Alaskan Gyre.*

3 August 2016: Transit to Icy Bay in excellent weather conditions.

4 August 2016: Transit to Icy Bay; continuing excellent weather conditions. Work on lab and multibeam system setup during transit. Arrive in Icy Bay late afternoon; anchor in central Taan Fjord near the beach. Science crew takes Zodiac to land to interface with NSF-funded land-based team.

5 August 2016: Complete lab setup in the morning, test seismic and multibeam equipment in Taan Fjord. Run GAMS test for POS GPS system; GAMS never comes online. Do not receive

RTK radio signal from land-based team (Dan Shugar). Despite these issues, perform an initial multibeam patch test in the afternoon. Patch test processing completed by Walton and McCall in the evening; strong solution found for roll, weak solutions for pitch and yaw. Anchor for the night at a beach in mid-fjord, near where the land-based team was camping.

6 August 2016: First full day of both MCS and multibeam surveying in Taan Fjord; MCS survey includes lines 1601-1607. MCS setup has both TAMU and UTIG streamers towing side-by-side, with TAMU streamer towed on the port side and UTIG on the starboard side. Good multibeam coverage achieved in upper Taan Fjord at landslide deposits; however, GAMS was never achieved so heading error was on the order of several degrees all day. Several longitudinal seismic profiles in both MCS and multibeam collected along the fjord. Anchor for the night at a beach in mid-fjord, near where the land-based team was camping.

7 August 2016: Full day of MCS and multibeam surveying in Taan Fjord; MCS survey includes lines 1608-1615. Achieve GAMS close to the start of surveying; multibeam becomes main priority for the day. Fill gaps in multibeam coverage in upper Taan Fjord, re-surveying some areas. One long longitudinal profile shot along most of fjord in both multibeam and MCS. Rest of MCS data shot where multibeam surveying allowed for longer, straight lines. Anchor in central Taan Fjord for the night.

8 August 2016: Last full day of MCS and multibeam surveying in Taan Fjord. MCS data include lines 1616-1648. Line 1648 is the last of the lines shot with the parallel streamer configuration. Much of the day spent shooting boxcar seismic profiles in upper and lower fjord, and filling in multibeam coverage in lower fjord. Anchor in central Taan Fjord for the night.

9 August 2016: Morning spent in Taan Fjord wrapping up Taan multibeam and MCS surveys, largely filling multibeam gaps in the lower fjord and extending outer bounds of the multibeam survey in the lower fjord. In the afternoon, start Icy Bay survey, focusing on MCS profiles. Tracklines in the upper bay somewhat limited by ice coverage; however, several long starting lines in the mid and upper bay shot successfully. MCS profiles shot include lines 1649-1658, with coincident multibeam collected for all lines. Starting today, we tow the long TAMU streamer even farther behind the boat with the intention of combining data from the UTIG and TAMU streamers, using the longer offsets and reducing streamer redundancy. All future MCS lines use this streamer configuration. After surveying, anchor in eastern Icy Bay.

10 August 2016: Good weather allows for MCS surveying outside of Icy Bay; several long deepwater lines shot in an attempt to tie the Icy Bay survey to pre-existing deepwater seismic surveys. MCS profiles shot include lines 1659-1661, with coincident multibeam collected for all lines. Stop surveying in mid-afternoon to transit back to Taan Fjord to pick up Captain Greg Snedgen, who takes over for Captain Billy Choate. Captain Snedgen analyzes fuel and water levels and determines we should re-fuel as soon as possible. Taking advantage of the relatively calm seas, depart for Yakutat late that evening and transit ~10 hours overnight.

11 August 2016: Arrive in Yakutat in early AM, refuel and resupply water. Discuss weather, decide to head back to Icy Bay in 6-8 foot following seas. Depart for Icy Bay at around 10 a.m., arrive in Icy Bay at around 6 p.m., making good time despite rough weather. Anchor near Icy

Bay Lodge.

12 August 2016: Full day of Icy Bay MCS and bathymetry surveying. Attempt to survey near outer bay; rough weather prevents extending out as far as 10 August's lines. Survey several bay-crossing lines in a zig-zag pattern to complement and cross 9 August's data in the mid-Bay. MCS line numbers include 1662-1672, with coincident multibeam collected for all lines. Anchor for the night near Icy Bay Lodge. Saustrup and Reece process acquired MCS data and develop workflows for extra-long streamer configuration.

13 August 2016: Full day of Icy Bay MCS and bathymetry surveying in Icy Bay. Some lines shot in mid-bay to complement previous lines and target suspected structures. Ice coverage in northern Bay allows for several long profiles in the upper, eastern part of Icy Bay past Taan Fjord near Yahtze Glacier. MCS line numbers include 1673-1689, with coincident multibeam collected for all lines. Anchor in Taan Fjord for the night. Saustrup and Reece continue to work on extra-long streamer processing workflows.

14 August 2016: Last full day of multibeam and MCS surveying. Spend the morning filling gaps in multibeam coverage around the edges of Taan Fjord and in outer Taan Fjord; no MCS. Deploy streamers in late morning and collect several MCS profiles in northern Icy Bay between Taan Fjord and Tsaa Fjord. MCS line numbers include 1690-1699, with coincident multibeam collected for all seismic lines.

15 August 2016: Complete seismic and bathymetry surveying in the morning with two final seismic lines (1700-1701). Begin DEMOB in the afternoon by disassembling, packing, and strapping down equipment for transit. Weather forecast does not allow for full 48+ hour transit to Homer so decision is made to stop in Seward to unload equipment and personnel. Begin transit to Seward in the evening due to a slightly more favorable forecast beginning that evening and lasting through the following day.

16 August 2016: Continue transit to Seward in reasonable, though occasionally rough, weather conditions (max of 6-8 foot seas). Scientists continue to work on seismic processing and cruise report when possible.

17 August 2016: Arrive in Seward in early AM. Unload equipment onto dock using the *Gyre* boom and winch. Walton, Gulick, and Reece then load equipment into the USGS box truck (which was driven from Anchorage by Alan Pongratz) to complete DEMOB. Scientists Walton, Gulick, and Reece disembark in Seward in order to catch plane flights the following day. Gulick accompanies the gear and the box truck to a FedEx location in Anchorage and ships equipment back to TAMU and UTIG. Reece and Walton take a bus back to Anchorage. The R/V *Alaskan Gyre* continues with Haeussler, McCall, Saustrup, and Captain Snedgen toward Homer for a short distance during the remaining good weather window and anchors at a fishing anchorage along the Kenai Peninsula to wait out a short storm.

