Report/Product Number: DOE-SMU-10180-Final

Title: Final Scientific/Technical Report of Gas Hydrate Dynamics on the Alaskan Beaufort Continental Slope: Modeling and Field Characterization

Type: Final Scientific/Technical Report

Reporting Period Start Date: October 1, 2012
Reporting Period End Date: March 31, 2017

Principal Author(s): Matthew J. Hornbach[1]
Frederick S. Colwell[2]
Robert Harris[2]

Report Issued: July 6, 2017

DOE Award Number: DE-FE0010180

1 **Southern Methodist University**
Huffington Department of Earth Sciences
P.O. Box 750395
Dallas, TX 75275-0395

2 **Oregon State University**
Corvallis, OR 97331

3 **United States Geological Survey,** Woods Hole, Mass.

Disclaimer

ABSTRACT

Methane Hydrates, a solid form of methane and water, exist at high pressures and low temperatures, occurs on every continental margin on Earth, represents one of the largest reservoirs of carbon on the planet, and, if destabilized, may play an important role in both slope stability and climate change. For decades, researchers have studied methane hydrates with the hope of determining if methane hydrates are destabilizing, and if so, how this destabilization might impact slope stability and ocean/atmosphere carbon budgets. In the past ~5 years, it has become well established that the upper "feather-edge" of methane hydrate stability (intermediate water depths of ~200-500 meters below sea level) represents an important frontier for methane hydrates stability research, as this zone is most susceptible to destabilization due to minor fluctuations in ocean temperature in space and time. The Arctic Ocean—one of the fastest warming regions on Earth—is perhaps the best place to study possible changes to methane hydrate stability due to ocean warming. To address the stability of methane hydrates at intermediate ocean depths, Southern Methodist University in partnership with Oregon State University and The United State Geological Survey at Woods Hole began investigating methane hydrate stability in intermediate water depths below both the US Beaufort Sea and the Atlantic Margin, from 2012-2017. The work was funded by the Department of Energy's (DOE) National Energy Technology Laboratory (NETL). The key goal of the SMU component of this study was to collect the first ever heat flow data in the Beaufort Sea and compare measured shallow (probe-based[1]) heat flow values with deeper (BSR-derived[2]) heat flow values, and from this, determine whether hydrates were in thermal equilibrium. In September 2016, SMU/OSU collected the first ever heat flow measurements in the US Beaufort Sea. Despite poor weather and rough seas, the cruise was a success, with 116 heat flow measurements acquired across the margin, spanning 4 transects separated by more than 400 km. Useable heat flow data exists for 97% (113) of probe heat flow measurements, revealing a clear picture of regional heat flow across the basin. During the past 8 months since the cruise, SMU researchers have processed the heat flow and thermal conductivity measurements and compared results to deeper heat flow estimates obtained from seismic data. The analysis reveals clear, consistent trends: All probe heat flow measurements in depths greater than 800 mbsl are consistent with BSR-derived values; heat flow measurements obtained in water depths between ~250-750 mbsl are systematically lower than those estimated from BSRs; and heat flow estimates in water depths shallower than ~250 mbsl are systematically warmer than deeper estimates. The consistency between shallow (probe) and deep (BSR) heat flow measurements at depths greater than ~750 m where ocean temperature changes are minimal supports the premise that the hydrates consist primarily of methane and represent a valuable tool for estimating heat flow. The anomalous cooling trend observed in the upper 250 m is consistent with expected seasonal effects observed in shallow ocean buoy measurements in the arctic, when cold, less dense melting sea ice cools the upper 200 m of the ocean during the summer as ice melting occurs. The discrepancy in heat flow at intermediate water depths is best explained via recent intermediate ocean temperature warming, where long-term (annual or longer) warming intermediate ocean bottom waters result in an anomalously low heat flow in shallow heat flow measurements. Using the characteristic 1D time-length scale for diffusion, we estimate that ocean temperature warming began no later than ~1200 years ago but arguably much more recently as results are limited by seismic resolution. More importantly, our analysis indicates methane hydrate is destabilizing not only in the upper feather edge (200-500 mbsl) but at depths as great as 750 mbsl. The intermediate ocean warming rate supports previous studies suggesting geologically rapid warming (>0.1 deg C/decade) at intermediate ocean depths in the Beaufort Sea. Assuming no further changes or additional warming, our analysis indicates methane hydrates will destabilize at seafloor depths shallower than 750 mbsl in the Beaufort Sea within the next ~3000 years.

---

[1] Probe outfitted with sensors inserted into the seafloor sediment

[2] Bottom-simulating reflector (BSR) seismic data indicates presence of hydrate deposits

TABLE OF CONTENTS

EXECUTIVE SUMMARY

In October 2012, Southern Methodist University in partnership with Oregon State University and The United State Geological Survey at Woods Hole, began investigating methane hydrate stability in deep water (>200 mbsf) environments below the Alaskan Beaufort Sea. In late 2014, the project was further expanded to include analysis of methane hydrates and slope stability off the US East Coast. This research became part of a 4.5 year study funded by the Department of Energy's (DOE) National Energy Technology Laboratory (NETL) to analyze methane hydrate stability on both the Atlantic and Beaufort Margins. Key goals of this study included integrating and processing marine seismic data collected at the USGS as well as other publically available data with dynamic 2D/3D/4D heat flow models developed at SMU to determine the depth, location, and dynamics of methane hydrate stability along the Alaskan Beaufort Margin and similar environments. A major component of this study was to constrain how the methane hydrate stability zone is changing with time by comparing shallow (probe) heat flow measurements with deep (BSR-derived) heat flow measurements. Additional goals of this study included determining areas where concentrated methane hydrate might exist in the subsurface and to understand the role methane hydrate plays in slope stability along continental margins.

To accomplish these goals, researchers used geophysical (seismic, heat flow, CTD/XBT) data combined with numerical models to assess methane hydrate stability in space and time. Researchers also integrated regional coring and biological data with methane hydrate stability models to place further constraints on hydrate dynamics. The USGS component of this research focused on addressing methane hydrate stability along the US Atlantic Margin; the SMU component focused on the US Beaufort Sea. To determine both if and where methane hydrate destabilization occurs along the Beaufort Margin, SMU and OSU researchers conducted a ~10 day heat flow and chirp-seismic imaging cruise in the Beaufort Sea in September of 2016. This research cruise was a tremendous success; we collected heat flow data at 116 sites, of which 113 (97+%) produced interpretable subbottom temperature data (with no penetration at only three stations). At each of these sites, we obtained 12 temperature measurements (11 of which usually provided subsurface temperatures, the other providing bottom water temperature), resulting in a total of 1,356 temperature measurements along the Beaufort Sea margin. These data were acquired along four transects running from the upper edge of the margin to a maximum depth of ~1700 mbsl. Along each of these transects, we also collected thermal conductivity measurements, all of which were remarkably uniform, averaging ~1.2 W/mK. In addition, we collected approximately ~200 km of 12 kHz chirp echosounder data at each of the heat flow stations, and in transits between heat flow penetration sites. These data demonstrate clear changes in stratigraphy and subsurface deformation, particularly within the hydrate stability zone. We also collected ocean temperature measurements at key depth intervals in the water column by deploying the heat flow probe at intermediate bottom water depths within the water column along each of the transects between penetration sites. Finally, we collected sediments directly from the probe, which were shipped to the SMU Geothermal Lab in Dallas for thermal conductivity measurements, to further constrain the thermal conductivity values and corresponding heat flow, as well as the sediment character along the margin.

With ocean temperatures, subsurface heat flow, thermal conductivity, and shallow subsurface structure constrained by these data, we have a much clearer picture of the location and dynamics of the methane hydrate stability zone along the US Beaufort margin, as well as the remarkably spatial variability in heat flow along the margin. Interestingly, the heat flow values along the deepest part of the western edge of the margin (>900 mbsl) indicate particularly high heat flow values—much higher than most continental margins—in the western U.S. Beaufort Sea, with several values exceeding 100 mW/m^2.

Results from this study fundamentally change our understanding of methane hydrate stability in the Arctic Ocean. Specifically, we show (see Phrampus et al., 2014; and Hornbach et al, in prep) that methane hydrates are unstable below much of the Beaufort Margin at depths hundreds of meters greater than the feather-edge of methane hydrate stability. Comparison of shallow (probe) heat flow measurements with deeper (BSR-derived) heat flow measurements demonstrate that methane hydrates are destabilizing to a depth of at least ~750 mbsl. This instability is likely the direct result of recent, significant ocean temperature warming of intermediate bottom water (sourced from the Atlantic). Our analysis indicates intermediate bottom water warming has occurred at least within the past ~1200 years but more likely within the last 100-200 years (see Hornbach et al. in prep; Phrampus et al., 2014). The depth of destabilization is therefore significantly greater than previous studies suggest (~750 as opposed 300-500 mbsl), and suggests a much larger reservoir of methane hydrate will destabilize along the margin within the next ~3000 years.

Although it appears unlikely that much of this hydrate will ultimately escape into the atmosphere, the impact of such broad-scale destabilization for both slope stability and ocean acidification remains unclear and warrants further study. Future studies should focus on (1) obtaining higher resolution multichannel seismic data that will not only confirm and better quantify methane hydrate concentrations and depths, but more importantly, the location and scale of warming and (2) ocean drilling that will ground-truth and more tightly constrain these results and their potential implications for slope stability and methane hydrate dissociation.

EXPERIMENTAL METHODS

Overview of Experimental Methods: Assessing Hydrate Stability in the U.S. Beaufort Sea.

The primary goal of this study is to determine if and where methane hydrates are destabilizing on the US Beaufort Margin. Methane hydrate stability depends to first-order on temperature. Any change in temperature conditions in the ocean or sub-seafloor therefore provide direct evidence for a dynamic, potentially unstable methane hydrate system. To address both if and where methane hydrates are destabilizing on the margin, and what role ocean temperatures play in hydrate stability, we employ a straight-forward approach: we compare high-fidelity deep versus shallow heat flow measurements along the margin. If heat flow from both shallow and deep measurements are statistically the same, this demonstrates that temperatures in the subsurface are in thermal equilibrium and that subsurface temperatures (and therefore methane hydrate) are stable. Alternatively, if we observe statistically significant differences between deep versus shallow heat flow measurements, it indicates a thermally dynamic, potentially unstable methane hydrate system exists in the subsurface.

submarine sediments below passive margins generally transfer heat via conduction and follow the standard 1-D conductivity heat flow equation

$$H = k\frac{dT}{dz}$$

Where H is heat flow (watts/m^2), k is thermal conductivity (typically 1 W/mK), dT/dz is the rate of change in temperature with depth. The equation above reveals that we only need two temperature and depth points to estimate regional heat flow: BSRs in seismic data provide both a temperature and depth at one location; additionally, ocean bottom temperature measurements (routinely obtained by oceanographers using XBTs/CTDs/Buoys) provide an additional measurement. Because BSRs often exist hundreds of meters below the seafloor, they offer an invaluable way to estimate deeper temperatures, and therefore, heat flow measurements based on deeper data points. As a result, researchers routinely use BSRs to estimate regional heat flow, and the accuracy of this approach is often within 10-15% of values derived from more direct borehole and heat flow probe measurements (e.g. Phrampus et al., in revision).

An additional method for measuring heat flow involves inserting a probe filled with thermistors into the seafloor (the Multipenetration Heat Flow Probe used in this research uses a 3.5 meter length lance pole centered into a weight stand. It is lowered from the ship until the integrated acoustic pinger indicates the seafloor is sufficiently close, at which point the tow line tension is released, allowing gravity to drive the weighted lance into the sediment. Twelve thermistors and heater wires are contained within a thin tube held at tension off to the side of the lance, like a ‘violin bow’ so as to avoid measuring thermal effects of the lance itself. Data is recorded in a logger located within the weight stand. The ship winch hoists the probe up out of the sediment, to 100-500 above seafloor, moves to the next measurement location, and the process is repeated.). This method, unlike the BSR approach, provides not just two temperature-depth measurements, but many more, depending on the number of thermistors available, and using a heat pulse of known temperature, can also directly estimate thermal conductivity. This approach may therefore be able to provide tighter constraints on both regional heat flow and thermal conductivity. The one drawback of these probes is that they only penetrate the upper 3-5 meters of sediment, so any recent changes to the shallow sedimentary environment or ocean temperature may lead to unexpected differences between measurements derived from probes and those from BSRs. As we note below, however, any differences between probe-derived and BSR-derived heat flow measurements provide potentially important information about past, present, and future methane hydrate stability.

In theory, if both BSR-derived measurements and probe-based measurements have (within uncertainty) the same estimated heat flow value, it implies all sediments from the seafloor to BSR depths are in thermal equilibrium and that no recent, significant fluid flow, hydrate dissociation, or ocean temperature changes have occurred. Alternatively, if a clear, statistically significant difference exists between BSR and probe-derived heat flow estimates exists, it indicates a dynamic, potentially non-steady-state methane hydrate system exists; it is these sites where we observe this discrepancy that require further, detailed analysis.

Finding the location where these discrepancies in shallow (probe based) heat flow measurements and deeper (BSR-derived) heat flow measurements exist however, first requires (1) calculating and constraining regional heat flow using deep (primarily BSR-based) measurements and (2) obtaining shallow (probe-based) heat flow and thermal conductivity measurements for comparison. The experimental section of this final report is therefore broken down into three components: Section (i) describe how we used BSRs in legacy seismic data combined with deep onshore boreholes to estimate heat flow from deeper temperature measurements and includes our first paper (Phrampus et al., 2014) that provides a thorough explanation of this approach. Section (ii) describes how we collected and analyzed shallow (probe-based) heat flow measurements in the US Beaufort Sea in fall of 2016 and includes our full cruise report outlining in detail the methods and approaches used. Finally, Section (iii) describes how we made post-cruise XRD/XRF/thermal conductivity measurements in the SMU Geothermal Lab facilities, and from this further constrain the physical, chemical, and thermal properties of Beaufort Margin sediments. As we note in our results section, we combined all of these studies to assess if, where, and how methane hydrates are destabilizing along the US Beaufort Margin (Hornbach et al., in prep).

(i): Defining deep (BSR/Well-derived) heat flow on the US Beaufort Margin.

To determine an initial background deep heat flow estimate for the U.S. Beaufort Sea, we used a combination of legacy seismic data collected in the US Beaufort Sea in 1977 combined with on-shore boreholes that measured temperature with depth at multiple locations along the North Slope of Alaska. The analysis, published in the Journal of Geophysical Research (Phrampus et al., 2014) demonstrates that the margin has an apparent average heat flow of approximately 40-60 W/m^2, (and thermal gradients of ~ 50-80 ^{o}C/km), values typical of marine environments. Importantly, however, the analysis also indicates that in water depths shallower than ~500 mbsl, BSRs appear anomalously deep compared to land-based heat flow measurements, and the study postulates that recent intermediate ocean bottom warming (on the order of 0.1 ^{o}C per decade for the past 40 years), represents a likely cause of the anomalously deep BSRs in this region. For a detailed description of these results and analysis, please see the JGR paper published in 2014 (Appendix 1). All heat flow measurements and associated uncertainties are provided in Table S1 of this publication.

(ii): Determining shallow (probe-derived) heat flow estimates on the US Beaufort Margin.

To determine whether shallow heat flow measurements match deeper BSR-derived heat flow measurements (and therefore, whether parts of the margin are out of thermal equilibrium), researchers at SMU and OSU collected new heat flow measurements on the US Beaufort Margin during a 10 day cruise in September 2016 on the *MV Norseman II*. A detailed discussion of the method, approach, and preliminary results of this cruise are provided in the full cruise report (Appendix 2) and in our draft manuscript (Hornbach et al., in prep). As discussed later in our results section, the cruise was a tremendous success, with 116 heat flow measurements made along four separate transects spanning more than 400 km of the margin. Results from this study (as discussed later) indicate clear discrepancies between shallow and deep heat flow measurements that provide direct insight into methane hydrate instability along the margin.

(iii): XRD,XRF, Divided Bar Thermal Conductivity Measurements on Beaufort Margin Sediments

During the fall 2016 heat flow cruise, we recovered several kilograms of submarine sediment. These sediments generally consisted of fine grain silts and muds and were often attached to the data logger and heat flow probe upon recovery on the ship's fantail. All sediments were carefully removed from the probe, packed/sealed in air-tight plastic bags, and stored in the ship refrigerator. Upon arrival in the Port of Nome, these samples were express-shipped under refrigeration to SMU's Geothermal Lab for further mineral/conductivity analysis.

Assessing regional heat flow requires high quality thermal conductivity measurements, and therefore, an important goal of this study is to determine the thermal properties of sediments in the Beaufort Sea. These sediment samples provided a means of obtaining the first direct, high-fidelity measurements of thermal conductivity in this region.

Thermal conductivity is the rate at which heat conducts through the sediment/rock medium. It varies by mineralogy, porosity, and *in situ* fluid. There are several types of devices for measuring thermal conductivity of rock samples, most commonly a needle probe or divided bar. Horai (1981) did a comparison between the needle probe and the divided bar methods and found a systematic difference of up to 20% (higher for divided bar) related to the oceanic sediments loosing water once removed from their in situ location (Von Herzen, 1987). Other methods of determining thermal conductivity include examining the sample mineral composition percentages to calculate the thermal conductivity based on known mineral conductance. Analyses of this type include an XRD, XRF, and microprobe. For this project, we estimated thermal conductivity using all divided bar, needle probe, and mineralogical methods and then compared results for final interpretation.

Needle probes are used for sampling soft rock materials such as mud. The probe sends heat into a sample and measures the rate the heat travels through it to determine the thermal conductivity. The heat transfer rate is compared with known standard values to determine the in situ measurement value. While at sea, we used the needle probe for an initial analysis of Beaufort Sea sediments.

Once the collected samples arrived in Dallas, we ran additional measurements using the divided bar apparatus in the SMU Geothermal Laboratory. This method also compares the sample values to known standards to calculate an absolute thermal conductivity. The divided bar is used for a variety of sample types, including core samples, crushed fragments, or unconsolidated sediments in a laboratory setting. In working with unconsolidated sediments, a known thermal conductivity cell is used to measure the material with open space filled with pore water. The conductivity result for the sediment frame are then converted to an in situ value using the equation below (Sass and Lachenbruch, 1971).

$$K_r = K_w\left(\frac{D^2}{d^2}\frac{K_c}{K_w} - \frac{D^2 - d^2}{d^2}\frac{K_p}{K_w}\right)^{\frac{1}{1-\phi}}$$

Where

K_r = Thermal conductivity of nonporous rock, mcal/cm sec °C (* .4184 = W/mK)

K_c = Measured conductivity of cell and contents, mcal/cm sec °C.

K_w = Thermal conductivity of water of average SMU temperature, 19.5°C = 1.429 mcal/cm sec °C.

K_p = Thermal conductivity of SMU plastic cell wall, 0.800 mcal/cm sec °C.

D = Outer diameter of SMU cell wall, 5.095 cm

d = Inner diameter of SMU cell wall, 4.778 cm

ϕ = Volume fraction of water in cell.

The divided-bar apparatus (Figure 1) uses a cold bath (15 °C) and a hot bath (25 °C) to create a temperature gradient within the sample to replicate a steady state environment (Blackwell and Spafford, 1987). The unconsolidated samples are compared to known standards of marble (12.663 mcal/cm sec °C or 5.298 W/mK) and silica glass (3.224 mcal/cm sec °C or 1.349 W/mK).