18 August 2016: Scientists Walton, Reece, and Gulick depart Anchorage for home. The R/V *Alaskan Gyre* continues on to Homer with Haeussler, McCall, Saustrup, and Captain Snedgen after waiting out a short storm.

19 August 2016: Haeussler, McCall, Saustrup, and Captain Snedgen arrive in Homer in the early AM and disembark. Haeussler and McCall drive USGS suburban back to Anchorage. Saustrup remains in Homer for personal vacation.

Equipment and Acquisition Setup

Figure 3. Lab setup during the 2016 Icy Bay/Taan cruise aboard the R/V *Alaskan Gyre*. Left: seismic. Below: multibeam. Photos by Maureen LeVoir Walton (2016).

Equipment aboard the *Alaskan Gyre* was set up in the lab (Fig. 3) and on the main deck outside the lab. Below are detailed descriptions of each piece of equipment and how it was used on board the R/V *Alaskan Gyre* during the 2016 cruise. See Appendix B for scale schematic representations of the boat and equipment layout.

R/V Alaskan Gyre (modified from http://alaska.usgs.gov/science/tools/Gyre.php)

Figure 4 (left). The R/V *Alaskan Gyre.* Photo by Maureen LeVoir Walton (2016).

The R/V *Alaskan Gyre* (Fig. 4) is a 50-foot fiberglass seiner that has been converted into a versatile research vessel for use by the U.S. Geological Survey. The vessel was built by Ledford Marine of Marysville, Washington in 1989 and is named after a series of wind driven currents that rotate counterclockwise in the Gulf of Alaska. The *Gyre* is designed for working in inside waters and coastal water of the open ocean; the fiberglass hull limits its ability to cruise in heavy ice. There is a main deck comprising the lab, work area, and indoor living area with a bunking area in the forepeak containing 4 bunks. There is a smaller upper deck above the living area containing the wheelhouse and additional storage space. Inside the belly of the boat, there is a "fish hold" area that is used for storage, and also contains three bunks. An enclosed "deck lab" encloses the aft third of the stern work deck. The vessel can safely and efficiently accommodate many types of scientific sampling. A number of instruments have been successfully deployed from the Alaskan Gyre including: CTD, side scan sonar, towed sonic tracking hydrophones, gravity core, ADCP, Eckman grab sampler, Shipeck dredge, Tucker trawl, plankton nets, long-line fisheries sampling, pot fisheries sampling, drop camera sleds, multi-channel seismic acquisition equipment, single-channel seismic acquisition equipment, and multibeam bathymetry equipment. A variety of electronic navigation equipment is onboard including a GPS chartplotter, depth sounder, and radar. The vessel is an excellent observation platform and has been used for surveys of sea birds and marine mammals as well as marine geology and geophysics.

For the Icy Bay/Taan geophysical experiment, the *Gyre* lab area was used for active multichannel seismic and multibeam bathymetry acquisition and monitoring equipment, as well as gear storage. Five laptop computers were used during the survey (one for navigation, two for seismic acquisition, one for multibeam acquisition, and one for acquisition log). One split monitor was run up to the wheelhouse with a long VGA cable to duplicate the multibeam or navigation displays for guidance. Raw MCS, bathymetry, logs, backups, and 1st-run processed data were stored on a combination of external hard drives.

Dura-Spark 240 sparker source

We utilized TAMU's sparker source, a Dura-Spark 240 (Fig. 5, Fig. 6), which is manufactured by Applied Acoustics (www.appliedacoustics.com). The sparker contains 240 negative-pulse sparker tips and an operational bandwidth of 300 Hz to 1.2 kHz. During our survey, the dominant frequency was ~600 Hz. The sparker was run using a power source in conjunction with a custom "shot box" firing controller that allowed for shots every 2 seconds throughout the survey. The sparker was grounded to the water by dragging a piece of rebar connected to the grounding wire.

Figure 5 (right). Stock photos of the Dura-Spark 240 (www.appliedacoustics.com)

Figure 6. The Dura-Spark on top of the fish hold aboard the R/V *Alaskan Gyre* during the 2016 cruise (photo by Maureen LeVoir Walton, 2016).

UTIG 24-channel high-resolution streamer (modified from www-udc.ig.utexas.edu/external/facilities/mcs)

The UTIG seismic receiver is a Beam Systems, Inc.® (Pearland, TX), 100 m (~72 m active), 24-channel, oil-filled, analog cable (Fig. 7). 72 hydrophones (Teledyne Model T-2) are grouped three to a channel, with group spacing at 3.125 m. The cable is 1.6 inch in diameter and gel-filled (Isopar M fluid). Nominal tow depth is 1 m or less. The cable can be easily deployed directly from the wooden shipping reel by hand, or can be wound around any available winch drum for mechanical deployment/recovery. During active acquisition aboard the *Alaskan Gyre*, a custom wooden A-frame was built for the streamer reel, which was kept on top of the fish hold. The streamer was always deployed from the starboard side by hand for the 2016 cruise.

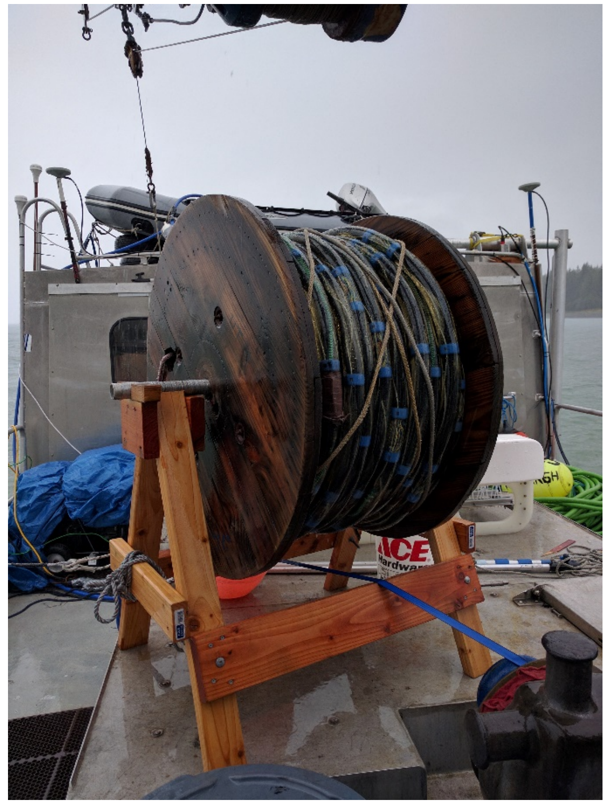


Figure 7 (right). Photo of the UTIG streamer aboard the R/V *Alaskan Gyre* during the 2016 cruise (photo by Maureen LeVoir Walton, 2016).

TAMU 24-channel high-resolution streamer

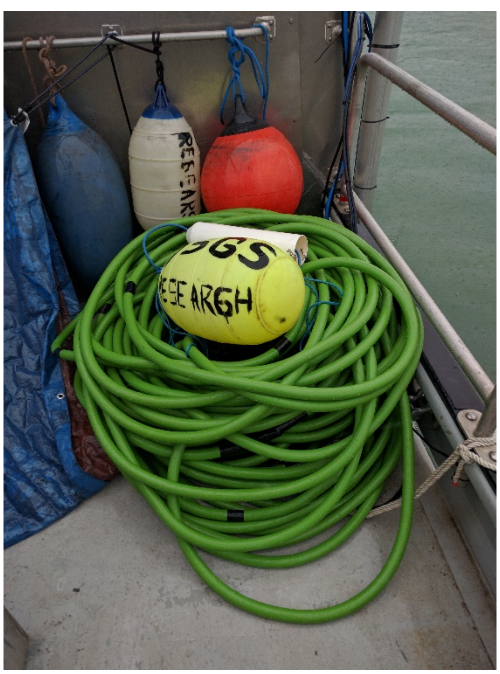
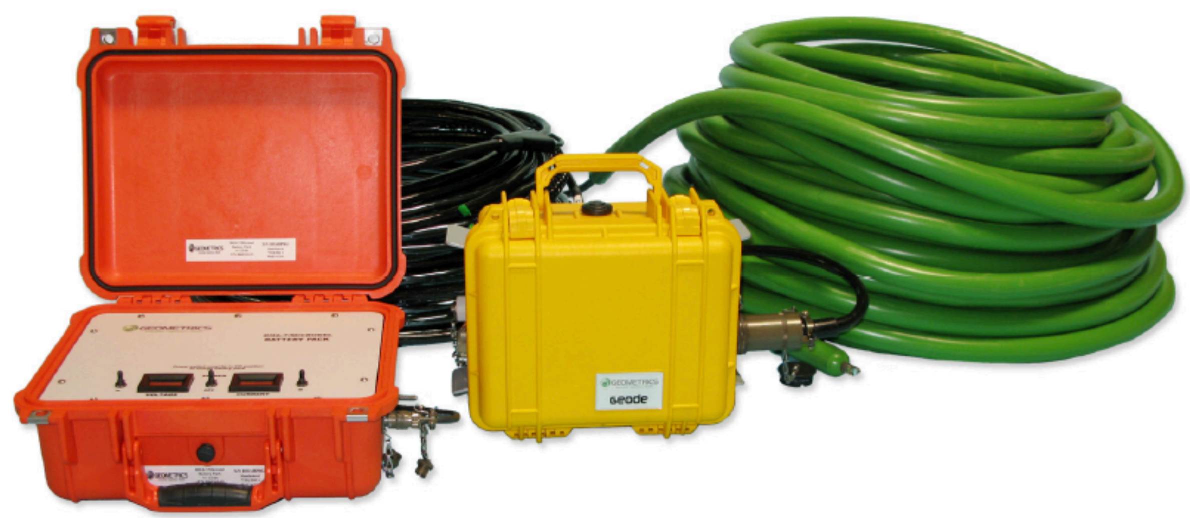


Figure 8 (left). TAMU MicroEel streamer on the deck of the *Alaskan Gyre*. Photo by Maureen LeVoir Walton (2016).

The TAMU seismic receiver streamer (Fig. 8, Fig. 9) was used in conjunction with the UTIG streamer to increase offsets, improve signal-to-noise ratios, create redundancy in the data, and to examine differences in data quality between the two receiver systems. The TAMU streamer, an analog solid streamer manufactured by Geometrics (www.geometrics.com), has 24 channels spaced at 6.25 m for a total active length of ~144 m. Each channel has 4 hydrophones, a custom configuration different than the usual 3, to improve the signal to noise ratio. During acquisition on the *Alaskan Gyre*, the TAMU streamer was stored on the port side of the main deck outside (Fig. 8), and deployed by hand from the port side. During the double, extra-long streamer configuration, the TAMU streamer was towed behind the UTIG streamer using a longer tow line. The TAMU streamer was always towed from the port side, and the UTIG streamer always towed from the starboard side regardless of the streamer configuration.

Figure 9. Stock photo of MicroEel streamer (www.appliedacoustics.com) with Geometrics geode seismic recorder (yellow box). Image also features a Geometrics streamer battery (orange box), and streamer tow line (black cable).



Geode seismic recorders (text modified from www-udc.ig.utexas.edu/external/facilities/mcs)

Both the UTIG and the TAMU streamers were used in conjunction with two geode seismic recorders (Fig. 9). For each streamer, analog signals from the streamer cable are digitized and recorded using a Geometrics® Geode 24-channel seismic recorder, and accompanying Geometrics® SGOS software running on a laptop. The Geode requires 12-volt battery (car battery or similar). Data are stored on disk typically in either SEG-2 or SEG-Y format. For this experiment, we recorded data in SEG-D format. Commonly, 1 second of data are recorded; for this experiment, we used a record length of 0.5 seconds. The two geodes were set up and operated in the lab of the *Alaskan Gyre*.

Teledyne Reson SeaBat T50-P multibeam sonar (modified in part from www.teledyne-reson.com)

The SeaBat T50-P (Fig. 10) is fully frequency agile from 190 to 420 kHz allowing for improved swath performance and reduced survey time under difficult conditions. The SeaBat T50-P is designed for fast mobilization on smaller vessels. The Portable Sonar Processor and sonar head form a compact system, securing minimal interfacing and low space requirements. Aboard the *Alaskan Gyre*, we generally employed a 200 kHz acquisition frequency and at least a 30 µs pulse length due to the deeper water bottom in the fjord-type setting. The multibeam was mounted on a custom pole on the port side of the lab on the *Gyre* (Fig. 11). Multibeam bathymetry data were initially loaded into Teledyne's PDS interpretation software. Some preliminary processing of the first patch test was done during acquisition, and CTDs were dynamically applied to incoming data when collected; aside from re-gridding for visualization, no other processing was done at sea.

Figure 10. Two views of the assembled Reson multibeam unit and custom multibeam arm aboard the R/V *Alaskan Gyre* during a transit in 2016 (photos by Maureen LeVoir Walton). For acquisition, the arm settles into a cradle mounted just below the lab on the port side of the ship.

CastAway CTD (modified from www.sontek.com)

Figure 11 (left). Stock image of the CastAway CTD (www.sontek.com).