Figure 1. The SMU Geothermal Laboratory divided-bar thermal conductivity measurement apparatus. Samples are placed in between the press where the wooden blocks are located in the picture. The upper unit is heated and the lower unit cooled with constant bath water. The amount of heat/cold that is transferred into the rock is measured by this process and is compared to standard samples to calculate an absolute thermal conductivity.

The unconsolidated sediment analysis for thermal conductivity measurements from the divided bar are directly impacted by the percentage of the water content measured in the sample (Table 1). We did not spin or remix the samples before loading them into the cell. The cells were overfilled with mud and then sealed by pushing the mud through a small hole on the side of the plastic to confirm all air was removed. Samples were then weight wet and put on the divided bar for measurement.

We found the divided bar conductivity measurements to have a maximum experimental error of ±10%, although most measurements have error below ±5%. The standard error values are representative of the variations in the divided bar for that sample during the same reading, except for BHF 3, which was run three separate times for repeatability. The BHF 3 site has the highest average values of 1.19 W/mK. BHF 7 site average value is 1.09 W/mK. BHF 8 site average value is 0.94 W/mK and the lowest is BHF 6 with a value of 0.91 W/mK. We believe sample 6, run "b" inaccurate due to a mismeasurement of water content in the sample.

Table 1. Thermal Conductivity Results run on the SMU Divided Bar. BHF6 run b accuracy may be compromised by mismeasurement of water content in the sample.

Sample	Weight (g)	water %	Ave (W/mK)	STD	Max (W/mK)	Min (W/mK)
BHF3 run a	31.53	0.50	1.21	0.017	1.28	1.15
BHF3 run b	33.34	0.41	1.18	0.048	1.22	1.12
BHF6 run a	28.76	0.42	0.91	0.002	0.92	0.91
BHF6 run b	28.29	0.42	0.75	0.026	0.78	0.72

BHF7 run a	33.12	0.49	1.08	0.004	1.09	1.07
BHF7 run b	31.30	0.50	1.10	0.050	1.16	1.04
BHF8 run a	30.17	0.45	0.95	0.004	0.95	0.94
BHF8 run b	31.65	0.45	0.94	0.037	0.97	0.89

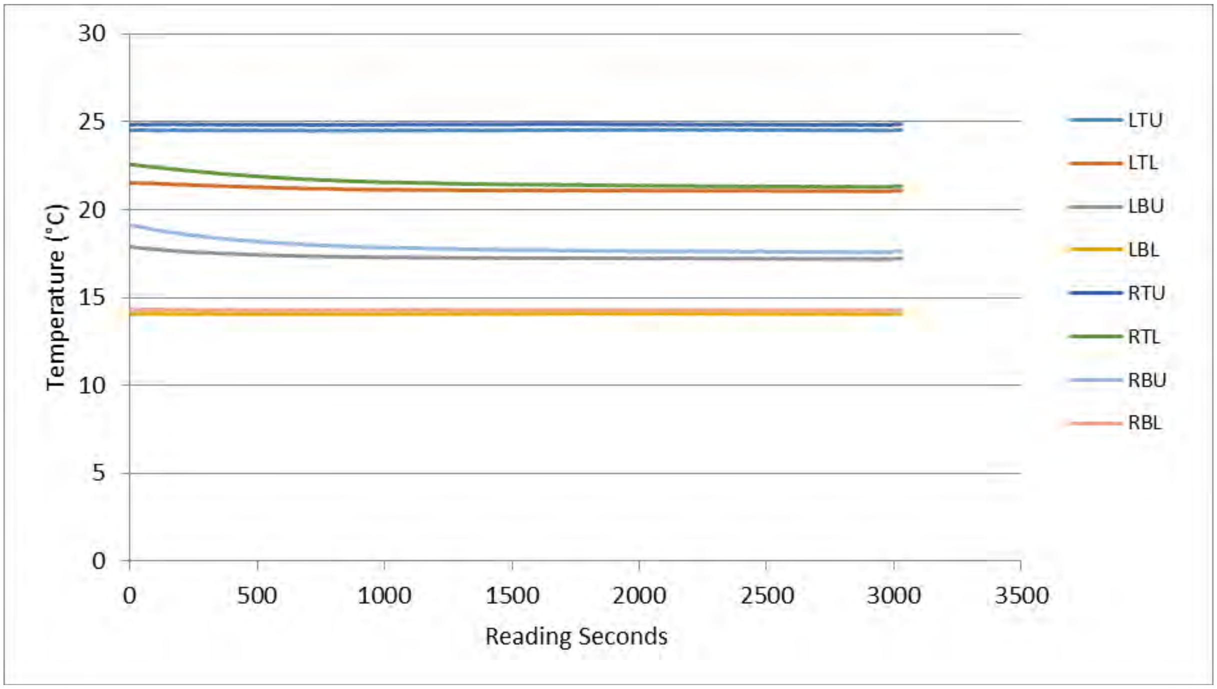


Figure 2. Example of Beaufort Sea mud sample BFH 3 divided bar readings. There is a left (L) and right (R) side of the bar. TU is top upper copper disk reading, TL is top lower reading, BU is bottom upper copper disk reading, BL is bottom lower copper disk reading.

Methods for Estimating Thermal Conductivities Using the Root-Squared Mean Equation

Roy, Beck and Touloukian (1981) showed that the average thermal conductivity of a rock sample λ_B may be estimated using the root-squared mean equation:

$$\lambda_B = \left[\sum_{i=1}^{n} \phi_i \sqrt{\lambda_i}\right]^2$$

where, ϕ_i and λ_i respectively refer to the fractional proportion and average thermal conductivity of the i^{th} mineral or fluid within the rock sample and, n refers to the total number of minerals and fluids within the sample.

We estimated ϕ_i using X-ray diffraction (XRD) analysis. We prepared the samples for XRD analysis by drying the samples at 40 degree Celsius for 24 hours and then using a mortar and pestle to grind 0.5 grams of each sample to a roughly homogenous particle size of ~1µm – i.e. approximately the consistency of a talc powder. Thereafter, we generated and digitally recorded the diffraction spectra (i.e. 2ϕ incidence angle as a function of intensity) using the Rigaku Ultima III X-ray diffractometer, which continuously bombards a flat lens of the powdered sample with Cu-Kα radiation. The radiation degree 2ϕ incident angles incrementally increased from 1° to 60° at a frequency of 1° per minute. We used Bragg's law to convert the degrees 2ϕ diffraction peaks to their corresponding crystal interplanar spacing -- commonly referred to as d-spacing. Since d-spacing is a unique identifier of crystalline minerals, we identified the minerals within the samples by comparing the d-spacing from the mud samples to the d-spacing of known minerals within the International Center for Diffraction Data mineral d-spacing database (i.e. PDF-4+). After identifying the minerals within the samples, we consulted empirically derived thermal conductivity tables (Clauser and Huenges, 1995) to determine the appropriate values of λ_i. Finally, we used the reference intensity ratio method (e.g. Hillier, 2000) to estimate the first-order fractional proportion for each mineral, ϕ_i.

Root-Squared Mean Equation Derived Thermal Conductivity Values

BH3		BH5		BH6		BH7		BH8	
Mineral	ϕ_i	**Mineral**	ϕ_i	**Mineral**	ϕ_i	**Mineral**	ϕ_i	**Mineral**	ϕ_i
Quartz	0.0362	Quartz	0.6131	Quartz	0.4623	Quartz	0.4512	Quartz	0.6018
Halite	0.0031	Halite	0.1015	Nimite	0.1457	Halite	0.0672	Halite	0.0411
Muscovite	0.9561	Muscovite	0.2854	Muscovite	0.1407	Muscovite	0.4052	Muscovite	0.0973
Dolomite	0.0046			Orthopyroxene	0.2513	Clinohypersthene	0.0764	Nimite*	0.1304
								Diopside	0.0391
								Phlogopite	0.0903

Table 2: Mineral proportion fraction for each sample derived from XRD analyses

The mud samples are predominantly composed of water, quartz, halite, muscovite, mica and pyroxenes (table above). Based on experimental analyses by Clauser and Huenges (1995), the average thermal conductivity of water, quartz, halite, muscovite, mica and pyroxenes is 0.65, 7.69, 4.55-6.55, 2.21-2.35 and 4.17-4.77 respectively. Using the root-mean squared method, we estimate that the average thermal conductivities for BH3, BH5, BH6, BH7 and BH8 is 1.08-1.09, 1.13-1.14, 1.27-1.31, 1.27 -1.30 and 1.22-1.23 respectively (see figure below).

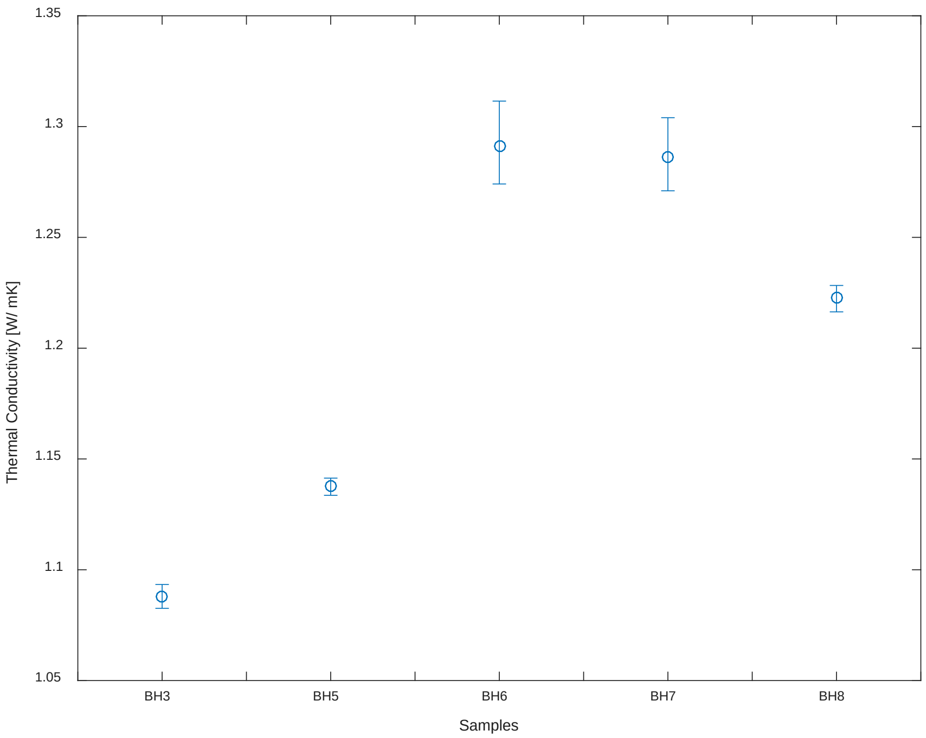


Figure 3: Thermal conductivity for each sample derived from the root-squared mean equation

As we note later in the results section, the measurements made in the laboratory used the divided bar apparatus, which yielded average thermal conductivity values of approximately ~0.9-1.2

W/mK, and nearly identical (within 10%) of values measured using the heat flow probe. This observation further supports the conclusion that thermal conductivity is nearly constant in the upper few meters of sediment in the Beaufort margin, with minimal variability in space, and that heat flow measurements can assume a nearly constant thermal conductivity value of approximately 1.1 W/mK provide a robust average thermal conductivity estimate for the region. Results for this work are part of work currently compiled and included in (Hornbach et al., in prep).

PRELIMINARY RESULTS

The Key Results from this work are currently in manuscript form and are outlined summarily below:

1. Heat flow values at upper (<250 mbsl) water depths appear anomalously low.

2. Heat Flow values at intermediate (250-750) water depths appear anomalously high compared to BSR values.

3. Heat flow values at depths greater than ~750 mbsl appear consistent with BSR derived values.

4. Thermal conductivity values are consistent with those found on other continental margins.

5. There is a clear increase in heat flow from east to west along the margin.

All of these results are included in a manuscript in preparation by Hornbach et al.

PRELIMINARY CONCLUSIONS

Below are the preliminary conclusions based on initial modeling of the methane hydrates system—these conclusion are currently in manuscript form and will be submitted in the coming months.

1. Intermediate Ocean Warming exists across ~400 km of the US Beaufort Margin from depths of ~300-700 mbsl—deeper than previous studies suggest.

2. The analysis suggests a ~5000 sq. km of the US Beaufort margin is destabilizing.

3. Based on 1D characteristic diffusion times and BSR depths, warming occurred *no later* than 3 ka.

4. Inversion/Forward Modeling Results with warming rates between 0.001 – 0.01 deg C/yr, indicate warming began more recently, 30-1000 years ago—rates of warming comparable to observed global surface warming.

5. At current rates, assuming no advection, the entire system will be back to steady state in 3-5ka.

6. Only a few locations where clear evidence of advection exists.

7. increasing deepwater heat flow to the west at depths > 800 m remains unclear and subject of further study.

In summary, the study demonstrates that methane hydrates are destabilizing rapidly over a large swath of the US Beaufort Margin, that this destabilization will likely continue for several thousands of years given current ocean temperatures (regardless of any additional ocean warming), and that this destabilization will continue to destabilize and release methane hydrate into the shallow seafloor sediments and ocean water with time.

SUGGESTED FUTURE STUDY

Rates of ocean warming remain unclear, yet are a critical for assessing both rate and scale of hydrate dissociation. Previous studies suggest little of this dissociated methane will likely make it to the atmosphere, but the impact on slope stability remains less clear. *Any planned/future long-term oil and gas infrastructure in these regions should assess/consider these uncertainties.*
Future studies in the Beaufort should strongly consider focusing on

(1) more accurately constraining the scale, location, timing, source, and evolution of *ocean warming* (ie. coupled oceanographic/paleoceanographic/geophysical studies).

(2) obtaining higher resolution multichannel seismic data in the Beaufort that will better quantify methane hydrate concentrations and phase boundary depths (and temperature shifts) in the Beaufort.

(3) Assessing/monitoring the physical properties in areas of apparent destabilization to better assess rates and more accurately forecast possible pressure/temperature changes with time (via drilling/instrumentation), as “snap-shots” can only provide a first-order assessment of where instability likely exists.

PRESENTATIONS ASSOCIATED WITH THIS WORK

Papers (Peer Reviewed Journals and Dissertations)

2014

"Widespread gas hydrate instability on the upper U.S. Beaufort margin"; Phrampus, Benjamin J.; Hornbach, Matthew J.; Ruppel, Carolyn D.; Hart, Patrick E.; *Journal of Geophysical Research: Solid Earth, Volume 119, Issue 12, pp. 8594-8609 (JGRB Homepage)* (12/1/2014).

"The ability of rock physics models to infer marine in situ pore pressure"; Matthew J Hornbach, Michael Manga; *Geochemistry, Geophysics, Geosystems: G3, Vol, 15, Issue 12, Pages 4769-4780* (12/10/2014).

2015

"Controls on gas hydrate system evolution in a region of active fluid flow in the SW Barents Sea"; Sunil Vadakkepuliyambatta,Matthew J. Hornbach,Stefan Bünz,Benjamin J. Phrampus; *Marine and Petroleum Geology, Volume 66, Part 4, September 2015, Pages 861-872* (9/1/2015).

"Gas hydrate as a proxy for contemporary climate change and shallow heat flow on the US east coast and north slope of Alaska"; Phrampus, Benjamin J.; *ProQuest Dissertations And Theses; Thesis (Ph.D.)--Southern Methodist University, 2015.; Publication Number: AAT 3739551; ISBN: 9781339302225; Source: Dissertation Abstracts International, Volume: 77-05(E), Section: B.; 168 p.* (12/19/2015).

In Review

"Atlantic Margin Heat Flow and Methane Hydrate Stability"; Benjamin J. Phrampus et al.; (In Review).

"The Heat flow evolution of the Western N. American Margin Derived from BSRs: Implications for Hydrocarbon Formation"; Benjamin J. Phrampus et al.; *Marine and Petroleum Geology*

In Preparation

"Significant Intermediate ocean water warming in the Arctic Ocean destabilizing Methane Hydrate"; Hornbach et al. (In Preparation).

"Heat Flow below the US Beaufort Margin"; Phrampus et al. (In Preparation).

American Geophysical Union, Fall Meeting Presentations

2012

"The role of ocean circulation on methane hydrate stability and margin evolution"; Hornbach, M. J.; Phrampus, B. J.; Ruppel, C. D.; Hart, P. E.; *American Geophysical Union, Fall Meeting 2012, abstract #T52B-07* (12/3-7/2012).

2013

"Alaskan Beaufort Sea Heat Flow and Ocean Temperature Analysis: Implications for Stability of Climate-Sensitive Continental Slope Gas Hydrates"; Phrampus, B. J.; Hornbach, M. J.; Ruppel, C. D.; Hart, P. E.; *American Geophysical Union, Fall Meeting 2013, abstract #B31I-06* (12/9-13/2013).

"Sources of Methane in Changing Arctic and Boreal Realms—Wetlands, Fires, Hydrates, Permafrost, Gasfields"; Benjamin Phrampus; (12/9-13/2013).

2015

"Mid- Atlantic Gas Hydrate, Heat Flow, and Basin Analysis: Implications to Hydrocarbon Production in the Carolina Trough"; Phrampus, B. J.; *American Geophysical Union, Fall Meeting 2015, abstract #B13B-0610* (12/14-18/2015).

"Marine Heat Flow Measurements of the Northern and Southern Hikurangi Margin, New Zealand"; Antriasian, A. M.; Harris, R. N.; Trehu, A. M.; Henrys, S. A.; Gorman, A. R.; Lauer, R. M.; Phrampus, B. J.; Colella, H.; Baker, D.; Rocco, N.; *American Geophysical Union, Fall Meeting 2015, abstract #T14B-04* (12/14-18/2015).

STUDENTS/RESEARCHERS SUPPORED BY THIS STUDY

Students from SMU include:
Ben Phrampus (who completed his Ph.D at SMU, and then moved to OSU as a post-doc, completing this project).

Vashan Wright, a Ph.D student at SMU, initially helped test and prepare sonar listening gear for the cruise, and later measured thermal conductivity samples in the lab.

Casey Brokaw, a Master's student at SMU, who has been working to integrate regional land-based Heat flow datasets in the Arctic with what we find offshore. Sailed in September 2016 and was recognized by the crew for excellent teamwork.

Madeline Jones, a Master's student at SMU, sailed in September 2016 and integrate heat flow data with the ocean bottom temperature data to help constrain hydrate stability.

Harrison Schumann (undergraduate who helped with conductivity analysis)
Evan Snyder (undergraduate who helped with conductivity analysis)

Michael Graw with OSU (Graduate student working on geochemistry)

REFERENCES

Beardsmore, G.R. and Cull, J.P., 2001. Crustal Heat Flow, Cambridge, *Cambridge University Press*, pp. 324.

Blackwell, D.D. and Spafford, R.E, 1987. " Experimental methods in continental heat flow", *in* C.G. Sammis, and T.L. Henyey eds., Experimental Methods in Physics, Part B - Field Measurements, **24**, *Geophysics*: Academic Press, 189-226.

Carslaw, H.S., and Jaeger, J.C. 1959. Conduction of heat in Solids. Oxford, *Oxford University Press*, pp. 510.

Clauser, Christoph, and Ernst Huenges. "Thermal conductivity of rocks and minerals." *Rock physics & phase relations: a handbook of physical constants* (1995): 105-126.

Hillier, Steve. "Accurate quantitative analysis of clay and other minerals in sandstones by XRD: comparison of a Rietveld and a reference intensity ratio (RIR) method and the importance of sample preparation." *Clay Minerals* 35, no. 1 (2000): 291-302.

Horai, K., 1981. Thermal conductivity of sediments and igneous rocks recovered during DSDP Leg 60. Initial Report Deep Sea Drilling Project, 60, 807-834.