The CastAway CTD (conductivity, temperature, depth; Fig. 11) is a small, rugged and technically advanced CTD designed for profiling to depths of up to 100 m. The system incorporates modern technical features which allow it to achieve a 5 Hz response time, fine spatial resolution and high accuracy. It uses a six-electrode flow-through conductivity cell with zero external field coupled with a rapid response thermistor to attain high measurement accuracies. The instrument is simple to deploy, does not require a pump and is hydrodynamically designed to free fall rate of 1 m/s. Each CastAway CTD cast is referenced with both time and location using its built-in GPS receiver. Latitude and longitude are acquired both before and after each profile. Plots of conductivity, temperature, salinity and sound speed versus depth can be viewed immediately on the CastAway's integrated color LCD screen in the field. Raw data can be easily downloaded via Bluetooth to a Windows computer for detailed analysis and /or export at any time.

Aboard the *Alaskan Gyre*, we generally collected at least one CTD profile per day during multibeam acquisition, usually in deeper area(s) of the day's surveyed locations. We used a fishing pole to deploy and retrieve the CastAway, and Bluetooth to download the data to a Windows machine after each cast. All CTD casts were logged in the multibeam log. We occasionally had to record coordinates manually when we weren't able to acquire a GPS fix with the CastAway. During active acquisition, CTD data were imported into Reson and applied dynamically to incoming multibeam files.

Global Positioning Systems (GPS) (modified in part from www.applanix.com)

Ordinarily, navigation data for a cruise are acquired from a portable GPS antenna or copied from the vessel's own GPS system (NMEA), if such is available. In the case of the *Alaskan Gyre*, several GPS systems were used to acquire navigation data (Figure 12). The most sophisticated system, an Applanix POS MV system, was used in conjunction with the Reson mutibeam unit. POS MV blends GNSS data with angular rate and acceleration data from an inertial measurement unit (IMU) and heading from GNSS Azimuth Measurement System (GAMS) to produce a robust and accurate full six degrees of freedom Position and Orientation solution. All POS MV models are designed for use with multibeam sonar systems, enabling adherence to IHO (International Hydrographic Survey) standards on sonar swath widths of greater than ± 75 degrees under all dynamic conditions. During the 2016 cruise, we set up the two Applanix antennas on the roof of the lab, with the primary antenna on the port side (Fig. 12). During acquisition we encountered some issues acquiring a GAMS fix, particularly in the first two days of the cruise, but were later able to achieve more consistent success with positioning by forcing GAMS. Most multibeam data acquired without GAMS was re-surveyed with GAMS.

In order to obtain accurate positioning and heading, it is necessary to carefully measure the exact location of the multibeam unit relative to the location of the IMU. It is best to place the IMU close to the center of gravity of the vessel; however, on a smaller vessel like the *Alaskan Gyre*, this is less important, so we opted to mount the IMU as close to the multibeam unit as possible in order to minimize measurement errors (see Appendix B for vessel schematics). The IMU was mounted on top of the lab on the port side, nearly directly above where the multibeam unit was situated during data acquisition. The separation between the IMU and the multibeam unit is required input for both the Reson PDS software and the POS MV software. POS MV and Reson have different coordinate systems: positive directions for POS MV are fore (x), starboard (y), and down (z); for Reson, the axes are positive starboard (x), fore (y), and up (z). Table 1 shows the offset of the multibeam unit relative to the IMU in both coordinate systems. See Appendix B for schematic illustrations of the boat and equipment layout.

Table 1 (right). Distance of the multibeam unit relative to the IMU in coordinate systems for both POS MV and Teledyne Reson PDS.

	POS MV	Reson
X	-4.1 cm	-60.9 cm
Y	-60.9 cm	-4.1 cm
Z	438.7 cm	-438.7 cm

Figure 12 (left). Image looking aft of the *Alaskan Gyre* deck during acquisition. Three of the four GPS units used during acquisition can be seen mounted on the roof of the lab. The two Applanix units (flatter disks, longer poles) are located on opposite sides of the lab. The UTIG seismic GPS is mounted on the front of the starboard side ladder. The TAMU seismic GPS (not pictured) was mounted on the rear rung of that same starboard side ladder.

In addition to the POS MV system, two other GPS units were used with the seismic system. Both GPS units were mounted on the ladder on the starboard side of the lab (Fig. 12). During acquisition, navigation data from these GPS units were also stored on disk and can be merged into SEGY headers. Charts and real-time navigation can be displayed on a laptop using commercial software, in this case, Fugawi (www.fugawi.com), which was occasionally also used on the bridge for navigation.

UTIG Processing of Multibeam Data

All lines were converted to Caris format for processing.

- Roll correction: Applied a roll correction of -1.65 to data collected on 8/6/17 and 8/7/2016, -1.950 to data from 8/8/16 to 8/12/16 and -2.25 to 8/13/16 to 8/15/16.
- Pitch correction: Applied pitch correction of -1.350 to data collected from 8/12/16 to 8/15/16
- Applied sound velocity profile (SVP) corrections made from collected data from CTD casts in the field.
- Actual tide data only exists up to 8/9/17. For data from 8/6/17 to 8/9/17 we used the mean low low water recorded at the tidal gauge at the 1983 moraine (M1983tide). A tidal model was applied to multibeam data collected from 8/10/17 to 8/15/17. The model was created by taking measured local tide data to create a predicted tide using the tidal fitting tool box in MATLAB (https://www.mathworks.com/matlabcentral/fileexchange/19099-tidal-fitting-toolbox code written by Aslak Grinsted).
- Data were edited using the Swath Editor in Caris to eliminate false pings. Once all lines had been cleaned with the Swath Editor additional outliers were edited by selecting smaller areas eliminating outlying points in the Subset Editor.

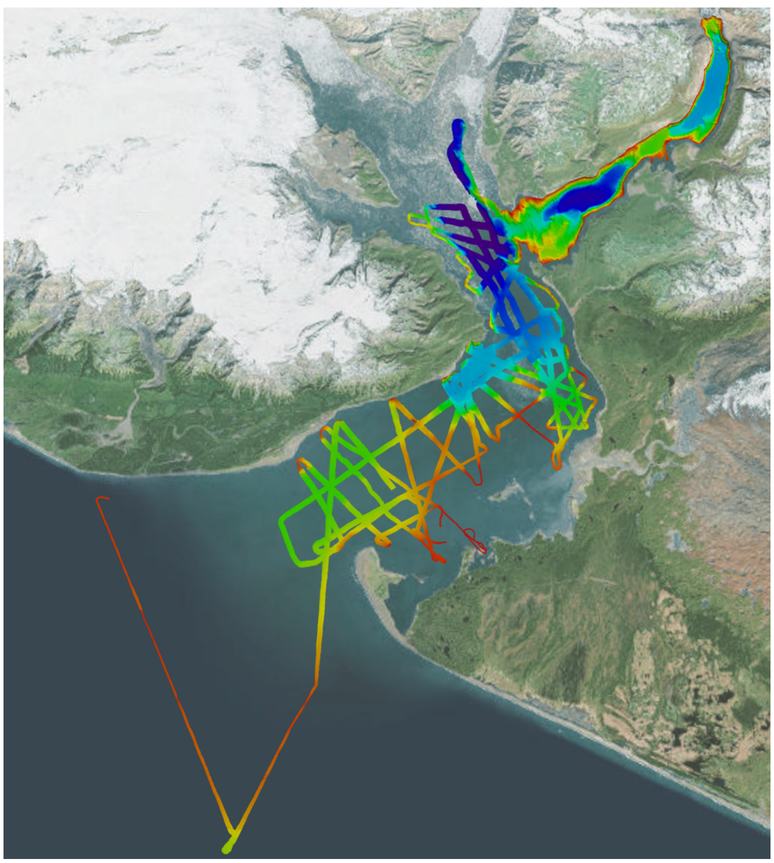


Figure 13 (left). Fully processed bathymetry coverage in Icy Bay and Taan Fjord, a screenshot from Caris HIPS and SIPS 9.1 software (www.caris.com). Projection and coordinates are UTM (Zone 7N). Background map of Alaskan coast is from ArcMap world imagery (www.esri.com).

At-Sea Processing of MCS Data

Preliminary processing of the MCS data was done while at sea aboard the *Alaskan Gyre* using Paradigm's Echos software (www.pdgm.com). Below is a summary of an example preliminary processing flow.

Preliminary processing flow

- SEG-D convert and import into Paradigm's Echos software
- Define geometry and populate headers
- [for extra-long streamer configuration] combine traces and update headers
- Bandpass filter
- Reverse streamer polarity (UTIG streamer)
- Spherical divergence gain (using water velocity)
- CDP sort
- NMO correction (based on a simple velocity function)
- Offset muting
- Stack
- F/K migration (1450 m/s)

<u>UTIG Processing of MCS Data</u>

Once back at UTIG, we reprocessed all lines using Paradigm's Echos 15 software. Summary of processing steps:

- Updated geometry definition using lat/long navigation values to define shot point locations and the CMP spacing (3.125m)
- Defined the seafloor and muted all signals above
- Repeated preprocessing steps to remove noise: bandpass filter, source deconvolution, gain correction, removed receiver ghost
- CDP sort: sorted the shot gathers into common depth point gathers
- Velocity analysis to create a 2D velocity model. Velocity picks were made from supergathers of 2 CDPs selected in intervals of every 125 CDPs.
- NMO correction for arrival time differences due to source-receiver separation. Mute applied to distortion from NMO on shallow wavelets.

Examples of preliminary and processed data

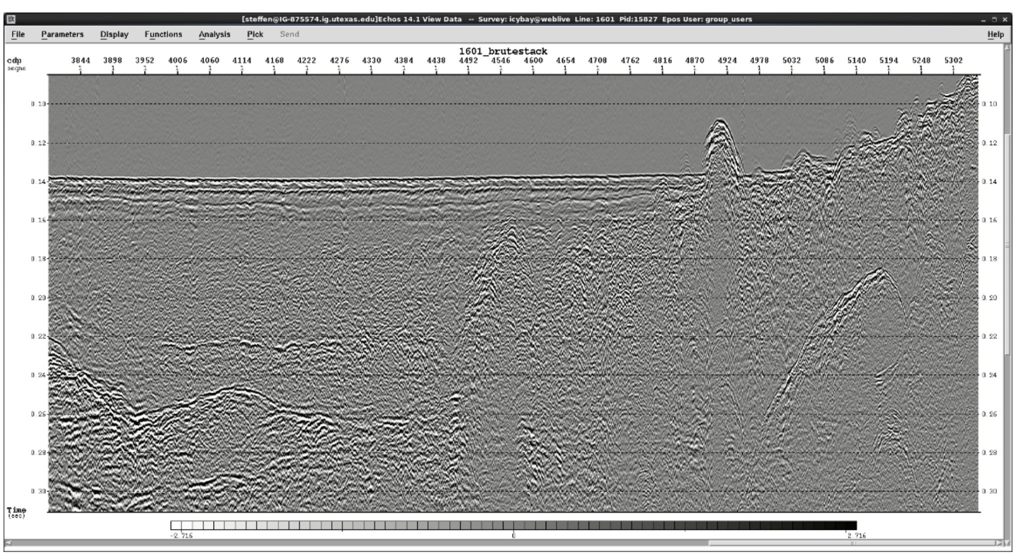


Figure 14 (left). Brutestack (preliminary processing) of UTIG streamer line1601. Vertical axis shows two-way travel time (TWTT), horizontal axis shows CDP number.

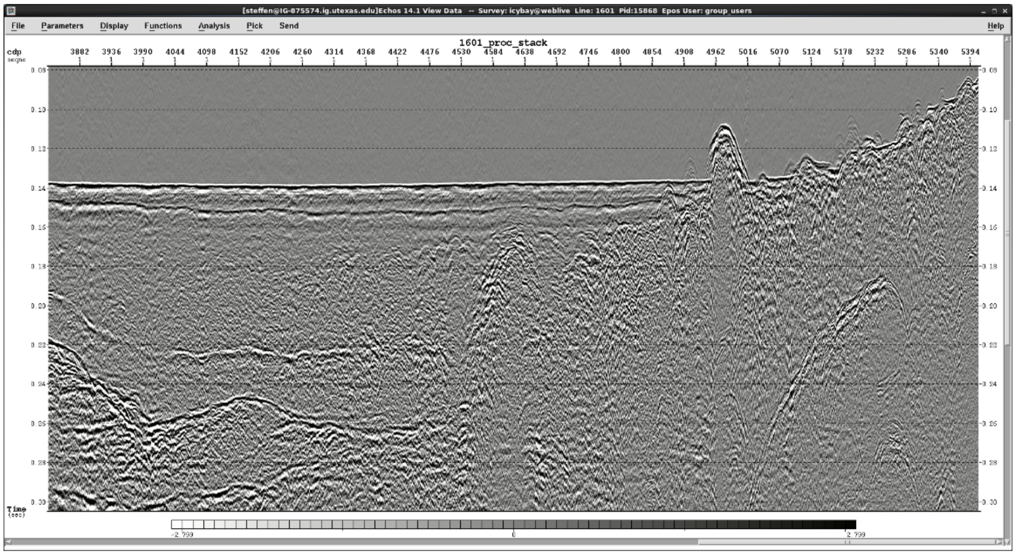


Figure 15 (left). De-ghosted version (a second-pass improvement) of UTIG streamer line 1601. Vertical axis shows TWTT, horizontal axis shows CDP number.