Sass, J.H., A.H. Lachenbruch and J.R. Munroe, 1971. Thermal conductivity of rocks from measurements on fragments and its application to heat flow determinations, Journal of Geophysical Research., 76, 3391-3401.

Von Herzen, R.P., Measurement of oceanic heat flow, pp. 227-264, within C.G. Sammis, and T.L. Henyey eds., Experimental Methods in Physics, Part B - Field Measurements, 24, Geophysics: Academic Press, p. 623, 1987.

APPENDICES

Appendix 1: BSR derived heat flow, published in JGR, 2014. (License to include appears at end.)
Appendix 2: US. Beaufort Sea Cruise Report.
Appendix 3: Atlantic Research Summary.

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE

10.1002/2014JB011290

Widespread gas hydrate instability on the upper U.S. Beaufort margin

Benjamin J. Phrampus[1], **Matthew J. Hornbach**[1], **Carolyn D. Ruppel**[2], **and Patrick E. Hart**[3]

[1]Huffington Department of Earth Sciences, Southern Methodist University, Dallas, Texas, USA, [2]U.S. Geological Survey, Woods Hole, Massachusetts, USA, [3]U.S. Geological Survey, Menlo Park, California, USA

Key Points:

- Methane hydrates are destabilizing beneath >5000 km^2 of Beaufort Sea upper slope
- Recent upper ocean temperature warming is causing hydrate instability
- Complex heat flow exists beneath the U. S. Beaufort continental margin

Supporting Information:

- Readme
- Text S1
- Table S1
- Figure S1

Correspondence to:
B. J. Phrampus,
bphrampus@smu.edu

Citation:
Phrampus, B. J., M. J. Hornbach, C. D. Ruppel, and P. E. Hart (2014), Widespread gas hydrate instability on the upper U.S. Beaufort margin, *J. Geophys. Res. Solid Earth*, *119*, doi:10.1002/2014JB011290.

Received 15 MAY 2014
Accepted 28 OCT 2014
Accepted article online 5 NOV 2014

Abstract The most climate-sensitive methane hydrate deposits occur on upper continental slopes at depths close to the minimum pressure and maximum temperature for gas hydrate stability. At these water depths, small perturbations in intermediate ocean water temperatures can lead to gas hydrate dissociation. The Arctic Ocean has experienced more dramatic warming than lower latitudes, but observational data have not been used to study the interplay between upper slope gas hydrates and warming ocean waters. Here we use (a) legacy seismic data that constrain upper slope gas hydrate distributions on the U.S. Beaufort Sea margin, (b) Alaskan North Slope borehole data and offshore thermal gradients determined from gas hydrate stability zone thickness to infer regional heat flow, and (c) 1088 direct measurements to characterize multidecadal intermediate ocean warming in the U.S. Beaufort Sea. Combining these data with a three-dimensional thermal model shows that the observed gas hydrate stability zone is too deep by 100 to 250 m. The disparity can be partially attributed to several processes, but the most important is the reequilibration (thinning) of gas hydrates in response to significant (~0.5°C at 2σ certainty) warming of intermediate ocean temperatures over 39 years in a depth range that brackets the upper slope extent of the gas hydrate stability zone. Even in the absence of additional ocean warming, 0.44 to 2.2 Gt of methane could be released from reequilibrating gas hydrates into the sediments underlying an area of ~5–7.5 × 10^3 km^2 on the U.S. Beaufort Sea upper slope during the next century.

1. Introduction

Methane hydrates, ice-like solids that consist of methane and water that are stable at moderate pressures and low temperatures, are believed to be widespread in Arctic Ocean continental slope and rise sediments [e.g., *Kvenvolden and Grantz*, 1990; *Biastoch et al.*, 2011; *Reagan et al.*, 2011]. The Arctic Ocean and surrounding landmasses have experienced rapid warming on short-term (decadal) time scales [e.g., *Johannessen et al.*, 2004]. On longer time scales, warming of more than 10°C since the Last Glacial Maximum (LGM) has been linked to permafrost thaw, reduced Arctic Ocean sea ice cover and possibly methane hydrate destabilization [*Brigham and Miller*, 1983; *Allen et al.*, 1988; *Paull et al.*, 2007; *Shakhova et al.*, 2010]. In the marine system, the impingement of warming ocean waters on continental slopes, which host the most climate-sensitive gas hydrate deposits [*Kvenvolden*, 1993; *Ruppel*, 2011], not only leads to breakdown (dissociation) of gas hydrates into constituent methane and water but also can increase subsurface fluid pressures and reduce slope stability [e.g., *Kayen and Lee*, 1991; *Flemings et al.*, 2003; *Hornbach et al.*, 2004]. Methane that migrates to the seafloor after dissociation may be released into the ocean, enhancing water column methane oxidation that leads to increased ocean acidification and deoxygenation [*Kvenvolden*, 1988; *Dickens et al.*, 1995; *Archer*, 2007; *Camilli et al.*, 2010; *Biastoch et al.*, 2011]. Due to the potential for methane destabilization and release, unraveling the connections between climate warming and methane hydrate dynamics on the Beaufort Sea margin has important implications for marine sediment mechanics, Arctic Ocean chemistry, and possibly atmospheric greenhouse gas concentrations.

In typical deepwater marine gas hydrate systems, gas hydrates can in theory exist at the seafloor. In practice, outside seep areas, gas hydrate does not usually occur as shallow as the seafloor because anaerobic methane oxidation processes within the sulfate reduction zone that lies within the uppermost meters of sediments consume most of the methane [*Reeburgh*, 2007]. To first order, the base of gas hydrate stability (BGHS) is controlled by the geothermal gradient and hydrostatic pressure within the saturated and generally high-porosity sediments that make up the uppermost hundreds of meters on most continental margins. The BGHS often manifests in seismic data as a strong, reverse-polarity bottom-simulating seismic reflector (BSR) [*Shipley* *et al*., 1979; *Kvenvolden and Grantz*, 1990; *Andreassen et al*., 1997]. The negative impedance contrast at the BSR reflects the layering of higher-velocity, hydrate-bearing sediments over lower-velocity, gas-charged sediments [*Holbrook et al*., 1996]. The presence of a BSR is a sufficient condition for the likely occurrence of gas hydrate in sediments, but gas hydrate sometimes exists without an underlying BSR [*Holbrook et al*., 1996]. BSR depths, combined with hydrate stability models [*Sloan and Koh*, 2008], have long been used to constrain subsurface temperature regimes [*Yamano et al*., 1982] and to assess the degree to which the sediments are in steady state thermal equilibrium [e.g., *Ruppel*, 1997; *Ruppel and Kinoshita*, 2000; *Hornbach et al*., 2004; *Hornbach et al*., 2008; *Phrampus and Hornbach*, 2012]. Where the gas hydrate stability zone (GHSZ) is out of equilibrium with contemporary ocean temperature and heat flow conditions, the contemporary distribution of gas hydrates may sometimes reflect past conditions. Future adjustments in the distribution of gas hydrates would be expected to bring the system back into equilibrium.

In this study, we use the regional 1977 ocean temperature data, long-term ocean temperature data, and heat flow observations combined with numerical models to predict the steady state location of the GHSZ in the U.S. Beaufort Sea. We then compare modeled steady state GHSZ with direct observations of BSRs revealed in regional seismic data. The results allow us to delineate where methane hydrates may be destabilizing on the U.S. Beaufort continental margin.

2. Setting

The study area is the continental slope of the U.S. part of the Beaufort Sea, roughly between the shelf break (~100 m water depth) on the south and the continental rise (~3000 m water depth) on the north. The region stretches ~600 km from the offshore extension of the U.S.-Canada border (141st meridian west) on the east to Barrow, Alaska, on the west. To date, no comprehensive methane hydrate stability analysis has been conducted along this margin.

Owing to differences in data availability, the number of past studies, and the geologic, structural, glacial, sea level, and sedimentation histories, we focus only on the U.S. part of the Beaufort Sea margin. Our results are likely not fully applicable to the Beaufort Sea offshore Canada, which differs from the U.S. part of the margin in having experienced Laurentide glaciation [*Dyke and Prest*, 1987], strong sedimentary influence of the Mackenzie River [*Carmack et al*., 1989], a petroleum system history that has left the shelf sediments charged with gas [*Blasco et al*., 2011], and active compressive deformation [*Houseknecht et al*., 2012].

West of Flaxman Island on the U.S. Beaufort Sea margin, the continental slope is a rifted margin terrace that overlies increasingly attenuated continental crust as the base of the continental slope transitions into the Canada Basin. Along this part of the Beaufort Sea, the Brooks Range fold and thrust belt lie well inland and is bordered to the north by the wide North Slope coastal plain (Colville foreland) and a classic passive margin offshore. Near the Canning River, the fold and thrust belt curve northward and then veer east, finally intersecting the present-day coastline near the U.S.-Canada border. The Beaufort shelf and continental slope east of the Canning River is part of the Canning-Mackenzie deformed margin (CMDM), most of which lies within Canadian waters. Offshore, the CMDM is characterized by folding [*Houseknecht et al*., 2012], mud diapirism, and pingo-like features [*Paull et al*., 2007; *Blasco et al*., 2011; *Hart et al*., 2011].

The large-scale tectonics—typical passive margin on the west transitioning to a passive margin undergoing active compression on the east—is reflected in the morphology of the continental slope, where most gas hydrate discussed in this study occurs. North of Prudhoe Bay, the continental slope is steep, deepening by 900 m over a distance of ~11 km (4.7° average slope), compared to the shallower slope (~1.4°) off the Canning River region (Figure 1). The steep continental slope north of Prudhoe Bay occurs where the passive margin province begins to transition eastward to the CMDM. The wider, gentler continental slope within the CMDM is where the connection between large-scale slope failures and gas hydrate/gas-charged sediments was first investigated [*Kayen and Lee*, 1991]. Close to the seafloor, this area has also been most strongly affected by glacial scouring associated with a floating ice sheet that may have extended from the Amundsen Gulf across the Beaufort Sea to the Chukchi Plateau during late Pleistocene glaciation [e.g., *Engels et al*., 2008].

This study focuses on the deepwater gas hydrate system within the continental slope and rise of the U.S. Beaufort Sea. In this area, most of the sedimentary section is Cenozoic, progradational, postrift, and clastic prism deposits from the Brooks Range and Arctic Foothills [*Grantz et al*., 1990; *Houseknecht and Bird*, 2011],

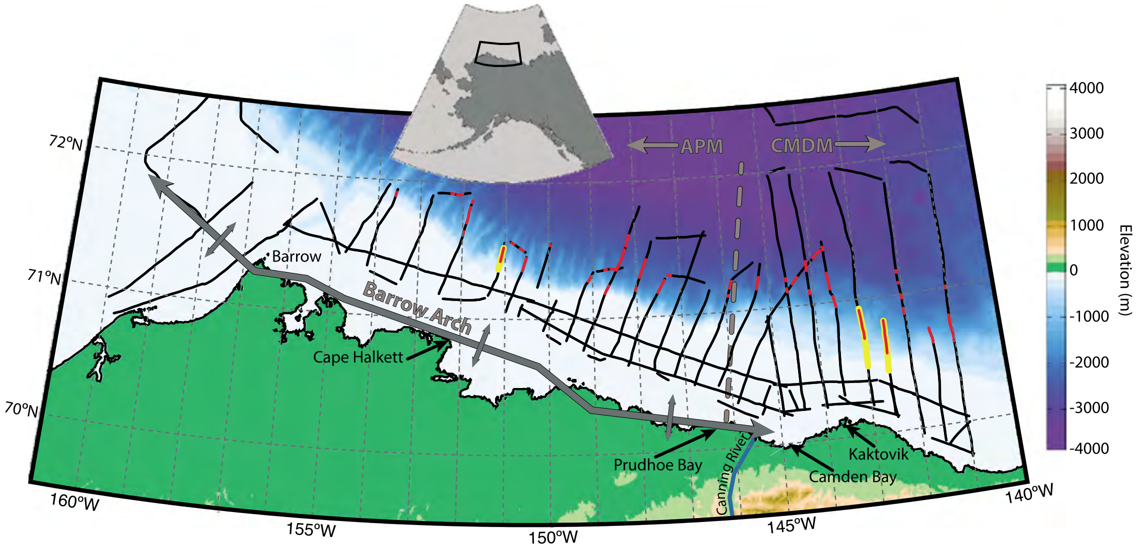


Figure 1. U.S. Beaufort Sea study area with key geologic features including the Barrow Arch, Alaskan passive margin, and Canning-Mackenzie deformed margin (CMDM) [*Houseknecht and Bird*, 2006]. Seismic lines from the 1977 USGS surveys are shown in black [*Andreassen et al.*, 1995]. The red represents the minimum extent of BSRs in the Beaufort Sea based on seismic interpretations. The seismic lines that most clearly reveal dynamic (nonsteady state) hydrate stability zones are shown in bold yellow. These lines are 767, 718, and 730 from west to east, respectively.

with additional sediment derived from the ancestral Mackenzie River to the east [*Houseknecht et al.*, 2012]. The sediments form a seaward thickening wedge that mantles the pre-Mississippian Beaufort rift shoulder and the prerift and synrift deposits associated with opening of the Canada Basin [*Houseknecht et al.*, 2012].

The shelf ($<$100 m water depth) in the study area did not undergo continental glaciation during the LGM but was instead exposed subaerially during the sea level lowstand [*Dyke et al.*, 2002]. This led to the formation of permafrost and possibly permafrost-associated gas hydrate in the sediments that now comprise the shelf. During subsequent sea level rise of 100 m or more, the permafrost and gas hydrate has probably mostly thawed, and recent seismic analyses indicate that permafrost probably does not remain beyond ~30 km (~20 m isobath) from the present-day coastline [*Brothers et al.*, 2012]. Permafrost-associated gas hydrates, which are not known to form BSRs and whose existence on the U.S. Beaufort Sea shelf is probably not widespread, are not considered in this study.

Sea level rise of 100 m or more since the late Pleistocene has played an important role not only on the continental shelf but also on the U.S. Beaufort Sea upper slope (~100 to 500 m water depth). The upper slope lay close to the late Pleistocene shoreline and may have been the locus of deltaic sedimentation from ancestral rivers and deposition from the Brooks Range into the early Holocene [*Grantz et al.*, 1990]. During the latter part of the Holocene, much of the central and eastern parts of the margin have been sediment starved. The Colville River is the only large river on the U.S. Beaufort Sea coastline, but its annual discharge and sediment load are a fraction of those of the Mackenzie River or the great rivers of the Siberian arctic. A branch of the Mackenzie River sediment plume sometimes veers west across the Beaufort Sea upper slope, providing enhanced sediment loads.

The extent of deepwater gas hydrates on the U.S. Beaufort continental slope and rise was first mapped in 1977 by the U.S. Geological Survey (USGS), which used multichannel seismic (MCS) data along 24 lines to delineate BSRs, building on the results of earlier, single-channel surveys [*Grantz et al.*, 1976]. The 1977 MCS data were acquired with a 2400 m long streamer and a five air gun, 22,700 cm^3 array [*Grantz et al.*, 1982; *Andreassen et al.*, 1995]. Data are 24-fold with a trace spacing of 50 m. Velocity uncertainty increases with depth in the seismic data set, reaching ±12.7% at the deepest observed BSR. In these data, the BSR could be identified in 80% of the ~40,000 km^2 gas hydrate province [*Grantz et al.*, 1976; *Kvenvolden and Grantz*, 1990; *Andreassen et al.*, 1995]. Starting at ~350 m below sea level (mbsl) on the upper continental slope, the GHSZ thickens seaward, with the BSR reaching ~770 m below seafloor (mbsf) at 3200 mbsl.

3. Data and Methods

Determining the steady state morphology of the GHSZ in the Beaufort Sea requires constraints on the two key boundary conditions that control the stability of gas hydrates at any given depth: bottom water temperature (BWT) and regional heat flow. Currently, heat flow is poorly constrained in the Beaufort Sea, and ocean temperatures, although well constrained from water column conductivity-temperature-depth (CTD) data, are warming with time [*Melling*, 1998]. Below, we describe the methods used to constrain both ocean temperature and regional heat flow to develop a steady state gas hydrate stability model for the Beaufort Sea that we then compare with the 1977 USGS seismic observations.

3.1. Ocean Temperature

Accurately predicting the thickness of the GHSZ requires a clear understanding of ocean temperature with depth. Using the World Ocean Database [*Levitus et al*., 1998], we extracted 1088 CTD casts collected in the study area (Figure 2a). Most of the CTD data were acquired during two annual periods between calendar days 50 and 150 (winter-spring) and 200 and 300 (summer-fall; Figure 2b). CTD data exist from 1976 to 2008 for the winter-spring period and from 1971 to 2010 for summer-fall period. For shallow water depths (≤200 mbsl), consistent CTD data extend back 39 years in the summer-fall. For deeper depths (≥300 mbsl), a maximum of 25 years of CTD data is available. Within these constraints, we calculate seasonal average ocean temperatures with depth.

We analyzed raw data from 100 to 1000 mbsl at 5 m intervals for each of the 1088 CTD casts to generate averages. To reduce the potential for systematic error with temperature at each depth, we determine the average and standard deviation temperature value in each interval by averaging all values within a ±5 m depth range. We then combine all results for each year and calculate an average temperature and standard deviation (example in Figure 3). This produces an estimate and standard deviation of winter-spring/summer-fall ocean temperature with depth for each year.

Finally, we calculate a mean and standard deviation long-term (up to 39 years) annual rate of temperature change in the Beaufort Sea at each depth interval by using Monte Carlo simulations that incorporate our measured annual temperature-depth values and associated uncertainties. To initiate the Monte Carlo simulation, we choose a random average yearly temperature within the normally distributed error at each depth for each year. We then run Monte Carlo simulations through 1000 realizations in which each realization uses a least squares approach to estimate the slope (i.e., linear rate of temperature change) that best fits the annual temperature variation with depth. From these results, we determine the average temperature variation for each depth, for each year, for all past years. This produces a plot of linear changes in ocean temperatures for the winter-spring and summer-fall time periods (Figure 4).

The result generally matches other ocean temperature observations that indicate steady ocean temperature warming at intermediate water depths in the Beaufort Sea [e.g., *Melling*, 1998]. We determine the average yearly temperature change by calculating the statistical mean and standard deviation of the winter-spring and summer-fall temperature changes, assuming that the winter-spring and summer-fall temperature changes each represent 50% of the data set. This approach removes bias introduced due to the summer-fall sample count greatly outnumbering the winter-spring sample count. The result represents the average rate of linear temperature change along the Beaufort continental margin and reveals that the dominant change in ocean temperatures occurs at ~300–550 mbsl (Figure 4). Below 550 mbsl, we see no statistically significant evidence for ocean temperature change across the region.

3.2. Heat Flow

Developing a model that estimates the depth to the base of methane hydrate stability also requires regional constraints on heat flow. Thirty-four terrestrial heat flow measurements are available from borehole measurements on the North Slope of Alaska (Figure 5 and Table S1 in the supporting information) [*Lachenbruch and Marshall*, 1969; *Lachenbruch et al*., 1982; *Deming et al*., 1992]. Offshore, heat flow can be inferred only indirectly [e.g., *Houseknecht and Bird*, 2011]. In the U.S. Beaufort Sea, wells are almost exclusively in the coastal zone, with only a few wells drilled on the middle to outer shelf and none on the upper continental slope. None of the offshore wells has publicly available data that constrain thermal regimes in the uppermost hundreds of meters of sediment. However, one well (Aurora) located ~6 km from shore on the central U.S. Beaufort coast provides thermal gradient data at depths >300 mbsl (Figure 5 and Table S1 in the supporting information) [*Paul*, 1994]. Given the paucity of offshore data, we rely on both onshore thermal

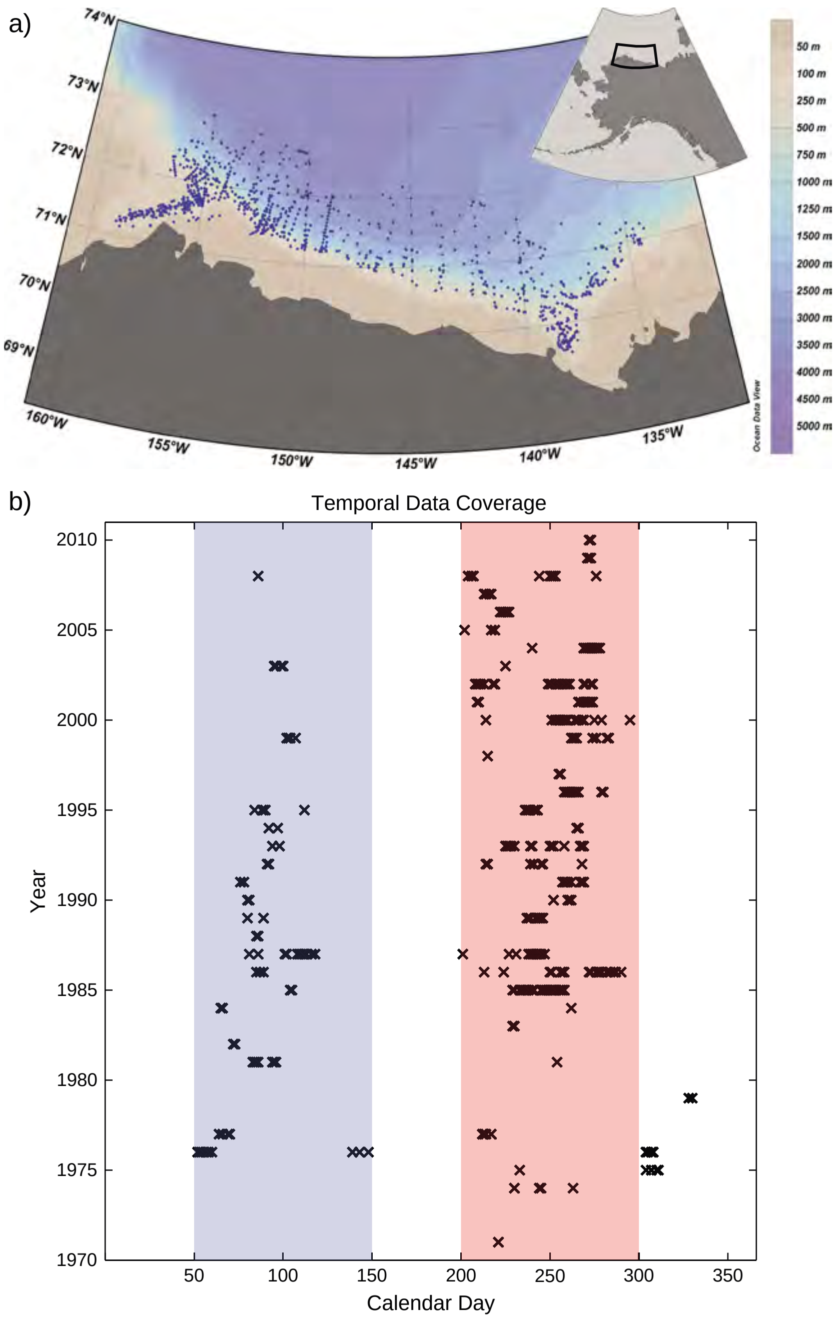


Figure 2. (a) Bathymetric map of study area with the location of 1088 CTD stations shown in blue. (b) Plot showing the day of the year each of the 1088 CTDs were collected. This study analyzes data between calendar days 50–150 (blue) and 200–300 (red), which have the highest data density.

data and constraints based on the depth of deepwater (>1000 mbsl) BSRs to constrain regional heat flow. Previous studies indicate that ocean temperatures at depths greater than 1000 mbsl have experienced no significant change within the last 5000–10,000 years, consistent with our own analysis of CTD data for up to 39 years [e.g., *Waelbroeck et al*., 2002; *Westbrook et al*., 2009; *Marín-Moreno et al*., 2013]. This implies that deepwater BSRs represent a useful tool for estimating first-order heat flow in the deepwater Beaufort Sea.

The compiled heat flow map is shown in Figure 5. Such an interpolated heat flow map has inherent weaknesses since it combines onshore and offshore areas that have different geologic, cryospheric, tectonic, subsidence, and thermal histories and interpolates values between onshore and deepwater areas, directly

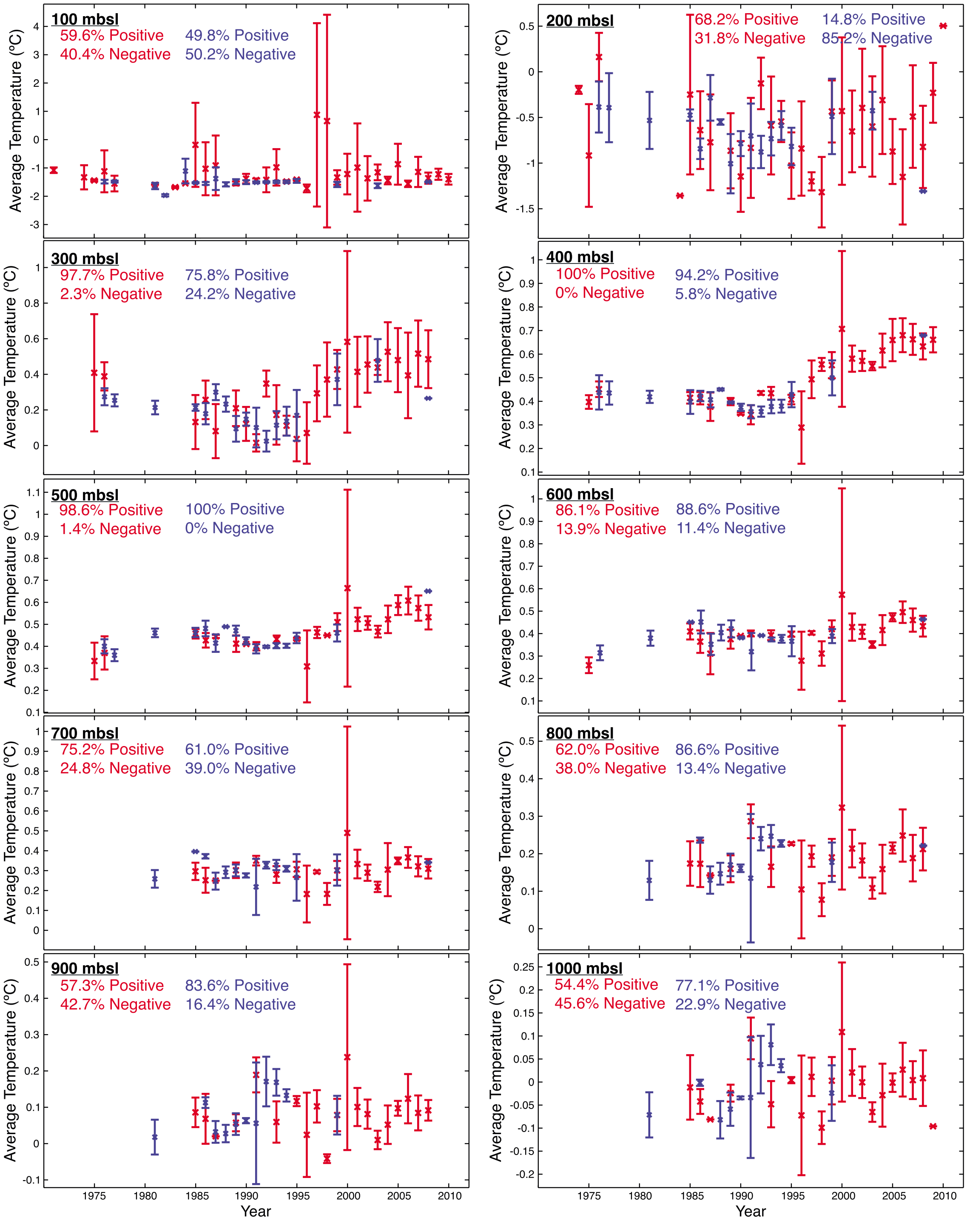
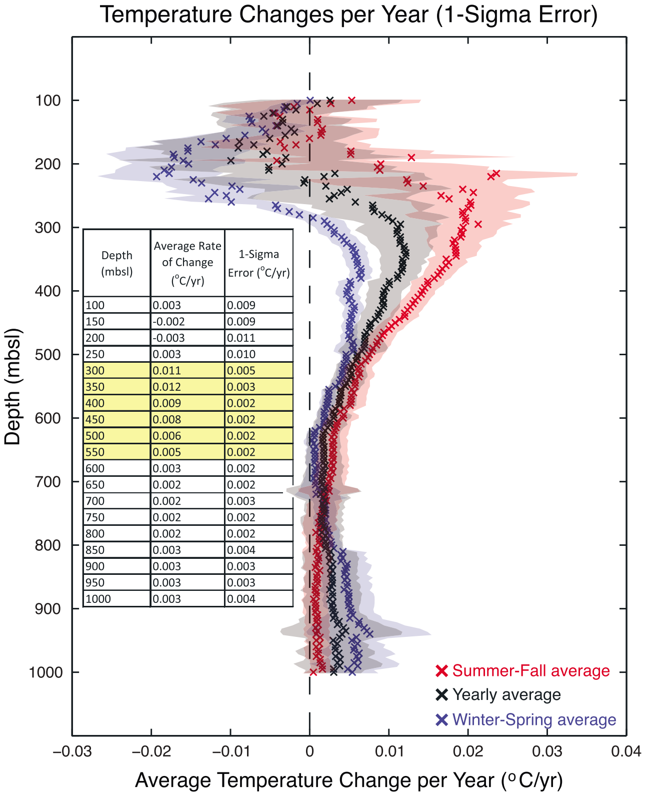


Figure 3. Plot of average temperatures per year at each depth interval with 1 sigma error plotted for each year for the summer-fall (red) and winter-spring (blue) time frames. Temperature limits (*y* axis) are not equal for each plot. Percentages represent the total percent of positive and negative slopes obtained during the Monte Carlo simulation, implying either average temperature warming or cooling, respectively, for the past 25–39 years at each depth interval.

across the shelf. Along much of this margin, the map is also interpolated across the Beaufort hingeline, the crest of which is known as the Barrow Arch. This structural feature runs near the coastline for hundreds of kilometers and acts as an important boundary for some sedimentary and petroleum systems (Figure 1) [*Houseknecht and Bird*, 2006]. Our analysis therefore represent only a first-order approach to assessing heat flow in the Beaufort Sea and has large uncertainties that we quantify below.



Depth (mbsl)	Average Rate of Change (°C/yr)	1-Sigma Error (°C/yr)
100	0.003	0.009
150	-0.002	0.009
200	-0.003	0.011
250	0.003	0.010
300	0.011	0.005
350	0.012	0.003
400	0.009	0.002
450	0.008	0.002
500	0.006	0.002
550	0.005	0.002
600	0.003	0.002
650	0.002	0.002
700	0.002	0.003
750	0.002	0.002
800	0.002	0.002
850	0.003	0.004
900	0.003	0.003
950	0.003	0.003
1000	0.003	0.004

Figure 4. Plot of the average linear change in temperature over the 25–39 year time frame with 1 sigma error estimations resulting from the Monte Carlo simulations in the shaded regions. The different colors represent the different seasons (winter versus summer), with the black data representing the statistical average yearly variations in ocean temperatures. The table shows the numerical data represented by the yearly (black) data in the figure.

3.2.1. Terrestrial Heat Flow

A database of terrestrial heat flow measurements has been developed for the Alaskan North Slope, an area generally characterized by continuous permafrost hundreds of meters thick [*Osterkamp and Payne*, 1981; *Osterkamp et al.*, 1985; *Collett et al.*, 1988]. For this reason, we focus on conductive heat flow instead of thermal gradients, which are strongly affected by the unique thermal conductivity structure of permafrost sediments. *Deming et al.* [1992] used boreholes to obtain 27 North Slope heat flow measurements with an average uncertainty of ±19 mW/m^2 (Table S1 in the supporting information). *Lachenbruch et al.* [1982] used observation wells and drill cuttings to determine an average heat flow of ~55 ± 6 mW/m^2 in the Prudhoe Bay region, with an additional two wells described by *Lachenbruch and Marshall* [1969] having unknown uncertainty (Table S1 in the supporting information). Taken together, the data reveal variable heat flow across the Alaskan North Slope, which encompasses a range of lithologies, petroleum systems, and tectonic settings [*Houseknecht and Bird*, 2011].

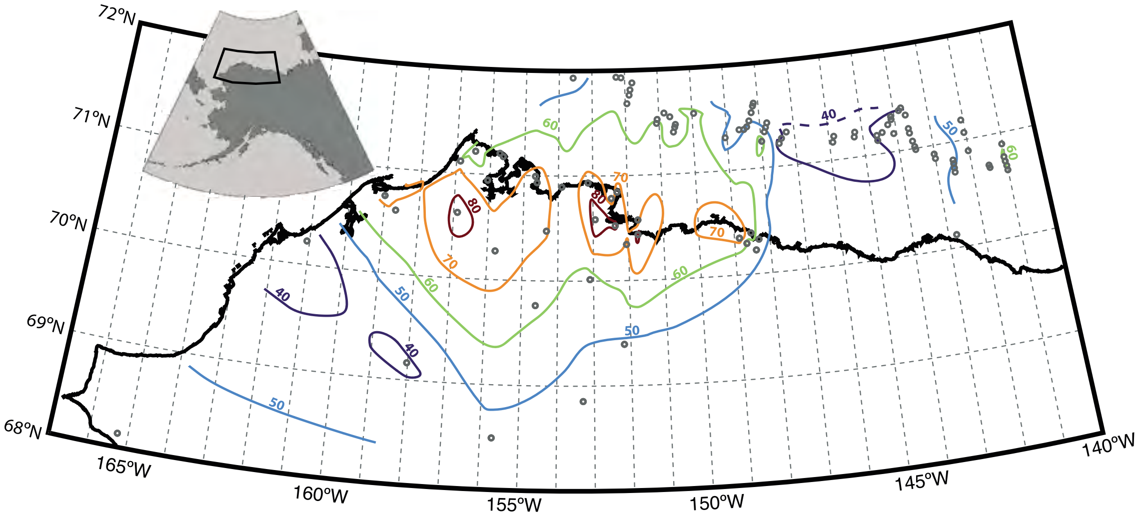


Figure 5. Regional heat flow map created by integrating previously published land heat flow data [*Lachenbruch and Marshall*, 1969; *Lachenbruch et al.*, 1982; *Deming et al.*, 1992] with heat flow estimations using deepwater (>1000 mbsl) BSRs [*Yamano et al.*, 1982]. Each dot represents a heat flow estimation with variable error (Table S1 in the supporting information).

3.2.2. Deepwater Heat Flow

We use BSR depths extracted from legacy USGS seismic data [*Grantz et al.*, 1982] to constrain thermal gradients and infer heat flow in the uppermost part of the sedimentary section, following the method of *Yamano et al.* [1982]. The seafloor boundary condition (bottom water temperature) is constrained using existing databases of oceanographic measurements (section 3.1). The BSR temperature T is determined using standard stability models for pure methane [*Sloan and Koh*, 2008] and assuming hydrostatic pressure at subseafloor depth z of the BSR. Heat flow q is calculated from

$$q = k\frac{dT}{dz} \tag{1}$$

where dT/dz denotes the geothermal gradient and and k is the thermal conductivity. BSRs at midslope water depths on the U.S. Beaufort margin are continuous and smooth, showing no evidence of warping due to significant fluid advection. We therefore assume that regional heat flow is dominated by conduction, consistent with heat transfer at other continental margin locations where continuous BSRs exist [e.g., *Yamano et al.*, 1982; *Ruppel et al.*, 1995].

Ocean water temperatures are constrained using data from 76 CTD casts that were conducted in 1977 (the year of the seismic data acquisition) and extracted from the World Ocean Database [*Levitus et al.*, 1998]. BSR depths are determined from the legacy USGS MCS data. We identified the BSR as a reverse-polarity reflector in migrated USGS seismic data and confirmed the location of BSRs via interval velocity analysis, with lower seismic velocities observed below BSRs compared to higher velocities in the overlying GHSZ [e.g., *Holbrook et al.*, 1996].

Uncertainty in BSR depths propagates into heat flow uncertainty, and we account for this via statistical analysis of interval velocities obtained from 1977 USGS common midpoint gathers. Interval velocities have increasing error with depth [*Dix*, 1955]. Not surprisingly, we find that BSR depth uncertainty using interval velocities depends upon BSR depth below the seafloor, with higher uncertainty at deeper BSR depths due to the additive nature of interval velocity errors. Specifically, we find the greatest depth uncertainty of approximately ±50 m occurs at the greatest depths ($>$1000 mbsf). For shallow BSRs along the upper continental slope, depth uncertainty is significantly lower (±15–20 m).

With BSR depth and seafloor temperature constrained, we estimate heat flow by calculating the temperature at the BSR. The temperature required for gas hydrate to be stable at the depth of the BSR is determined using the Canning Seafloor Mound Gen program, which accounts for salinity, gas composition, and pressure effects [*Sloan and Koh*, 2008]. Based on the CTD database, salinity in the Beaufort Sea averages approximately 34.85‰ and varies by no more than 2–3% across the region for water depths where BSRs exist, consistent with observed salinities in the CTD casts and with previously published values [e.g., *Melling*, 1998]. We therefore use seawater salinities in this analysis. We assume a hydrostatic pressure regime and pure methane as the hydrate former, consistent with regional inferences [*Hart et al.*, 2011]. We calculate sediment thermal gradients for all the observed BSRs located beneath the seafloor at depths greater than 1000 mbsl and average the thermal gradients for each seismic line every 100 shots (~5 km).

To convert thermal gradient to heat flow, we use regionally measured thermal conductivity values and weighted average values. The thermal conductivities of marine sediments typically vary between 0.8 and 1.6 W/m K [e.g., *Ratcliffe*, 1960] and are controlled by lithology, porosity, pressure, temperature, and the effective thermal properties of the pore-filling fluid (e.g., seawater, gas, or hydrate). Little is known about the sediments on the upper continental slope on the Beaufort margin, although coring programs encountered indurated strata close to the seafloor [*Barnes et al.*, 1982]. Assuming porosity values of 35–60% for the upper few hundred meters of ice-free, hemipelagic sediments, combined with direct observations of deepwater conductivities [*Lachenbruch and Marshall*, 1966], we adopted a constant thermal conductivity of 1.1 ± 0.3 W/m K both in the determination of heat flow and in the application of the numerical model. On average, this thermal conductivity value is slightly higher than typical shallow marine sediments (~1 W/m K), but this may be justified because sediments on Arctic Ocean margins are often overconsolidated [e.g., *Hamilton*, 1976; *Reimnitz et al.*, 1980; *Reimnitz et al.*, 1988].