Summary of Results

Our MCS data show a glacial trough present along the northwest shore of Icy Bay (Fig. 16). The glacial trough aligns with mapped structural trends onshore and offshore, but no direct evidence of faults or structural offset is present in the MCS data. However, glacial troughs of similar morphology are found in previously collected crustal scale seismic data outside the mouth of Icy Bay. These offshore troughs are located on the footwall of previously mapped faults and folds in the Pamplona Zone (Worthington et al., 2010), suggesting that once the glaciers left the mountains the ice preferentially flowed and eroded along the strike of the faults and folds. Onshore, to the east of Icy Bay, studies of the adjacent Agassiz Glacier found faster surficial ice flow speeds when the glacier flowed parallel to faults, which also supports the hypothesis that glaciers preferentially flow and erode along faults. Based the location of the trough, similarities to offshore fault-parallel troughs, and onshore studies of surficial ice speeds, we interpret the trough mapped in Icy Bay as part of this project to be structurally controlled and use its location to infer the placement of the offshore extension of the Malaspina fault (Fig. 17). Key implications of this work are: 1) correlation between surficial glacial processes and fault patterns, 2) updated mapping allowing confidence in mapping active faults from offshore to onshore in the Yakutat-North America collision, and 3) the lack of surface ruptures in Icy Bay implies that the Yakutat-North America collision fails both as subduction style plate interface earthquakes from Icy Bay and west as exemplified by the Mw 8.1 Sept 4th 1899 event and as shallow thrusting events from Icy Bay and east as exemplified by the Mw 8.2 Sept 10th 1899 event. Future work is needed to quantify the slip deficits with this insight into hazards potential in southeast Alaska and examine the possibility of repeats of the dual earthquake 1899 scenario.

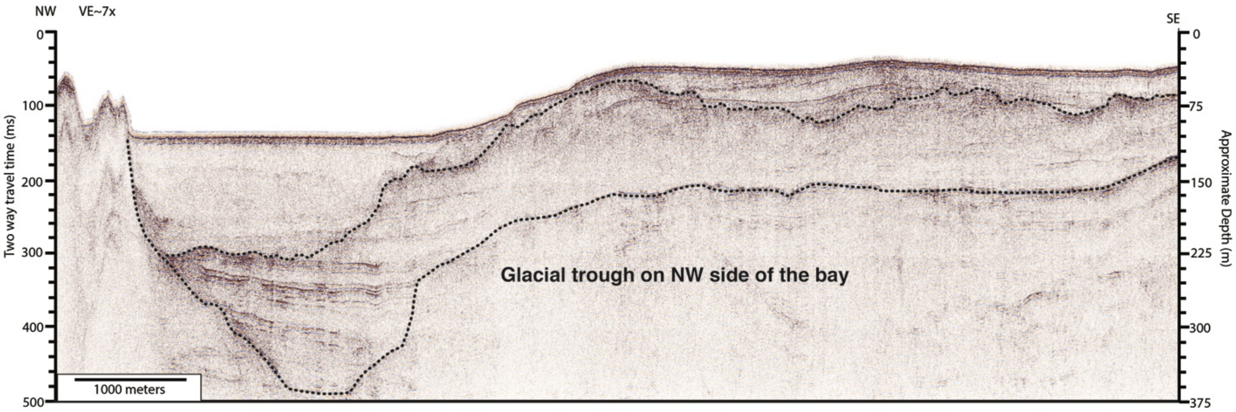


Figure 16. Processed seismic line from Icy Bay showing the glacial trough that is present along the NW side of the bay. Location of the seismic line is shown in Figure 4.

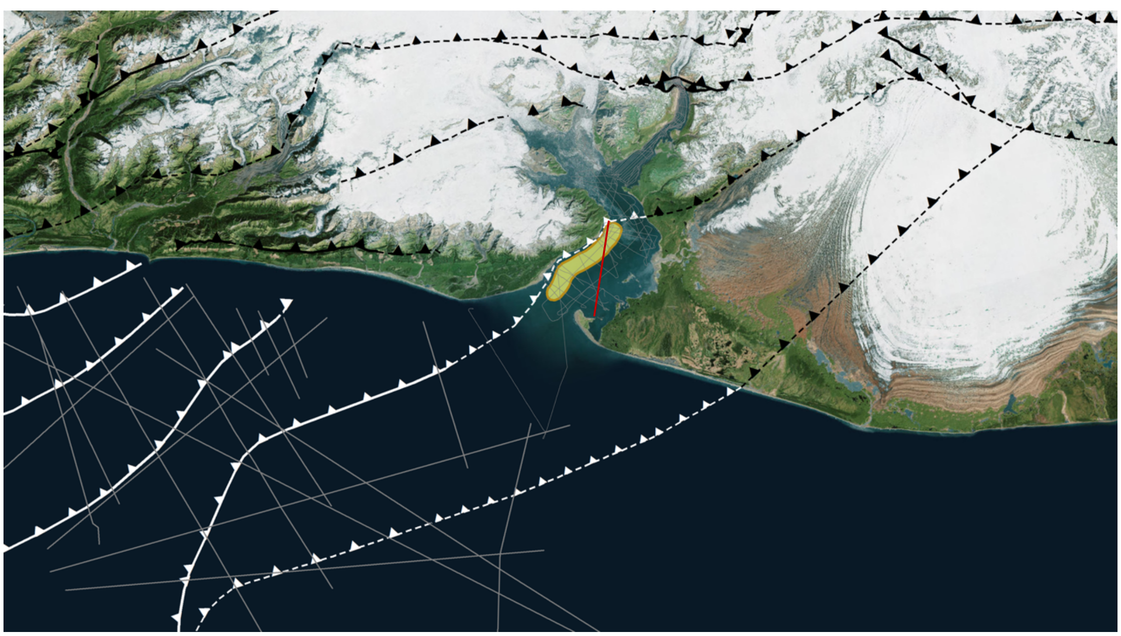


Figure 17. Updated fault map of Icy Bay and surrounding area. Onshore fault locations from Miller (1971), Plafker (1987), Pavlis et al. (2012), Chapman et al. (2012) Elliot et al. (2013) and Cotton et al. (2014). Offshore faults modified from Worthington et al. (2010). Glacial trough is outlined in yellow. Seismic line in figure 16 is shown in red.

Publications

McCall, N., et al. (2016), Studying onshore-offshore fault linkages in Icy Bay and Taan Fjord to assess geohazards in southeast Alaska, AGU 2016 Fall Meeting, San Francisco, CA.

McCall, N., et al (2017) Fault geometries and glacial conduits in Icy Bay, Alaska: Implications for the September 1899 earthquakes, GSA 2017 Annual Meeting, Seattle, WA

*An additional paper is currently in progress regarding the onshore-offshore fault connections in Icy Bay, as outlined in results section of this report.

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Appendix A: Summary of MCS lines

Line	Date	First shot (TAMU)	Last shot (TAMU)	First shot (UTIG)	Last shot (UTIG)	Notes
1601	8/6/2016	1122	3587	125	4098	UTIG 1601 is the same as TAMU 1601 and 1602
1602	8/6/2016	3588	4064	4112	7993	
1603	8/6/2016	4099	7110			No 1603 for UTIG, TAMU abort (4235) and restart (4603)
1604	8/6/2016	7111	9100	7996		
1605	8/6/2016	9100	9342			
1606	8/6/2016	9342	11096	10220	12075	
1607	8/6/2016	11096	13840	12075	14792	
1608	8/7/2016	13855	16648	14830	17608	
1609	8/7/2016	16648	17878	17608	18812	UTIG on SEGY
1610	8/7/2016	17998	19557	18813	20568	
1611	8/7/2016	19558	20486	20693		Streamer straight at 19980 (TAMU), 20968 (UTIG); EOL due to snagged streamer
1612	8/7/2016	20487	20923	21490	21922	in turn at 20880 (TAMU), 21880 (UTIG)
1613	8/7/2016	20924	22357	21923	23364	in turn; Streamer Straight process from here at 22260 (TAMU), 23050 (UTIG); in turn at 22330 (TAMU), 23330 (UTIG)
1614	8/7/2016	22358	23453	23365	24462	
1615	8/7/2016	23454	24208	24463	25216	Streamer Straight process from here at 22510 (TAMU), 23510 (UTIG)
1616	8/8/2016	24211	24470	25230	25340	in turn at 24175 (TAMU)
1617	8/8/2016	24471	24752	25410	25680	Streamer Straight process from here at 24242 (TAMU), 25240 (UTIG); Lost triggers until 25340 at 25280 (UTIG)
1618	8/8/2016	24753	24945	25690	25890	slower speed 4 kts; hard turn to port at 24900 (TAMU), 25840 (UTIG)
1619	8/8/2016	24946	25233	25895	26154	UTIG on SEGD; Streamer Straight process from here at 25357 (TAMU), 26260 (UTIG)
1620	8/8/2016	25234	25592	26155		lose power at EOL; Streamer Straight process from here at 25737 (TAMU); Lost triggers until 26670 at 26660 (UTIG)

Line	Date	First shot (TAMU)	Last shot (TAMU)	First shot (UTIG)	Last shot (UTIG)	Notes
1621	8/8/2016	25593	25673			lost power line is junk; no 1621 UTIG; Streamer Straight process from here at 26211 (TAMU), 27065 (UTIG)
1622	8/8/2016	25674	26093	26560	26980	Streamer Straight process from here at 26805 (TAMU), 27655 (UTIG); starting turn at 27070 (TAMU), 27955 (UTIG)
1623	8/8/2016	26094	26519	26981	27400	Streamer Straight process from here at 27147 (TAMU), 28020 (UTIG)
1624	8/8/2016	26540	26721	27401	27599	Streamer Straight process from here at 27310 (TAMU), 28160 (UTIG); turning to port at 27550 (TAMU), 28460 (UTIG)
1625	8/8/2016	26722	27097	27600	27990	Streamer Straight process from here at 27614 (TAMU), 0 (UTIG)
1626	8/8/2016	27098	27243	27991	28141	Streamer Straight process from here at 27930 (TAMU), 28820 (UTIG); in turn at 29034 (UTIG)
1627	8/8/2016	27244	27571	28142	28482	Streamer Straight process from here at 28160 (TAMU), 29115 (UTIG)
1628	8/8/2016	27572	27866	28483	28785	Streamer Straight process from here at 28270 (TAMU), 29210 (UTIG); in turn at 29340 (UTIG)
1629	8/8/2016	27867	28126	28786	29059	Streamer Straight process from here at 28523 (TAMU), 29460 (UTIG); in turn at 29618 (UTIG)
1630	8/8/2016	28127	28221	29060	29163	Streamer Straight process from here at 28770 (TAMU), 29707 (UTIG); in turn at 29840 (UTIG)
1631	8/8/2016	28222	28399	29164	29350	in turn; Streamer Straight process from here at 29000 (TAMU), 29940 (UTIG); in turn at 30055 (UTIG)
1632	8/8/2016	28400	28705	29351	29659	Streamer Straight process from here at 29220 (TAMU), 30170 (UTIG); in turn at 30555 (UTIG)
1633	8/8/2016	28706	28939	29660	29893	Streamer Straight process from here at 29400 (TAMU), 30385 (UTIG); in turn at 30555 (UTIG)
1634	8/8/2016	28940	29166	29894	30128	Streamer Straight process from here at 29695 (TAMU), 30650 (UTIG); in turn at 30838 (UTIG)
1635	8/8/2016	29167	29364	30129	30327	Streamer Straight process from here at 29960 (TAMU), 30921 (UTIG); in turn at 31155 (UTIG)

Line	Date	First shot (TAMU)	Last shot (TAMU)	First shot (UTIG)	Last shot (UTIG)	Notes
1636	8/8/2016	29365	29608	30328	30578	Streamer Straight process from here at 30100 (TAMU)
1637	8/8/2016	29609	29895	30579	30874	slow turn at 30273 (TAMU), 31715 (UTIG)
1638	8/8/2016	29896	30200	30875	31205	Streamer Straight process from here at 32088 (TAMU), 33075 (UTIG)
1639	8/8/2016	30221	30477	31206	31472	Streamer Straight process from here at 33338 (UTIG); slow turn at 34345 (UTIG)
1640	8/8/2016	30478	32046	31475	33043	Streamer Straight process from here at 33400 (TAMU); turning to port at 34700 (UTIG)
1641	8/8/2016	32047	32299	33044	33299	line straighter but lots of wiggles at 34335 (TAMU), 35580 (UTIG)
1642	8/8/2016	32327	33368	33300	34365	Streamer Straight process from here at 35879 (TAMU), 36870 (UTIG)
1643	8/8/2016	33369	33736	34370	34734	Streamer Straight process from here at 36455 (TAMU), 37456 (UTIG)
1644	8/8/2016	33737	34269	34735	35269	wiggle line; Streamer Straight process from here at 37037 (TAMU), 38032 (UTIG)
1645	8/8/2016	34296	35794	35270	36812	Streamer Straight process from here at 38591 (UTIG); bad triggers so start and stopped at 38598 (UTIG); clean at 38599 (UTIG); start of more bad triggers at 38681 (UTIG); end of bad triggers at 38709 (UTIG)
1646	8/8/2016	35795	36377	36813	37388	Streamer Straight process from here at 38420 (TAMU)
1647	8/8/2016	36378	37010	37389	38016	Streamer Straight process from here at 38700 (TAMU)
1648	8/8/2016	37011	37520	38017	38526	Streamer Straight process from here at 39025 (TAMU); Speed change to 2 kts because of ice at 40300 (TAMU); Return to 4 kts at 40488 (TAMU)
1649	8/9/2016	37522	37955	38527	38952	bad triggers; some bad triggers but fixed at 46405 (UTIG)
1650	8/9/2016	37967	38394	38968	39386	Streamer Straight process from here at 45910 (TAMU), 46975 (UTIG); ice under streamer at 46475 (TAMU); ice off at 46500 (TAMU); tangled streamers at 46900 (TAMU)
1651	8/9/2016	38395	38639	39387	39631	UTIG straight; a couple bad shots appended after; Bend to starboard