3.2.3. U.S. Beaufort Sea Heat Flow Map

Interpolating land and sea heat flow results, we produce an initial heat flow map across the U.S. Beaufort Sea (Figure 5). The map shows evidence of moderate heat flow (~40 ± 11 mW m^{-2}) relative to the surroundings near 146°W, 71°N (approximate shelf break north of Flaxman Island), bordered to the east and west by heat flow values that are nearly 50% higher. The analysis therefore suggests a spatially variable shallow heat flow regime across the Beaufort margin. Currently, we are unable to constrain the cause of this spatially variable heat flow. Deep fluid advection (causing increased heat flow), shallow fluid advection (causing reduced heat flow), and/or variations in sediment thickness and composition, basement morphology, and the degree of attenuation of continental crust may contribute to the inferred pattern of heat flow variability.

3.3. Three-Dimensional Conductive Heat Flow Model

To model steady state methane hydrate stability in the Beaufort Sea at depths shallower than 1000 mbsl, we use a 3-D finite difference scheme that incorporates variable seafloor temperature and accounts for thermal refraction (i.e., lateral variations in the thermal regime caused by variations in bathymetry and boundary conditions across the study area) effects. The approach is identical to previously published 2-D/3-D steady state hydrate stability models [e.g., *Hornbach et al.*, 2012; *Phrampus and Hornbach*, 2012]. The 3-D heat flow model has open side boundary conditions, with temperature initially increasing linearly with depth, constant BWT at the top boundary, and a Neumann basal boundary condition defined by the heat flow map (Figure 5). Model resolution, scale, and dimensions as constrained by the legacy USGS seismic lines and by regional multibeam seafloor data [e.g., *Grantz et al.*, 1982; *Andreassen et al.*, 1995; *Ryan et al.*, 2009; *Haxby et al.*, 2010] are 20 m in the vertical and 50 m in both horizontal directions.

Ocean water temperature with depth is constrained using 1977 CTD data described in section 3.1. Sediment thermal gradients for each seismic line are imported point by point from the heat flow map (Figure 5). Based on the CTD database, salinity in the Beaufort Sea averages approximately 34.85‰; nonetheless, we account for possible freshwater discharge on the slope or rise [*Dugan and Flemings*, 2000; *Pohlman et al.*, 2011] by varying salinity between freshwater (0‰) and the maximum salinity (34.85‰) as part of end-member uncertainty calculations. We then estimate BGHS depth using standard gas hydrate phase boundary methods, assuming pure Structure I methane hydrate [*Sloan and Koh*, 2008].

To extract steady state BGHS depths from the model, we use end-member values that incorporate uncertainties in pore water salinity, pore pressure, heat flow, and velocity-depth uncertainties. Unlike uncertainties in salinity, pressure, and velocity, uncertainties in heat flow vary spatially in the model. All spatial uncertainties are incorporated directly into the BGHS depth estimation to 1 sigma in the model results (Figure 6).

4. BGHS Modeling Results

To compare results for the model-predicted steady state GHSZ with direct observations of BSRs (i.e., the assumed BGHS), we used three seismic profiles: Line 767 in the western U.S. Beaufort Sea and Lines 730 and 718 in the eastern U.S. Beaufort, all of which show clearly observable BSRs (Figures 1 and 6). As expected, a comparison between the predicted steady state BGHS depths and the observed BSRs reveals that the BSRs lie within the predicted BSR zone (calculated assuming uncertainties on input parameters) at water depths greater than the midslope (>1000 mbsl). These are the water depths at which we used a subset of BSR depths to constrain the heat flow map, and as expected, the BSRs are in near steady state conditions in this area. On the upper slope (300–600 mbsl), clear discrepancies exist between predicted and observed BSR depths. In particular, at water depths shallower than ~600 mbsl, observed BSRs are systematically deeper than steady state model predictions (Figure 6). Model results for Lines 718 and 730 (Figures 6a and 6b), which are located within the CMDM (Figure 1), generally match observed BSRs for seafloor depths greater than 1000 mbsl. At shallower depths, predicted steady state BGHS depths and observed BSR depths diverge as the water depth decreases, with the predicted depths systematically shallower than the observed BSRs. Line 767 (Figure 6c), located the farthest west, displays this anomaly as well, but the disparity between observed and predicted BSRs is most pronounced in Lines 718 and 730.

5. Discussion

Multiple phenomena could explain the anomalously deep BSRs observed in seismic data on the upper slope of the U.S. Beaufort Sea margin. Many of the factors that affect the depth of the GHSZ (e.g., variations in pore

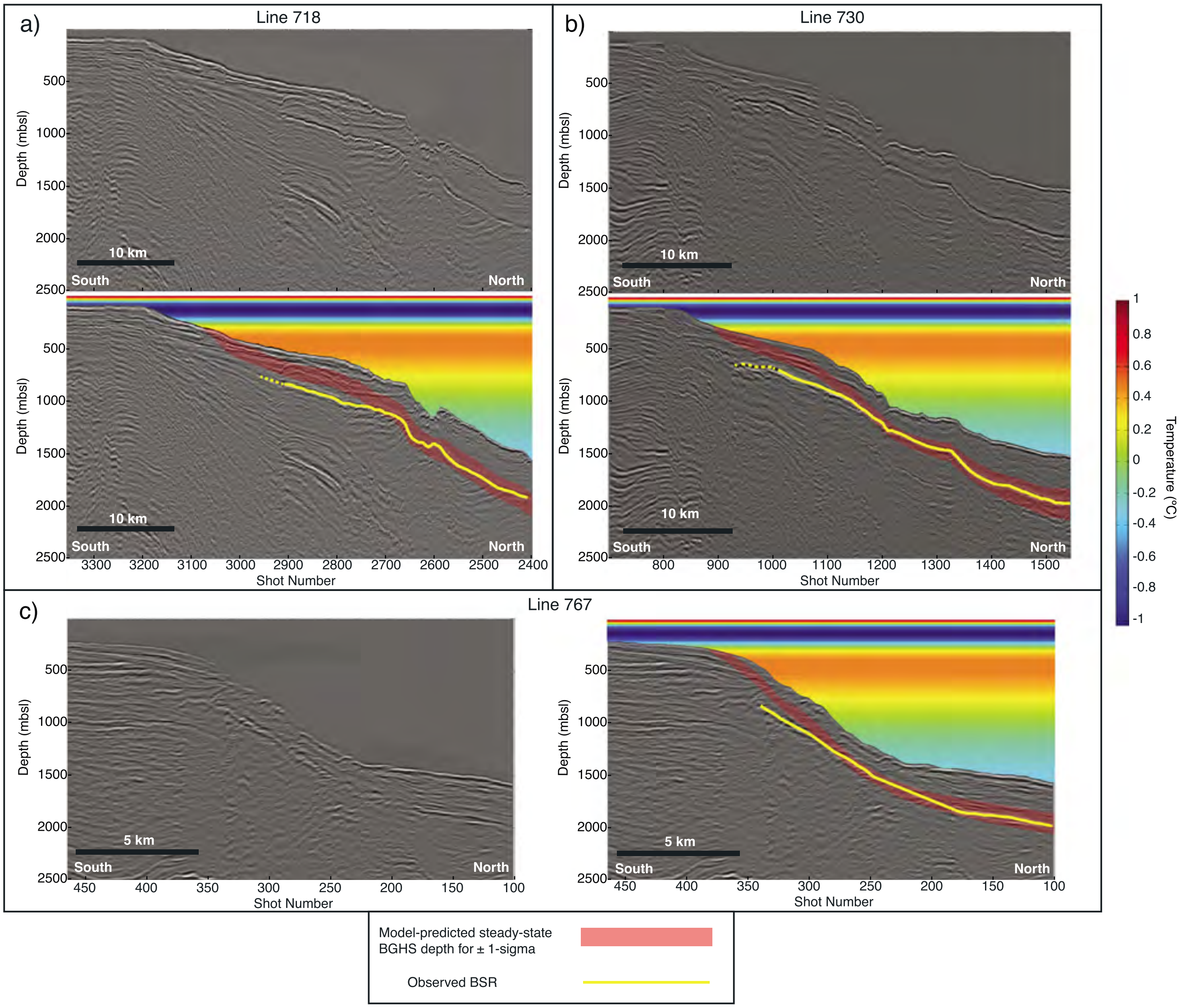


Figure 6. Depth converted seismic lines (a) 718, (b) 730, and (c) 767. For each line, we determine the depth to the BGHS to ±1 sigma (red region), with the observed BSRs marked (yellow). The 1977 Beaufort Sea ocean temperatures are shown for each seismic line. Model-predicted results show that the GHSZ pinches out at 300–350 mbsl. There is a distinct discrepancy between observed and predicted BSRs corresponding to seafloor depths of 300–550 mbsl. Lines (a) 718 and (b) 730 demonstrate this anomaly the best, with line (c) 767 providing a subtler example.

water salinity, velocity-depth uncertainties, and heat flow uncertainty) are already accounted for in the modeling though. We estimate that uncertainties in regional heat flow could be as large as ~35%. Anomalously deep BSRs on the upper continental slope require heat flow to be as much as ~27 mW/m^2 less than the regional estimates (42–56 mW/ m^2), which is significantly larger than our 1 sigma uncertainty of ~15 mW/m^2 (Figure 5). Below, we explore other processes that could explain why observed BSR depths are generally deeper than modeled BGHS depths at seafloor depths of 300–600 m along the upper continental slope on this margin.

5.1. Gas Composition

The guest molecules that are incorporated into gas hydrate strongly affect stability conditions [*Kvenvolden*, 1998; *Sloan and Koh*, 2008] and thus the thickness of the GHSZ. For example, the inclusion of higher-order thermogenic gases (e.g., ethane) in the gas hydrate lattice would cause the BGHS to occur at greater depths than predicted by the model, which assumes Structure I gas hydrate hosting 100% methane. If gases other than methane were the cause of anomalously deep observed BSRs on the upper continental slope, our analysis implies increasing amounts of higher-order thermogenic gas in the shallow sediments moving up the slope from ~1000 mbsl to ~300 mbsl across the entire U.S. Beaufort Sea margin. We calculate that a mixture of ~15% ethane and ~85% methane by volume would be required to produce observed BSR depths in Lines 718 and 730. A mixture of ~12% ethane and ~88% methane by volume would explain the anomaly observed on Line 767.

Due to the presence of the Barrow Arch, there are clear differences between the maturation of petroleum systems onshore (Alaskan North Slope) and offshore (Beaufort Sea), meaning that it cannot be assumed that world-class deposits like those near Prudhoe Bay extend offshore uninterrupted [*Houseknecht et al*., 2012]. *Houseknecht and Bird* [2011] predict 23 trillion cubic feet (TCF) of gas associated with crude oil and 19 TCF of nonassociated gas under the continental slope. As yet there are no samples confirming these reservoirs nor evidence that these thermogenic gases reach near-seafloor sediments. The only gas hydrate sample recovered from beyond the shelf break on this margin was retrieved not on the upper slope but at ~2500 m water depth above the Canning Seafloor Mound diapiric structure [*Hart et al*., 2011]. Postcruise analysis of residual gas in the core liner revealed $>$95% methane and less than 1% of strictly thermogenic higher-order hydrocarbons. These results, coupled with carbon isotopic analyses, led *Hart et al*. [2011] to conclude that the gas was either a mixed thermogenic source with some secondary microbial methane or primary microbial methane that had oxidized in the core liner during storage.

5.2. Erosion/Sedimentation Effects

Recent, rapid sedimentation can lead to BSRs that are located at greater depths than steady state models predict [*Ruppel*, 2003; *Martin et al*., 2004; *Hornbach et al*., 2008]. Such BSRs eventually migrate to shallower depths as the sediments undergo thermal reequilibration at a rate controlled by their thermal diffusivity. Currently, the sedimentation rate on the upper continental slope on the U.S. Beaufort margin is poorly constrained. *Reimnitz et al*. [1977] obtained an average sedimentation rate of 0.06 cm yr^{-1} on the U.S. Beaufort shelf, which is far closer to sediment sources than the upper slope, by dividing the observed average thickness of recent (Holocene) sediments (3 m) by the 5 kyr period that their study area had been water covered. *Lewis* [1977] and *Macdonald et al*. [1998] obtained higher rates (0.05 to 0.2 cm yr^{-1} and ~0.8 cm yr^{-1}, respectively) for study areas in Canada near the Mackenzie Delta, which is the only major river on the Beaufort margin. All of these estimates are probably too high to be applied to the entire U.S. Beaufort Sea continental slope and rise, which is currently relatively sediment starved. Nonetheless, we calculate that sedimentation rates of 0.06–0.08 cm/yr will yield heat flow reduction of up to ~2% (~1 mW/m^2) over the course of ~10 kyr, consistent with results in other sedimentary environments [e.g., *Hutchison*, 1985; *Manga et al*., 2012]. This heat flow effect is much too small to explain the disparity between the observed and predicted BSRs.

Rapid or even catastrophic (submarine slides) erosion or sedimentation could strand BSRs at shallower or greater depths, respectively, than would be consistent with contemporary equilibrium conditions. Based on the 1977 USGS seismic data, *Kayen and Lee* [1991] described widespread slope failures on the U.S. Beaufort margin, particularly within the CMDM. To explain the difference in observed and model-predicted BSRs, it requires several hundreds of meters of sediment to have been added recently (during the late Holocene) on the upper slope, but submarine slope failures would have removed, not added, sediment along the upper edge of the margin [e.g., *Kayen and Lee*, 1991]. Thus, slide deposits are an improbable explanation for the anomalously deep BGHS along the upper slope. Additionally, glacial scouring, which affects part of the upper slope in this area [e.g., *Engels et al*., 2008], removes material overlying the BSR. This should lead to anomalously shallow BSRs (not BSRs that are too deep) as the BSRs begin to reequilibrate after the removal of near-seafloor sediments.

5.3. Uplift

Certain patterns of uplift could produce an observed BGHS that is out of equilibrium with present-day ocean temperature structure. As noted in section 2, the U.S. Beaufort Sea margin did not experience continental glaciation during late Pleistocene cold periods [*Dyke et al*., 2002]. Nonetheless, the U.S. Beaufort margin has likely been affected by isostatic rebound in response to the removal of the Laurentide ice sheet (located southeast of the study area) between 10,000 and 14,000 years ago [*Dyke and Prest*, 1987]. Offshore the

Mackenzie River, the uplift associated with rebound reached tens of meters during the late Pleistocene. An additional, although slower, component of uplift to the west within the CMDM is related to the continued northern movement of the Brooks Range [*Mazzotti et al*., 2008; *Houseknecht and Bird*, 2011]. Notably, Lines 718 and 730 through the CMDM display the greatest discrepancy between predicted and observed BSR.

Uplift processes that affect the upper continental slope could change the GHSZ if they resulted in (a) reduced water coverage and thus reduced hydrostatic pressure in the sediments and (b) movement of the seafloor to a shallower, warmer part of the ocean thermocline. In either case, a BSR originally at greater depths within the sediments would readjust to shallower depths to be in equilibrium with present-day conditions. In Lines 718 and 730, the BSR is too deep by a maximum of ~100 and ~250 m, respectively. Constraining the details of the equilibration history of the gas hydrate stability zone following uplift requires better constraints not only on the timing and amount of uplift but also on gas hydrate concentrations and distributions at these sites. Because gas hydrate dissociation is an endothermic process, larger amounts of gas hydrate lead to greater retardation of the dissociation process.

5.4. Offshore Groundwater Discharge

Offshore groundwater discharge from the North Slope of Alaska could potentially enhance hydrate formation on the upper continental slope and potentially explain the observed discrepancy between observed and predicted BSRs. Our model already takes into account the formation of gas hydrate in the presence of fresh pore water as one end-member, and fresh pore water cannot explain the anomalous observed BSRs. In theory, if submarine groundwater discharge from permafrost is cold enough and moves fast enough to transfer fluids from the shelf to the upper slope, this discharge could cool the sediments of the upper slope and deepen the location of the GHSZ. *Deming et al*. [1992] suggested a flow on the order of 0.1 m/yr from the North Slope toward the shelf and slope. We developed a 2-D advection-diffusion model for groundwater discharge perpendicular to the coast (supporting information). Our results show that a flow of ~0.2 m/yr from the shelf to the upper slope could in theory explain the anomalously deep BGHS we observe on the upper slope; however, this explanation requires a physically unreasonable 1600 m thick cold water (~0°C) plume to migrate laterally toward the upper slope (Figure S1 in the supporting information). Such a plume would substantially reduce observed terrestrial heat flow values [e.g., *Deming et al*., 1992]. Alternatively, we can model a thinner groundwater plume that explains anomalously deep BSRs along the U.S. Beaufort Sea upper slope, but doing so requires flow rates a factor of 5 or more larger than previous models suggest [*Deming et al*., 1992].

5.5. Intermediate Ocean Temperature Changes

A plausible explanation for the discrepancy between observed and predicted BSR depths on parts of the Beaufort upper continental slope shallower than 1000 mbsl is that BWT has not been constant [e.g., *Melling*, 1998; *Dmitrenko et al*., 2009]. Our analysis of ocean temperature change results shows evidence for multidecadal ocean warming (up to 39 years) of ~0.5°C in the Beaufort Sea at water depths of 300–550 mbsl (Figure 4). Uncertainties in mean annual ocean temperature and mean annual change in ocean temperature are high in waters shallower than ~300 mbsl, which is updip of the current depth at which methane hydrate could be stable. These uncertainties are attributed to large, high-frequency, intraannual ocean temperature variations that result in large uncertainty in the multidecadal temperature variation analysis [e.g., *Pickart*, 2004]. At depths greater than ~300 mbsl, however, we observe less uncertainty in average intraannual temperatures (Figure 4). Lower uncertainty combined with significant changes in average annual temperature provide statistically significant evidence (greater than 2 sigma) for annual ocean temperature warming at depths between 300 and 550 mbsl in the U.S. Beaufort Sea, directly coincident with anomalous BSR depths on the upper slope (Figures 4 and 6). Additionally, between 300 and 600 mbsl, the Monte Carlo analysis indicates a positive slope of more than 75% of the realizations for both winter-spring and summer-fall data sets (Figure 3), implying clear and statistically significant mean ocean temperature warming at these depths during this time period (Figure 4).

These results are consistent with previous studies indicating intermediate water depth warming in other parts of the Arctic over shorter time scales (300–500 mbsl) [e.g., *Melling*, 1998; *Shimada et al*., 2004; *Dmitrenko et al*., 2009; *McLaughlin et al*., 2009; *Westbrook et al*., 2009]. Such warming has been traced to warming of

Atlantic waters, which travel counterclockwise around the edges of the Arctic Ocean basin before reaching the Beaufort Sea, where there underlie Pacific waters [e.g., *Melling*, 1998; *Pickart*, 2004; *Dmitrenko et al.*, 2009].

We suggest that multidecadal ocean temperature warming of at least 1°C is the primary reason we observe a discrepancy between observed and predicted BSRs in the Beaufort Sea. Anomalously deep BSRs observed on the upper continental slope may still be adjusting to intermediate ocean temperature warming at multidecadal scales. Therefore, the anomalously deep BSRs observed on the upper slope likely represent paleo-BSRs that have yet to equilibrate to the warming BWT. Ocean temperature warming alone is not enough to explain all discrepancies between observed and predicted BSRs. For observed BSRs to be in steady state equilibrium requires BWT as cold as -2.3°C on the upper continental slope (300 to 550 mbsl), a temperature that is lower than the freezing point of seawater (-2°C) and colder than the lowest inferred benthic temperatures for the late Quaternary based on the analyses of benthic foraminifera [e.g., *Waelbroeck et al.*, 2002]. Therefore, although multidecadal ocean temperature warming plays an important role in ongoing destabilization of methane hydrate on the upper slope on the U.S. Beaufort Sea margin, other factors (e.g., groundwater discharge and/or uplift) could contribute to gas hydrate dynamics across this region.