Line	Date	First shot (TAMU)	Last shot (TAMU)	First shot (UTIG)	Last shot (UTIG)	Notes
1652	8/9/2016	38640	39003	39637	40013	UTIG straight; slight turn at end; good triggers at 60960 (UTIG); 90 degree turn to deal with seastate
1653	8/9/2016	39004	40866	40014	41871	UTIG straight; bad triggers so start and stopped at 62040 (UTIG)
1654	8/9/2016	40867	41297	41872	42314	wiggly line ice; Lost Generator at 62828 (TAMU), 62800 (UTIG); Back acquiring at 62864 (TAMU), 62850 (UTIG)
1655	8/9/2016	41298	43868	42315	44881	shutdown for seal at 72465 (TAMU), 72457 (UTIG); Reacquiring data at 72475 (UTIG); starboard turn at 72866 (UTIG)
1656	8/9/2016	41298	44181	44882	45221	Streamer Straight process from here at 72960 (TAMU), 72953 (UTIG); turning to port at 74317 (TAMU), 74317 (UTIG)
1657	8/9/2016	44182	45694	45222	46756	Streamer Straight process from here at 73620 (UTIG)
1658	8/9/2016	45695	48335	46757	49380	starting turn at 7264 (UTIG)
1659	8/10/2016	48345	49509	49381	50544	Streamer Straight process from here at 93075 (TAMU), 93050 (UTIG)
1660	8/10/2016	49510	55157	50545	56191	Streamer Straight process from here at 96400 (TAMU), 96440 (UTIG); Missed some triggers at 96515 and 97050 (UTIG)
1661	8/10/2016	55163	59820	56197		Streamer Straight process from here at 97931 (TAMU), 97880 (UTIG); missed some triggers at 97907 (TAMU)
1662	8/12/2016	60891	61784	60900	62020	some bad UTIG triggers; Streamer Straight process from here at 98840 (TAMU), 98816 (UTIG)
1663	8/12/2016	61785	62034	62021	62539	90 degree turn to starboard at EOL; Battery cable pulled, restart recording system at 101028 (UTIG), restart for UTIG at 101029
1664	8/12/2016	62035	62542	62540		in turn; Streamer Straight process from here at 102420 (TAMU)
1665	8/12/2016	62543	66821		66817	Streamer Straight process from here at 102780 (TAMU), 102670 (UTIG); Port deviation for ice at 102950 (UTIG)

Line	Date	First shot (TAMU)	Last shot (TAMU)	First shot (UTIG)	Last shot (UTIG)	Notes
1666	8/12/2016	66822	67174	66818	67160	line is a turn; Course change ice at 105559 (TAMU), 105483 (UTIG); Marine mammal shutdown at 105656 (TAMU), 105591 (UTIG); Restart- First good shot at 105696 (TAMU), 105630 (UTIG)
1667	8/12/2016	67175	69169	67161	69166	Streamer Straight process from here at 0 (TAMU), 106012 (UTIG)
1668	8/12/2016	69170	69980	69167	69977	finished turn, straight on course at 107815 (TAMU), 107710 (UTIG); Geode stopped, data gap at 108810 (UTIG)
1669	8/12/2016	69981	71460	69978	71456	Streamer Straight process from here at 110386 (TAMU), 110156 (UTIG); deviated around ice numerous times at 112035 (TAMU), 111148 (UTIG)
1670	8/12/2016	71461	72904	71457	72899	
1671	8/12/2016	72905	74372	72900	74366	
1672	8/12/2016	74373	76283	74367	76277	
1673	8/13/2016	76284	77123		77113	
1674	8/13/2016	77125	77302	77114	77291	
1675	8/13/2016	77303	78789	77292	78778	
1676	8/13/2016	78790	79962	78779	79952	
1677	8/13/2016	79963	80167	79953	80157	
1678	8/13/2016	80168	82773	80158	82764	UTIG forgot to change line for a couple of shots
1679	8/13/2016	82774	83667	82765	83658	
1680	8/13/2016	83668	84416	83659	84406	
1681	8/13/2016	84417	84916	84407	84906	pause at beginning bad triggers
1682	8/13/2016	84917	85870	84907	85860	pause at beginning bad triggers
1683	8/13/2016	85871	87179	85861	87171	
1684	8/13/2016	87180	87356	87172	87347	
1685	8/13/2016	87357	88083	87348	88079	
1686	8/13/2016	88084	88644	88080	88641	
1687	8/13/2016	88645	92931	88642	92925	time synced TAMU
1688	8/13/2016	92932	94484	92926	94478	
1689	8/13/2016	94485	94709	94479	94703	
1690	8/14/2016	94718	96380	94705	96353	
1691	8/14/2016	96381	97870	96354	97836	in turn
1692	8/14/2016	97871	98732	97837	98703	
1693	8/14/2016	98733	99911	98704	99882	

Line	Date	First shot (TAMU)	Last shot (TAMU)	First shot (UTIG)	Last shot (UTIG)	Notes
1694	8/14/2016	99912	100143	99897	100120	
1695	8/14/2016	100144	102320	100121	102250	
1696	8/14/2016	102340	102708	102253	102640	
1697	8/14/2016	102709	104628	102641	104559	
1698	8/14/2016	104629	105975	104560	105909	
1699	8/14/2016	105976	107621	105910	107556	
1700	8/15/2016	107622	110240	107559	110155	
1701	8/15/2016	110241	113329	110156	113244	

Appendix B: Scale schematics of vessel and equipment setup