5.6. Implications

Regardless of the exact cause of the disparity between the predicted and observed BSR depths on the Beaufort slope, the necessary reequilibration of the BGHS with time due to multidecadal, intermediate ocean temperature warming requires ongoing and future hydrate dissociation along a potentially significant portion of the continental margin. Based on our preliminary analysis of the location of anomalous BSRs, we suggest that the zone of hydrate instability is 10 to 15 km wide in the along-slope direction on the upper continental slope along much of the U.S. Beaufort margin. Using these bounds, we estimate that ~5–7.5 × 10^3 km^2 could contain gas hydrates that are currently subject to dissociation on the upper slope. Over a 10 km wide swath of the upper slope, the seafloor deepens from 325 m to more than 575 m, while the theoretical GHSZ thickens from ~0 m to more than 200 m. If the thickness of sediments containing gas hydrate on the upper slope is taken as an average of 100 m, then the total sediment volume hosting potentially dissociating gas hydrates is in the range of ~5 to 7.5 × 10^{11} m^3. Assuming an average porosity of 30–50% and hydrate filling 2.5–5% of the available pore space (similar to Blake Ridge [*Holbrook et al.*, 1996]), and methane accounting for 12.9% by weight in Structure I gas hydrate, we estimate that ~0.44 to 2.2 Gt of methane, containing 0.33 to 1.65 Gt carbon, is currently destabilizing on the U.S. Beaufort Sea upper slope. The estimate scales linearly with changes in porosity, gas hydrate saturation in pore space, and the thickness of the hydrate-bearing zone. For example, for 50% porosity and 5% hydrate saturation in pore space and with an average stability zone thickness of 150 m over a 15 km wide swath of the upper slope, the upper bound estimate would increase by 1.5 times to ~2.48 Gt C in currently dissociating deposits. Further analysis and particularly in situ sampling (e.g., ocean drilling) are necessary to validate these estimates and the field parameters that are involved in the calculations.

The rate of dissociation of upper slope gas hydrates is unknown but has implications for the time scale at which these susceptible deposits respond to climate warming. On the U.S. Atlantic margin, an analysis of bubble sizes and emission rates observed at a handful of seeps was scaled up to yield an estimate of 15–90 Mg yr^{-1} CH_4 released at the seafloor [*Skarke et al.*, 2014]. Applying the upper bound emission rate to the U.S. Beaufort margin and assuming that the seafloor emission represents 10% of the gas released from dissociating methane hydrates (i.e., 80% consumed by oxidation in the sediments and another 10% retained in pore space), nearly 10^6 year would be required for complete breakdown of the lower bound estimate for upper slope gas hydrate on the U.S. Beaufort margin. This is unreasonably long given the dramatic climate change events that occur over time scales as short as 2 × 10^4 years. Another way to assess dissociation rates is to determine how much methane would be released at the seafloor if all of the upper slope gas hydrates in a 10 km swath on the U.S. Beaufort Sea margin were to dissociate over 100 or 500 year. Again assuming that only 10% of the released methane reaches the seafloor, the emission rates would be ~440 Gg yr^{-1} and 88 Gg yr^{-1} for 100 and 500 year dissociation episodes, respectively, for the case of 30% formation porosity and 2.5% hydrate saturation in pore space. These values are orders of magnitude higher than the emission rates estimated based on northern U.S. Atlantic margin seepage studies [*Skarke et al.*, 2014]. Future studies should focus on gathering direct evidence for upper slope gas hydrate dissociation and seepage to provide constraints on the location and rates of these processes.

The sediment thickness above the BSRs along the upper slope on the U.S. Beaufort margin is generally less than 250 m at most locations. The corresponding height of the gas column necessary to trigger fault reactivation, gas migration, and possible slope failure [*Kayen and Lee*, 1991; *Hornbach et al*., 2004] is therefore only a few tens of meters, assuming that the gas in the pores is interconnected. Our analysis therefore suggests an increased likelihood of slope failure along the upper slope in the coming century as gas hydrates continue to warm and dissociate across this region due to ocean temperature warming.

6. Conclusions

BSRs located beneath the U.S. Beaufort Sea continental slope appear too deep to coincide with a BGHS in steady state equilibrium. The cause of anomalously deep BSRs on the upper slope of the U.S. Beaufort Sea margin is uncertain and could reflect a combination of processes. Nonetheless, the observation of multidecadal ocean temperature warming at intermediate water depths provides at least a partial explanation for anomalously deep BSRs on the upper slope in this area. Our analysis of multidecadal variations in ocean temperatures reveals clear warming at intermediate depths (~300–550 mbsl). This warming requires some methane hydrates on the U.S. Beaufort Sea upper slope to destabilize and the BGHS to migrate to shallower depths to reach equilibrium in the future. The zone in which the BGHS is actively reequilibrating may cover an area of at least 5000 km^2. Even in the absence of continued future ocean warming, we conservatively estimate that ~0.44 to 2.2 Gt CH_4 will be released from gas hydrate into the sediments in the coming decades to centuries due to intermediate ocean temperature warming that has already occurred over the last ~39 years. This dissociation could promote slope failure by reducing sediment strength. If the gas were eventually released from the sediments at the seafloor above the dissociating gas hydrates, it would not be expected to reach the sea surface, instead dissolving in ocean waters [*McGinnis et al*., 2006] and oxidizing to CO_2 [*Mau et al*., 2007]. If some of the gas migrates updip and is emitted at the shelf break (~100 m), a fraction could reach the atmosphere directly [*McGinnis et al*., 2006].

The approach outlined here has applicability beyond the U.S. Beaufort Sea margin. Globally, the most climate-sensitive part of the deepwater gas hydrate system lies within the sediments of the upper continental slopes [*Kvenvolden*, 1993; *Ruppel*, 2011], where the GHSZ thins to nearly zero thickness and where intermediate ocean waters impinge. Other studies indicate that upper continental slope gas hydrate degradation may be relatively widespread on passive margins (e.g., Svalbard margin [*Westbrook et al*., 2009] and the U.S. Atlantic margin [*Phrampus and Hornbach*, 2012; *Brothers et al*., 2014; *Skarke et al*., 2014]). The application of the steady state 3-D thermal model in both high and middle-to-low-latitude areas will contribute to an understanding of the global distribution of gas hydrates that are out of equilibrium with present-day ocean temperature conditions.

Acknowledgments
This work was supported by the U.S. Department of Energy (DOE), grant DE-FE0010180 to SMU and a USGS-DOE interagency agreement DE-FE0005806. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. All data used in this analysis are publically available. The 1977 MCS data were obtained from the USGS, heat flow data from previously published works, and CTD data from the World Ocean Database.

References

Allen, D. M., F. A. Michel, and A. S. Judge (1988), The permafrost regime in the Mackenzie Delta, Beaufort Sea region, N.W.T. and its significance to the reconstruction of the palaeoclimatic history, *J. Quat. Sci.*, *3*(1), 3–13.

Andreassen, K., P. E. Hart, and A. Grantz (1995), Seismic studies of a bottom simulating reflection related to gas hydrate beneath the continental margin of the Beaufort Sea, *J. Geophys. Res.*, *100*(B7), 12,659–12,673, doi:10.1029/95JB00961.

Andreassen, K., P. E. Hart, and M. MacKay (1997), Amplitude versus offset modeling of the bottom simulating reflection associated with submarine gas hydrates, *Mar. Geol.*, *137*, 25–40.

Archer, D. (2007), Methane hydrate stability and anthropogenic climate change, *Biogeosci. Discuss.*, *4*(2), 993–1057.

Barnes, P. W., E. Reimnitz, and D. Fox (1982), Ice rafting of fine-grained sediment, a sorting and transport mechanism, Beaufort Sea, Alaska, *J. Sediment. Res.*, *52*(2), 493–502.

Biastoch, A., et al. (2011), Rising Arctic Ocean temperatures cause gas hydrate destabilization and ocean acidification, *Geophys. Res. Lett.*, *38*, L08602, doi:10.1029/2011GL047222.

Blasco, S., et al. (2011), 2010 State of Knowledge: Beaufort sea seabed geohazards associated with offshore hydrocarbon development, *Geol. Surv. of Can. Open File 6989*, 335, doi:10.4095/292616.

Brigham, J. K., and G. H. Miller (1983), Paleotemperature estimates of the Alaskan Arctic Coastal Plain during the last 125,000 years, in *Proceedings of the 4th International Conference on Permafrost*, pp. 80–85, Natl. Acad. Press, Washington, D. C.

Brothers, D., C. Ruppel, J. Kluesner, U. Brink, J. Chaytor, J. Hill, B. Andrews, and C. Flores (2014), Seabed fluid expulsion along the upper slope and outer shelf of the US Atlantic continental margin, *Geophys. Res. Lett.*, *41*, 96–101, doi:10.1002/2013GL058048.

Brothers, L. L., P. E. Hart, and C. D. Ruppel (2012), Minimum distribution of subsea ice-bearing permafrost on the US Beaufort Sea continental shelf, *Geophys. Res. Lett.*, *39*, L15501, doi:10.1029/2012GL052222.

Camilli, R., C. M. Reddy, D. R. Yoerger, B. A. Van Mooy, M. V. Jakuba, J. C. Kinsey, C. P. McIntyre, S. P. Sylva, and J. V. Maloney (2010), Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon, *Science*, *330*(6001), 201–204.

Carmack, E., R. Macdonald, and J. Papadakis (1989), Water mass structure and boundaries in the Mackenzie shelf estuary, *J. Geophys. Res.*, *94*(C12), 18,043–18,055, doi:10.1029/JC094iC12p18043.

Collett, T., Geological Survey (U.S.), Morgantown Energy Research Center, and United States Department of Energy (1988), Geologic interrelations relative to gas hydrates within the North Slope of Alaska, U.S. Department of the Interior, Geological Survey.

Deming, D., J. H. Sass, A. H. Lachenbruch, and R. F. De Rito (1992), Heat flow and subsurface temperature as evidence for basin-scale groundwater flow, North Slope of Alaska, *Geol. Soc. Am. Bull.*, *104*, 528–542.

Dickens, G. R., J. R. O'Neil, D. K. Rea, and R. M. Owen (1995), Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene, *Paleooceanography*, *10*(6), 965–971.

Dix, C. H. (1955), Seismic velocities from surface measurements, *Geophysics*, *20*(1), 68–86.

Dmitrenko, I. A., et al. (2009), Seasonal modification of the Arctic Ocean intermediate water layer off the eastern Laptev Sea continental shelf break, *J. Geophys. Res.*, *114*, C06010, doi:10.1029/2008JC005229.

Dugan, B., and P. B. Flemings (2000), Overpressure and fluid flow in the New Jersey continental slope: Implications for slope failure and cold seeps, *Science*, *289*(5477), 288–291.

Dyke, A. S., and V. K. Prest (1987), Late Wisconsinan and Holocene history of the Laurentide ice sheet, *Géogr. Phys. et Quat.*, *41*(2), 237–263.

Dyke, A. S., J. T. Andrews, P. U. Clark, J. H. England, G. H. Miller, J. Shaw, and J. J. Veillette (2002), The Laurentide and Innuitian ice sheets during the last glacial maximum, *Quat. Sci. Rev.*, *21*(1), 9–31.

Engels, J. L., M. H. Edwards, L. Polyak, and P. D. Johnson (2008), Seafloor evidence for ice shelf flow across the Alaska–Beaufort margin of the Arctic Ocean, *Earth Surf. Processes Landforms*, *33*(7), 1047–1063.

Flemings, P. B., X. Liu, and W. J. Winters (2003), Critical pressure and multiphase flow in Blake Ridge gas hydrates, *Geology*, *31*, 1057–1060.

Grantz, A., G. Boucher, and O. T. Whitney (1976), Possible solid gas hydrate and natural gas deposits beneath the continental slope of the Beaufort Sea, *U.S. Geol. Surv. Circular, 733*, 17.

Grantz, A., D. M. Mann, and S. D. May (1982), Tracklines of multichannel seismic-reflection data collected by the US Geological Survey in the Beaufort and Chukchi Seas in 1977 for which profiles and stack tapes are available, *U.S. Geol. Surv. Open File Rep.*, 82–0735.

Grantz, A., S. May, and P. Hart (1990), Geology of the Arctic continental margin of Alaska, *Geol. North Am.*, *50*, 257–288.

Hamilton, E. L. (1976), Variations of density and porosity with depth in deep-sea sediments, *J. Sediment. Res.*, *46*(2), 280–300.

Hart, P. E., J. W. Pohlman, T. D. Lorenson, and B. D. Edwards (2011), Beaufort Sea Deep-water gas hydrate recovery from a seafloor mound in a region of widespread BSR occurence, in *Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011)*, Edinburgh, Scotland.

Haxby, W., A. Melkonian, J. Coplan, S. Chan, and W. Ryan (2010), GeoMapApp freeware software, v. 2.3, Lamont-Doherty Earth Observatory, Palisades. [Available at http://jgs.geoscienceworld.org/cgi/content/full/168/2/333].

Holbrook, W. S., H. Hoskins, W. T. Wood, R. A. Stephen, and D. Lizarralde (1996), Methane hydrate and free gas on the blake ridge from vertical seismic profiling, *Science*, *273*(5283), 1840–1843.

Hornbach, M. J., D. M. Saffer, and W. S. Holbrook (2004), Critically pressured free-gas reservoirs below gas-hydrate provinces, *Nature*, *427*, 142–144.

Hornbach, M. J., D. M. Saffer, W. S. Holbrook, H. J. Van Avendonk, and A. R. Gorman (2008), Three-dimensional seismic imaging of the Blake Ridge methane hydrate province: Evidence for large, concentrated zones of gas hydrate and morphologically driven advection, *J. Geophys. Res.*, *113*, B07101, doi:10.1029/2007JB005392.

Hornbach, M. J., N. L. Bangs, and C. Berndt (2012), Detecting hydrate and fluid flow from bottom simulating reflector depth anomalies, *Geology*, *40*(3), 227–230.

Houseknecht, D. W., and K. J. Bird (2006), Oil and gas resources of the Arctic Alaska petroleum province, *U.S. Geol. Surv. Prof. Pap.*, 1732–A.

Houseknecht, D. W., and K. J. Bird (2011), Geology and petroleum potential of the rifted margins of the Canada Basin, *Geol. Soc. London Mem.*, *35*(1), 509–526.

Houseknecht, D., W. Burns, and K. Bird (2012), Thermal maturation history of Arctic Alaska and the southern Canada basin, Analyzing the Thermal History of Sedimentary Basins.

Hutchison, I. (1985), The effects of sedimentation and compaction on oceanic heat flow, *Geophys. J. R. Astron. Soc.*, *82*, 439–459.

Johannessen, O. M., et al. (2004), Arctic climate change: Observed and modelled temperature and sea-ice variability, *Tellus*, *56A*, 328–341.

Kayen, R. E., and H. J. Lee (1991), Pleistocene slope instability of gas hydrate laden sediment on the Beaufort sea margin, *Mar. Geotechnol.*, *10*(1–2), 125–141.

Kvenvolden, K. A. (1988), Methane hydrate-a major reservoir of carbon in the shallow geosphere?, *Chem. Geol.*, *71*(1), 41–51.

Kvenvolden, K. A. (1993), Gas hydrates—geological perspective and global change, *Rev. Geophys.*, *31*(2), 173–187, doi:10.1029/93RG00268.

Kvenvolden, K. A. (1998), A primer on the geological occurrence of gas hydrate, *Geol. Soc. London Spec. Publ.*, *137*(1), 9–30.

Kvenvolden, K. A., and A. Grantz (1990), Gas hydrates of the Arctic Ocean region, in *The Arctic Ocean Region, Geology of North America*, pp. 539–549, Geol. Soc. Am., Boulder, Colo.

Lachenbruch, A., and B. V. Marshall (1966), Heat flow through the Arctic Ocean floor: The Canada Basin-Alpha Rise Boundary, *J. Geophys. Res.*, *71*(4), 1223–1248, doi:10.1029/JZ071i004p01223.

Lachenbruch, A., and B. V. Marshall (1969), Heat flow in the Arctic, *Arctic*, *22*(3), 300–311.

Lachenbruch, A., J. H. Sass, B. V. Marshall, and T. H. Moses Jr. (1982), Permafrost, heat flow, and the Geothermal Regime at Prudhoe Bay, Alaska, *J. Geophys. Res.*, *87*(B11), 9301–9316, doi:10.1029/JB087iB11p09301.

Levitus, S., T. P. Boyer, M. E. Conkright, T. O'Brien, J. Antonov, C. Stephens, L. Stathoplos, D. Johnson, and R. Gelfeld (1998), NOAA Atlas NESDIS 18, World Ocean Database 1998: vol. 1: Introduction, 346 pp., Natl. Oceanic and Atmos. Admin., Silver Spring, Md.

Lewis, C. F. M. (1977), Bottom scour by sea ice in the southern Beaufort Sea. Dept. of Fisheries and the Environment, Beaufort Sea Tech. Rep. 23 (draft), Beaufort Sea Project, Victoria, British Columbia, 88.

Macdonald, R., S. Solomon, R. Cranston, H. Welch, M. Yunker, and C. Gobeil (1998), A sediment and organic carbon budget for the Canadian Beaufort Shelf, *Mar. Geol.*, *144*(4), 255–273.

Manga, M., et al. (2012), Heat flow in the Lesser Antilles island arc and adjacent back arc Grenada basin, *Geochem., Geophys., Geosyst.*, *13*, Q08007, doi:10.1029/2012GC004260.

Marín-Moreno, H., T. A. Minshull, G. K. Westbrook, B. Sinha, and S. Sarkar (2013), The response of methane hydrate beneath the seabed offshore Svalbard to ocean warming during the next three centuries, *Geophys. Res. Lett.*, *40*, 5159–5163, doi:10.1002/grl.50985.

Martin, V., P. Henry, H. Nouze, M. Noble, J. Ashi, and G. Pascal (2004), Erosion and sedimentation as processes controlling the BSR-derived heat flow on the Eastern Nankai margin, *Earth Planet. Sci. Lett.*, *222*(1), 131–144.

Mau, S., D. L. Valentine, J. F. Clark, J. Reed, R. Camilli, and L. Washburn (2007), Dissolved methane distributions and air-sea flux in the plume of a massive seep field, Coal Oil Point, California, *Geophys. Res. Lett.*, *34*, L22603, doi:10.1029/2007GL031344.

Mazzotti, S., L. J. Leonard, R. D. Hyndman, and J. F. Cassidy (2008), Tectonics, dynamics, and seismic hazard in the Canada-Alaska Cordillera, in *Active Tectonics and Seismic Potential of Alaska*, pp. 297–319, AGU, Washington, D. C.

McGinnis, D., J. Greinert, Y. Artemov, S. Beaubien, and A. Wüest (2006), Fate of rising methane bubbles in stratified waters: How much methane reaches the atmosphere?, *J. Geophys. Res.*, *111*, C09007, doi:10.1029/2005JC003183.

McLaughlin, F., E. C. Carmack, W. J. Williams, S. Zimmermann, K. Shimada, and M. Itoh (2009), Joint effects of boundary currents and thermohaline intrusions on the warming of Atlantic water in the Canada Basin, 1993–2007, *J. Geophys. Res.*, *114*, C00A12, doi:10.1029/2008JC005001.

Melling, H. (1998), Hydrographic changes in the Canada Basin of the Arctic Ocean, 1979–1996, *J. Geophys. Res.*, *103*(C4), 7637–7645, doi:10.1029/97JC03723.

Osterkamp, T., and M. Payne (1981), Estimates of permafrost thickness from well logs in northern Alaska, *Cold Reg. Sci. Technol.*, *5*(1), 13–27.

Osterkamp, T., J. Petersen, and T. Collet (1985), Permafrost thicknesses in the Oliktok point, Prudhoe Bay and Mikkelsen Bay areas of Alaska, *Cold Reg. Sci. Technol.*, *11*(2), 99–105.

Paul, L. E. (1994), Geological, Geochemical, and Operational Summary, Aurora Well, OCS Y-0943-1, Beaufort Sea, Alaska, US Department of the Interior, Minerals Management Service, Alaska OCS Region.

Paull, C. K., W. Ussler III, S. R. Dallimore, S. M. Blasco, T. D. Lorenson, H. Melling, B. E. Medioli, F. M. Nixon, and F. A. McLaughlin (2007), Origin of pingo-like features on the Beaufort Sea shelf and their possible relationship to decomposing methane gas hydrates, *Geophys. Res. Lett.*, *34*, L01603, doi:10.1029/2006GL027977.

Phrampus, B. J., and M. J. Hornbach (2012), Recent changes to the Gulf Stream causing widespread gas hydrate destabilization, *Nature*, *490*, 527–530, doi:10.1038/nature11528.

Pickart, R. S. (2004), Shelfbreak circulation in the Alaskan Beaufort Sea: Mean structure and variability, *J. Geophys. Res.*, *109*, C04024, doi:10.1029/2003JC001912.

Pohlman, J., T. Lorenson, P. Hart, C. Ruppel, C. Joseph, M. Torres, and B. Edwards (2011), Evidence for freshwater discharge at a gas hydrate-bearing seafloor mound on the beaufort sea continental slope, paper presented at AGU Fall Meeting, San Francisco, Calif., 5–9 Dec.

Ratcliffe, E. (1960), The thermal conductivities of ocean sediments, *J. Geophys. Res.*, *65*(5), 1535–1541, doi:10.1029/JZ065i005p01535.

Reagan, M. T., G. J. Moridis, S. M. Elliott, and M. Maltrud (2011), Contribution of oceanic gas hydrate dissociation to the formation of Arctic Ocean methane plumes, *J. Geophys. Res.*, *116*, C09014, doi:10.1029/2011JC007189.

Reeburgh, W. S. (2007), Oceanic methane biogeochemistry, *Chem. Rev.*, *107*(2), 486–513.

Reimnitz, E., P. Barnes, L. Toimil, and J. Melchior (1977), Ice gouge recurrence and rates of sediment reworking, Beaufort Sea, Alaska, *Geology*, *5*(7), 405–408.

Reimnitz, E., E. Kempema, R. Ross, and P. Minkler (1980), Overconsolidated surficial deposits on the Beaufort Sea shelf, U.S. Geol. Surv.

Reimnitz, E., S. M. Graves, and P. W. Barnes (1988), Beaufort Sea coastal erosion, sediment flux, shoreline evolution, and the erosional shelf profile, U.S. Geol. Surv.

Ruppel, C. (1997), Anomalously cold temperatures observed at the base of the gas hydrate stability zone on the U.S. Atlantic passive margin, *Geology*, *25*(8), 699–702.

Ruppel, C. (2003), Thermal state of the gas hydrate reservoir, in *Natural Gas Hydrate in Oceanic and Permafrost Environments*, edited by M. D. Max, pp. 29–42, Springer, Dordrecht, Netherlands.

Ruppel, C. (2011), Methane hydrates and contemporary climate change, *Nat. Educ. Knowl.*, *3*(10), 29.

Ruppel, C., and M. Kinoshita (2000), Fluid, methane, and energy flux in an active margin gas hydrate province, offshore Costa Rica, *Earth Planet. Sci. Lett.*, *179*(1), 153–165.

Ruppel, C., R. P. Von Herzen, and A. Bonneville (1995), Heat flux through an old (−175 Ma) passive margin: Offshore southeastern United States, *J. Geophys. Res.*, *100*(B10), 20,037–20,057, doi:10.1029/95JB01860.

Ryan, W. B., S. M. Carbotte, J. O. Coplan, S. O'Hara, A. Melkonian, R. Arko, R. A. Weissel, V. Ferrini, A. Goodwillie, and F. Nitsche (2009), Global Multi-Resolution Topography synthesis, *Geochem. Geophys. Geosyst.*, *10*, Q03014, doi:10.1029/2008GC002332.

Shakhova, N., I. Semiletov, A. Salyuk, V. Yusupov, D. Kosmach, and Ö. Gustafsson (2010), Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf, *Science*, *327*(5970), 1246–1250.

Shimada, K., F. McLaughlin, E. Carmack, A. Proshutinsky, S. Nishino, and M. Itoh (2004), Penetration of the 1990s warm temperature anomaly of Atlantic Water in the Canada Basin, *Geophys. Res. Lett.*, *31*, L20301, doi:10.1029/2004GL020860.

Shipley, T. H., M. H. Houston, R. T. Buffler, F. J. Shaub, K. J. McMillen, J. W. Ladd, and J. L. Worzel (1979), Seismic evidence for widespread possible gas hydrate horizons on continental slopes and rises, *AAPG Bull.*, *63*(12), 2204–2213.

Skarke, A., C. Ruppel, M. Kodis, D. Brothers, and E. Lobecker (2014), Widespread methane leakage from the sea floor on the northern US Atlantic margin, *Nat. Geosci.*, *7*, 657–661.

Sloan, E. D., and C. A. Koh (2008), *Clathrate Hydrates of Natural Gases*, 3rd ed., CRC Press, Boca Raton, Fla.

Waelbroeck, C., L. Labeyrie, E. Michel, J. C. Duplessy, J. McManus, K. Lambeck, E. Balbon, and M. Labracherie (2002), Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records, *Quat. Sci. Rev.*, *21*(1), 295–305.

Westbrook, G. K., K. E. Thatcher, E. J. Rohling, A. M. Piotrowski, H. Pälike, A. H. Osborne, E. G. Nisbet, T. A. Minshull, M. Lanoisellé, and R. H. James (2009), Escape of methane gas from the seabed along the West Spitsbergen continental margin, *Geophys. Res. Lett.*, *36*, L15608, doi:10.1029/2009GL039191.

Yamano, M., S. Uyeda, Y. Aoki, and T. H. Shipley (1982), Estimates of heat flow derived from gas hydrates, *Geology*, *10*(7), 339–343.

JOHN WILEY AND SONS LICENSE
TERMS AND CONDITIONS

Jul 06, 2017

This Agreement between Southern Methodist University -- Matthew Hornbach ("You") and John Wiley and Sons ("John Wiley and Sons") consists of your license details and the terms and conditions provided by John Wiley and Sons and Copyright Clearance Center.

License Number	4143190436222
License date	Jul 06, 2017
Licensed Content Publisher	John Wiley and Sons
Licensed Content Publication	Journal of Geophysical Research: Solid Earth
Licensed Content Title	Widespread gas hydrate instability on the upper U.S. Beaufort margin
Licensed Content Author	Benjamin J. Phrampus,Matthew J. Hornbach,Carolyn D. Ruppel,Patrick E. Hart
Licensed Content Date	Dec 9, 2014
Licensed Content Pages	16
Type of use	Government Report
Requestor type	Author of this Wiley article
Is the reuse sponsored by or associated with a pharmaceutical or medical products company?	no
Format	Electronic
Portion	Full article
Will you be translating?	No
Circulation	100
Title of the report	Final Scientific/Technical Report of Gas Hydrate Dynamics on the Alaskan Beaufort Continental Slope: Modeling and Field Characterization
Publisher of the report	SMU and/or U.S. Dept of Energy
Expected publication date	Jul 2017
Requestor Location	Southern Methodist University P.O. Box 750395 DALLAS, TX 75225 United States Attn: Matthew Hornbach
Publisher Tax ID	EU826007151
Billing Type	Invoice
Billing Address	Southern Methodist University P.O. Box 750395 DALLAS, TX 75225

United States
Attn: Matthew Hornbach

Total 0.00 USD

Terms and Conditions

TERMS AND CONDITIONS

This copyrighted material is owned by or exclusively licensed to John Wiley & Sons, Inc. or one of its group companies (each a"Wiley Company") or handled on behalf of a society with which a Wiley Company has exclusive publishing rights in relation to a particular work (collectively "WILEY"). By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms and conditions apply to this transaction (along with the billing and payment terms and conditions established by the Copyright Clearance Center Inc., ("CCC's Billing and Payment terms and conditions"), at the time that you opened your RightsLink account (these are available at any time at http://myaccount.copyright.com).

Terms and Conditions

- The materials you have requested permission to reproduce or reuse (the "Wiley Materials") are protected by copyright.

- You are hereby granted a personal, non-exclusive, non-sub licensable (on a stand-alone basis), non-transferable, worldwide, limited license to reproduce the Wiley Materials for the purpose specified in the licensing process. This license, and any CONTENT (PDF or image file) purchased as part of your order, is for a one-time use only and limited to any maximum distribution number specified in the license. The first instance of republication or reuse granted by this license must be completed within two years of the date of the grant of this license (although copies prepared before the end date may be distributed thereafter). The Wiley Materials shall not be used in any other manner or for any other purpose, beyond what is granted in the license. Permission is granted subject to an appropriate acknowledgement given to the author, title of the material/book/journal and the publisher. You shall also duplicate the copyright notice that appears in the Wiley publication in your use of the Wiley Material. Permission is also granted on the understanding that nowhere in the text is a previously published source acknowledged for all or part of this Wiley Material. Any third party content is expressly excluded from this permission.

- With respect to the Wiley Materials, all rights are reserved. Except as expressly granted by the terms of the license, no part of the Wiley Materials may be copied, modified, adapted (except for minor reformatting required by the new Publication), translated, reproduced, transferred or distributed, in any form or by any means, and no derivative works may be made based on the Wiley Materials without the prior permission of the respective copyright owner.For STM Signatory Publishers clearing permission under the terms of the STM Permissions Guidelines only, the terms of the license are extended to include subsequent editions and for editions in other languages, provided such editions are for the work as a whole in situ and does not involve the separate exploitation of the permitted figures or extracts, You may not alter, remove or suppress in any manner any copyright, trademark or other notices displayed by the Wiley Materials. You may not license, rent, sell, loan, lease, pledge, offer as security, transfer or assign the Wiley Materials on a stand-alone basis, or any of the rights granted to you hereunder to any other person.

- The Wiley Materials and all of the intellectual property rights therein shall at all times remain the exclusive property of John Wiley & Sons Inc, the Wiley Companies, or their respective licensors, and your interest therein is only that of having possession of and the right to reproduce the Wiley Materials pursuant to Section 2 herein during the continuance of this Agreement. You agree that you own no right, title or interest in or to the Wiley Materials or any of the intellectual property rights therein. You shall have no rights hereunder other than the license as provided for above in Section 2. No right, license or interest to any trademark, trade name, service mark or other branding ("Marks") of WILEY or its licensors is granted hereunder, and you agree that you shall not assert any such right, license or interest with respect thereto

- NEITHER WILEY NOR ITS LICENSORS MAKES ANY WARRANTY OR REPRESENTATION OF ANY KIND TO YOU OR ANY THIRD PARTY, EXPRESS, IMPLIED OR STATUTORY, WITH RESPECT TO THE MATERIALS OR THE ACCURACY OF ANY INFORMATION CONTAINED IN THE MATERIALS, INCLUDING, WITHOUT LIMITATION, ANY IMPLIED WARRANTY OF MERCHANTABILITY, ACCURACY, SATISFACTORY QUALITY, FITNESS FOR A PARTICULAR PURPOSE, USABILITY, INTEGRATION OR NON-INFRINGEMENT AND ALL SUCH WARRANTIES ARE HEREBY EXCLUDED BY WILEY AND ITS LICENSORS AND WAIVED BY YOU.

- WILEY shall have the right to terminate this Agreement immediately upon breach of this Agreement by you.

- You shall indemnify, defend and hold harmless WILEY, its Licensors and their respective directors, officers, agents and employees, from and against any actual or threatened claims, demands, causes of action or proceedings arising from any breach of this Agreement by you.

- IN NO EVENT SHALL WILEY OR ITS LICENSORS BE LIABLE TO YOU OR ANY OTHER PARTY OR ANY OTHER PERSON OR ENTITY FOR ANY SPECIAL, CONSEQUENTIAL, INCIDENTAL, INDIRECT, EXEMPLARY OR PUNITIVE DAMAGES, HOWEVER CAUSED, ARISING OUT OF OR IN CONNECTION WITH THE DOWNLOADING, PROVISIONING, VIEWING OR USE OF THE MATERIALS REGARDLESS OF THE FORM OF ACTION, WHETHER FOR BREACH OF CONTRACT, BREACH OF WARRANTY, TORT, NEGLIGENCE, INFRINGEMENT OR OTHERWISE (INCLUDING, WITHOUT LIMITATION, DAMAGES BASED ON LOSS OF PROFITS, DATA, FILES, USE, BUSINESS OPPORTUNITY OR CLAIMS OF THIRD PARTIES), AND WHETHER OR NOT THE PARTY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. THIS LIMITATION SHALL APPLY NOTWITHSTANDING ANY FAILURE OF ESSENTIAL PURPOSE OF ANY LIMITED REMEDY PROVIDED HEREIN.

- Should any provision of this Agreement be held by a court of competent jurisdiction to be illegal, invalid, or unenforceable, that provision shall be deemed amended to achieve as nearly as possible the same economic effect as the original provision, and the legality, validity and enforceability of the remaining provisions of this Agreement shall not be affected or impaired thereby.

- The failure of either party to enforce any term or condition of this Agreement shall not constitute a waiver of either party's right to enforce each and every term and condition of this Agreement. No breach under this agreement shall be deemed waived or excused by either party unless such waiver or consent is in writing signed by the party granting such waiver or consent. The waiver by or consent of a party to a breach of any provision of this Agreement shall not operate or be construed as a waiver of or consent to any other or subsequent breach by such other party.

- This Agreement may not be assigned (including by operation of law or otherwise) by you without WILEY's prior written consent.

- Any fee required for this permission shall be non-refundable after thirty (30) days from receipt by the CCC.

- These terms and conditions together with CCC's Billing and Payment terms and conditions (which are incorporated herein) form the entire agreement between you and WILEY concerning this licensing transaction and (in the absence of fraud) supersedes all prior agreements and representations of the parties, oral or written. This Agreement may not be amended except in writing signed by both parties. This Agreement shall be binding upon and inure to the benefit of the parties' successors, legal representatives, and authorized assigns.

- In the event of any conflict between your obligations established by these terms and conditions and those established by CCC's Billing and Payment terms and conditions, these terms and conditions shall prevail.

- WILEY expressly reserves all rights not specifically granted in the combination of (i) the license details provided by you and accepted in the course of this licensing transaction, (ii) these terms and conditions and (iii) CCC's Billing and Payment terms and conditions.

- This Agreement will be void if the Type of Use, Format, Circulation, or Requestor Type was misrepresented during the licensing process.

- This Agreement shall be governed by and construed in accordance with the laws of the State of New York, USA, without regards to such state's conflict of law rules. Any legal action, suit or proceeding arising out of or relating to these Terms and Conditions or the breach thereof shall be instituted in a court of competent jurisdiction in New York County in the State of New York in the United States of America and each party hereby consents and submits to the personal jurisdiction of such court, waives any objection to venue in such court and consents to service of process by registered or certified mail, return receipt requested, at the last known address of such party.

WILEY OPEN ACCESS TERMS AND CONDITIONS

Wiley Publishes Open Access Articles in fully Open Access Journals and in Subscription journals offering Online Open. Although most of the fully Open Access journals publish open access articles under the terms of the Creative Commons Attribution (CC BY) License only, the subscription journals and a few of the Open Access Journals offer a choice of Creative Commons Licenses. The license type is clearly identified on the article.

The Creative Commons Attribution License

The Creative Commons Attribution License (CC-BY) allows users to copy, distribute and transmit an article, adapt the article and make commercial use of the article. The CC-BY license permits commercial and non-

Creative Commons Attribution Non-Commercial License

The Creative Commons Attribution Non-Commercial (CC-BY-NC)License permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.(see below)

Cruise Report:

First Heat Flow Measurements of the U.S. Beaufort Margin with implications for Methane Hydrate Stability in the U.S. Arctic Ocean

All data collected aboard the *M/V Norseman II*
September 11th - September 25th, 2016

All funding for this research provided by The United States Department of Energy, National Energy Technology Laboratory,
DOE Award No.: DE-FE0010180
Gas Hydrate Dynamics on the Alaskan
Beaufort Continental Slope:
Modeling and Field Characterization
Project Period: October 1, 2012 –March 31st, 2017

This cruise report written for and provided to the United States Department of Energy by
Matthew J. Hornbach (Southern Methodist University)
Rob Harris (Oregon State University)
Ben Phrampus (Oregon State University)
Madeline Jones (Southern Methodist University)
Casey Brokaw (Southern Methodist University)

Table of Contents

I. Project Summary

In October 2012, Southern Methodist University in partnership with Oregon State University and The United State Geological Survey at Woods Hole, began investigating methane hydrate stability in deep water (>100 mbsf) environments below Alaskan Beaufort Sea. In late 2014, the project was further expanded to include analysis of methane hydrates and slope stability off the US east coast. This research is part of a now 4.5 year study funded by the Department of Energy's (DOE) National Energy Technology Laboratory (NETL) that analyzes methane hydrate stability on both the Atlantic and Beaufort Margin. Key goals of this study include integrating and processing marine seismic data collected at the USGS as well as other publically available data with dynamic 2D/3D/4D heat flow models developed at SMU to determining the depth, location, and dynamics of methane hydrate stability along the Alaskan Beaufort Margin and similar environments. A major component of this study is to constrain how the methane hydrate stability zone is changing with time. Additional goals of this study include determining areas where concentrated methane hydrate might exist in the subsurface and to understand the role methane hydrate plays in slope stability along continental margins. To accomplish these goals, researchers use geophysical (seismic, heat flow, CTD/XBT) data combined with numerical models to assess methane hydrate stability in space and time. Researchers also integrate regional coring and biological data with methane hydrate stability models to place further constraints on hydrate dynamics. The USGS component of this research focus on addressing methane hydrate stability along the US Atlantic Margin; the SMU component focus on the US Beaufort Sea.

Researchers on this project have already shown (see Phrampus et al., 2014) that methane hydrates is likely unstable below much of the Beaufort Margin as a direct result of recent, significant ocean temperature warming of intermediate bottom water (sourced from the Atlantic). Though ocean temperature warming particularly within the past 40 years is well documented in the Beaufort, ocean temperature alone does not define where the methane hydrate stability zone might exist. Specifically, methane hydrate stability is also dependent on subsurface temperature, and therefore, subsurface heat flow. Currently, however, regional heat flow in the Beaufort Sea is very poorly constrain, with, to date, no known published heat flow measurements for the entire US Beaufort Margin. As a result, researchers have had to rely on more distant measurements of heat flow made on land (along the North slope), as well as those made in the Canadian Beaufort, and measurements extrapolated from deep-water gas hydrate bottom simulating reflectors (BSR) below the deeper part of the Beaufort Margin where bottom water temperature changes have been insignificant, to estimate what the regional heat flow is along the margin. While these approaches provide a rough, first order estimate for heat flow along the US Beaufort margin that provide approximate estimates for heat flow, ultimately, much higher resolution heat flow estimates are necessary to fully constrain how stable (or unstable) methane hydrates may actually be along the margin. In addition, heat flow measurements can provide crucial insight into where high fluid flow, and advective fluid transport (i.e. where fluid migration) is occurring along the sea bottom. Current models suggest methane hydrates should be destabilizing along the upper edge of the continental margin, at depths of 200-300 mbsl. If true, it is reasonable to hypothesize that we should see evidence for advective heat flow potentially more prevalent in this region compared to deeper zones where methane hydrates remain more stable. A key goal of this study is therefore to assess the location of the upper feather edge of the hydrate stability zone in the Beaufort Margin, and, using newly acquired heat flow data combined with ocean temperature measurements, assess the long term stability of methane hydrate below the Beaufort Sea.

II. Primary Cruise Objectives

Heat flow and methane hydrate stability along the U.S. Beaufort Margin are poorly understood. To our knowledge, no systematic, direct, or dedicated heat flow study of the U.S. Beaufort Margin exists. Heat flow estimates can be derived in this region from Bottom Simulating Reflectors (BSRs) (e.g. Phrampus et al., 2014), however, significant uncertainty in regional heat flow estimates using this technique exists. Key objectives for this study are to use new heat flow, ocean temperature, and chirp echosounder data collected in the Beaufort to

(1) Constrain regional subsurface thermal gradients, thermal conductivity, and heat flow of sediments on the US Beaufort Margin.

(2) Determine the style (diffusive versus advective) and location of heat flow variability along the U.S. Beaufort Margin.

(3) Verify and quantify how potential changes in submarine ocean temperatures change in space and time, influence methane hydrate stability along the US Beaufort Margin.

III. Preliminary Results

The ten-day research cruise was a tremendous success. During the cruise, we collected heat flow data at 116 sites, of which 113 (97+%) produced interpretable subbottom temperature data (with no penetration at only three stations). At each of these sites, we obtained 12 temperature measurements (11 of which usually provided subsurface temperatures, the other providing bottom water temperature), resulting in a total of 1344 temperature measurements at the US Beaufort Sea margin. These data were acquired along four transects running from the upper edge of the margin in water depths as shallow as ~200 mbsl to a maximum depth of ~1700 mbsl. Thermal conductivity was measured by firing a pulse at more than 10 deployments (more than 100 thermistor measurements) all of which revealed a remarkably consistent thermal conductivity, averaging ~1.1W/mK. In addition, we collected approximately ~200 km of 12 kHz chirp echosounder data at each of the heat flow stations, and in transits between heat flow penetration sites. These data demonstrate clear changes in stratigraphy and subsurface deformation, particularly within the hydrate stability zone. We also collected ocean temperature measurements at key depth intervals in the water column by deploying the heat flow probe at key depth intervals within the water column along each of the transects between penetration sites. Finally, we collected sediments directly from the probe, and have used these sediments to further constrain thermal conductivity and sediment character along the margin.

With ocean temperatures, subsurface heat flow, thermal conductivity, and shallow subsurface structure constrained by these data, we have already begun developing a much clearer picture of the location and dynamics of the methane hydrate stability zone along the US Beaufort margin, as well as the remarkably spatial variability in heat flow along the margin. Preliminary results of our heat flow analysis indicate that ocean currents play a significant role in ocean temperature and methane hydrate stability from depths of 200-900 mbsl. Below 900 mbsl, however, temperature gradients in shallow sediments of the Beaufort are consistently linear, indicating virtually no influence of ocean currents. Perhaps most intriguing, heat flow values along the deeper part of the margin (>900 mbsl) indicate surprisingly high heat flow values—much higher than typical continental margins—in the western U.S. Beaufort Sea, with several values exceeding 100 mW/m^2. Based on our analysis of heat flow along these four transects that span more than 500 km of the US Beaufort Margin, heat flow generally increases from east to west, although anomalously high zones are also observed at a few locations along the eastern half of the margin as well. Weak BSRs below high heat flow sites combined with the observation that few passive margins have such high heat flow values without significant advection, support the hypothesis that heat transport along the outer western US Beaufort margin is in some instances advection-dominated. The clear observation of elevated, most-likely advection-driven heat flow along the western US Beaufort (that perhaps extends for more than 100 kilometers east-west along he margin) represents a new and unusual discovery; the cause of this high heat flow anomaly warrants further investigation.

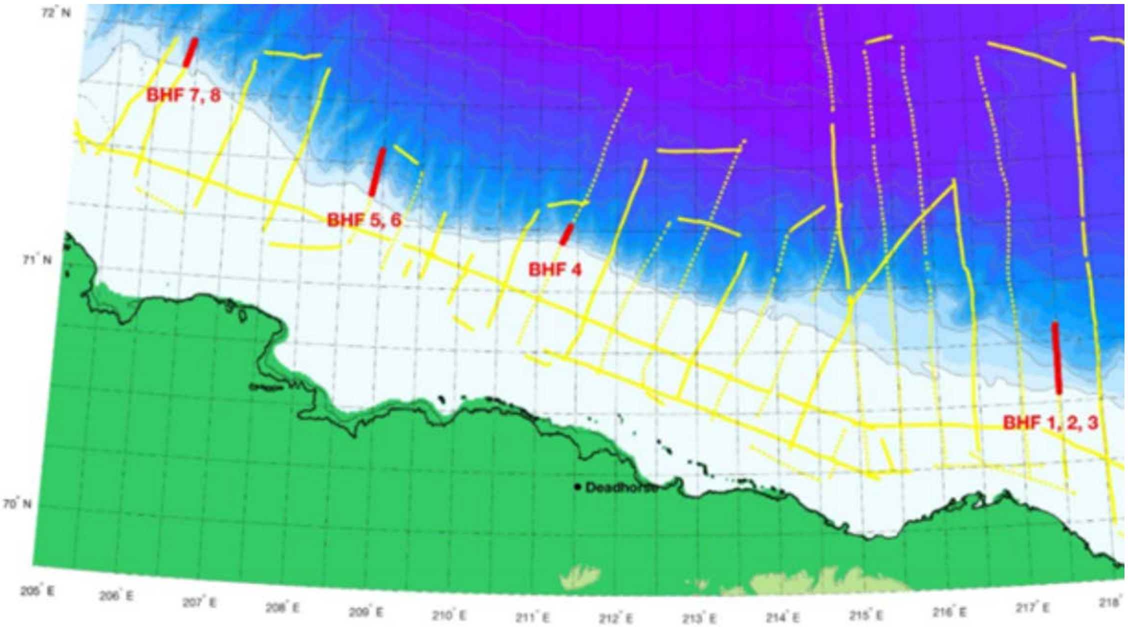
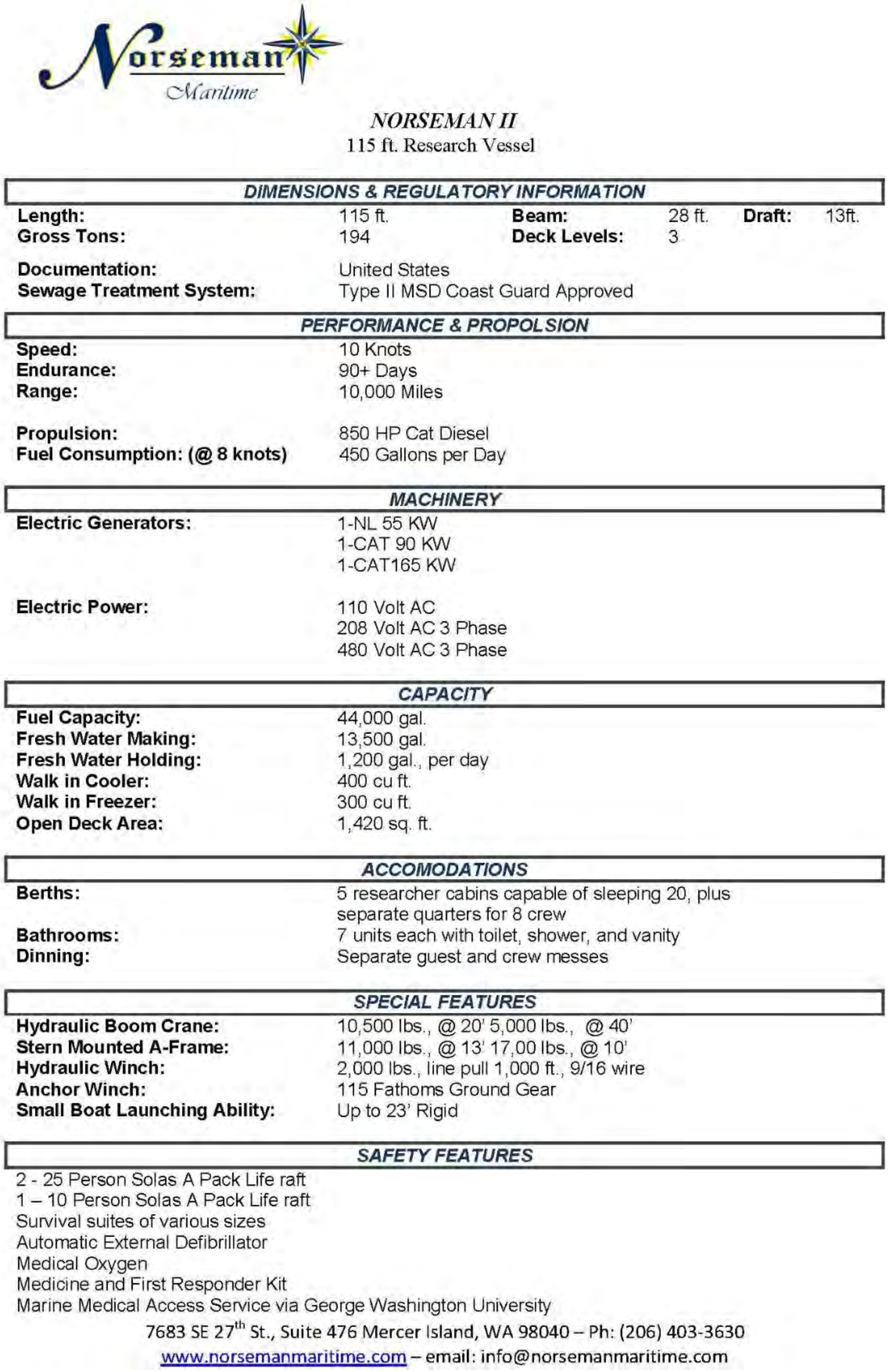


Figure 1. Map showing the location of USGS seismic lines collected in 1977 (yellow), and the location of the four heat flow transects where 116 heat flow probe deployments occurred in September, 2016 on the R/V Norseman II.

IV. Research Vessel: R/V Norseman II

The R/V Norseman II is one of two scientific research vessels owned and operated by Norman Maritime out of Mercer Island, WA. The 116 ft vessel was originally designed and used for fishing in the Bering Sea, and has been retrofitted for scientific use. It houses a crane, a large A-frame, and an ice-hardened hull that enable operation in ice. Although she is not an ice-breaker, the Norseman II is capable of traveling through icy water, and, as demonstrated on this cruise, is capable of maneuvering and encountering significant (car-to-house-sized) multi-year (blue) ice in the Beaufort. The ship was contracted to SMU/OSU by Olgoonik-Fairweather LLC (OF). OF secured the Norseman II for the duration of the 2016 open water Arctic season, which they partitioned into shorter duration contracts to a variety of organizations, spreading the mobilization and demobilization expenses across multiple clients.



Norseman Maritime

NORSEMAN II

115 ft. Research Vessel

DIMENSIONS & REGULATORY INFORMATION

Length:	115 ft.	**Beam:**	28 ft.	**Draft:**	13ft.
Gross Tons:	194	**Deck Levels:**	3		
Documentation:	United States				
Sewage Treatment System:	Type II MSD Coast Guard Approved				

PERFORMANCE & PROPOLSION

Speed:	10 Knots
Endurance:	90+ Days
Range:	10,000 Miles
Propulsion:	850 HP Cat Diesel
Fuel Consumption: (@ 8 knots)	450 Gallons per Day

MACHINERY

Electric Generators:	1-NL 55 KW 1-CAT 90 KW 1-CAT165 KW
Electric Power:	110 Volt AC 208 Volt AC 3 Phase 480 Volt AC 3 Phase

CAPACITY

Fuel Capacity:	44,000 gal.
Fresh Water Making:	13,500 gal.
Fresh Water Holding:	1,200 gal., per day
Walk in Cooler:	400 cu ft.
Walk in Freezer:	300 cu ft.
Open Deck Area:	1,420 sq. ft.

ACCOMODATIONS

Berths:	5 researcher cabins capable of sleeping 20, plus separate quarters for 8 crew
Bathrooms:	7 units each with toilet, shower, and vanity
Dinning:	Separate guest and crew messes

SPECIAL FEATURES

Hydraulic Boom Crane:	10,500 lbs., @ 20' 5,000 lbs., @ 40'
Stern Mounted A-Frame:	11,000 lbs., @ 13' 17,00 lbs., @ 10'
Hydraulic Winch:	2,000 lbs., line pull 1,000 ft., 9/16 wire
Anchor Winch:	115 Fathoms Ground Gear
Small Boat Launching Ability:	Up to 23' Rigid

SAFETY FEATURES

2 - 25 Person Solas A Pack Life raft
1 – 10 Person Solas A Pack Life raft
Survival suites of various sizes
Automatic External Defibrillator
Medical Oxygen
Medicine and First Responder Kit
Marine Medical Access Service via George Washington University

7683 SE 27th St., Suite 476 Mercer Island, WA 98040 – Ph: (206) 403-3630
www.norsemanmaritime.com – email: info@norsemanmaritime.com

ELECTRONICS & COMMUNICATIONS

Wheelhouse:
Simrad AP 50 Auto Pilot, COMNAV Copilot Commander Autopilot, JRC GPS Compass, COMNAV G2 Navigator GPS Compass, 2 - Furuno GP-32 GPS Receivers, Furuno FCV 295 Video Depth Sounder with Airmar 309 Digital Transducer, 4 Deck cameras with Speco Technologies hard drive recorder, 3 Standard Horizon VHF handheld radios, 1 handheld Iridium Phone, Inmarsat Global Xpress Satellite phone and high-speed data system, Inmarsat Fleet Broadband 500 System, Iridium Open Port System, Furuno 1510-D 72NM 10kw X Band Radar, Furuno 2125 96NM 25kw X Band ARPA Radar,
VHFs: 1 Sea 157, 2 Icom ICM 504; Single Sidebands: Sea322, Sea222

Wheelhouse Computers:
Navigation Computer - Acer running TimeZero Trident
Communication and Navigation Backup – Dell Tower
RDI Bridge Watch
Epson 3540 All-in-One Wireless Printer

Science Station Electronics:
Workhorse Mariner 300kz (Acoustic Doppler Current Profiler) ADCP,
Seabird SBE 21 Thermosalinograph, Seabird 38 remote temperature, RD-33 Display, Remote Navigation Display (from the bridge), 1 Sea 157 VAF, Furuno GP – 32 GPS, Epson Wireless Printer

Science Station Data Availability:
Location – via Aft and Forward GPS
Weather
Depth
Heading

SKIFF SPECIFICATIONS

18' Rigid hull with center consul
90 HP Honda Outboard Engine
Standard Horizon VHF with AIS
COMNAV AIS

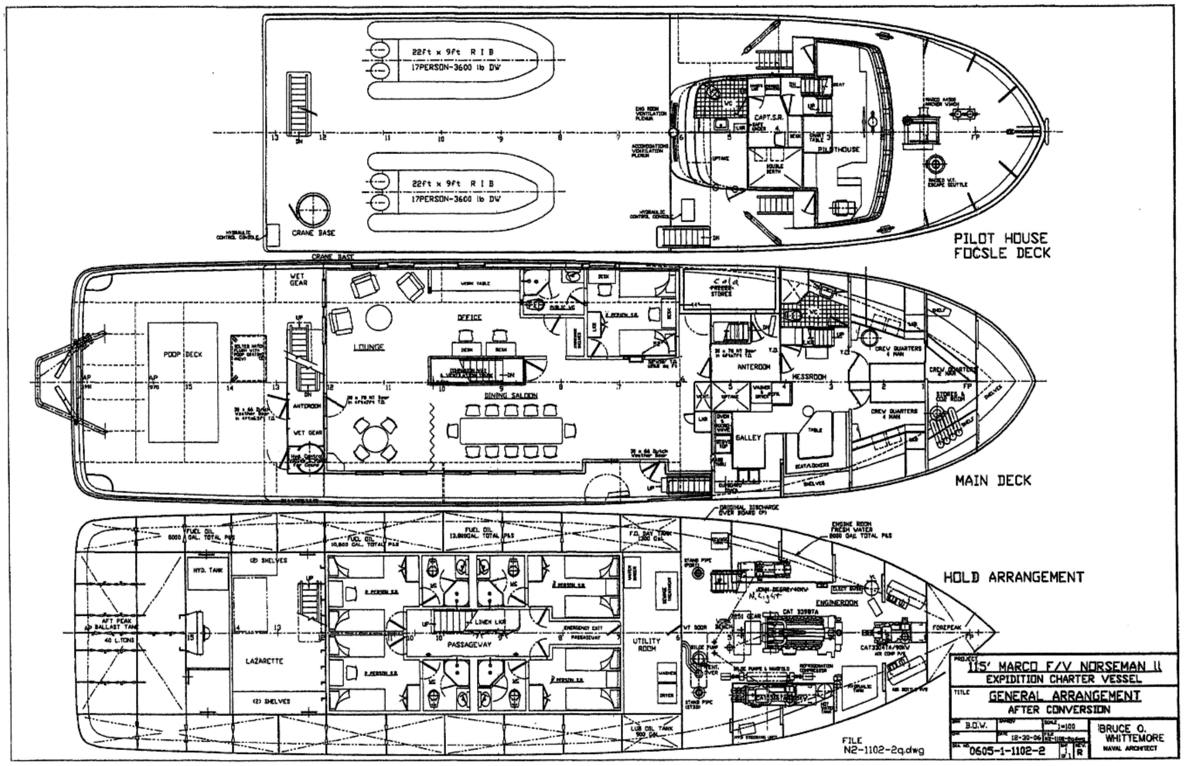


Figure 4: Norseman II Deck Plan

Her enforced hull comes however at a price, as her effective maximum cruising speed is only 8-9 knots, and her round bottom makes for a motion-rich ride. Because of this, it can be difficult and challenging at times to deploy and/or retrieve heavy or awkwardly sized/shaped equipment (such as OSU's heat flow probe) in moderate seas (i.e. Swells greater than 6 feet). Additionally, the scientific facilities onboard the Norseman II are limited, as there is no hull mounted echosounder system, no devoted wireline cable extending beyond 100 m, no winch display nor winch deployment speed control at 60-90 m/min or greater, as is often needed for control sea floor impacts, and the ship has no dynamic positioning or DGPS.

The advantage of the Norseman II however, is that the ship is fully capable of operating in icy conditions, it has a fantail with enough room and A-frame clearance for the 3.5 m HF probe, it has a superbly capable captain and crew who can hold position on site and were able to come up with creative ways to make things work despite no cable or hull-mounted transducers available, and the ship's daily rate is relatively inexpensive compared to standard UNOLS vessels.

V. Shipboard Personnel

The cruise was supported by a 5 person team of shipboard researchers, a 9 man ship crew, and land based logistical support personnel.

i. Science Party

Casey Brokaw (SMU)

2nd year graduate student (Masters), Southern Methodist University, specializing in heat flow modeling and thermal conductivity measurement/analysis for his master's degree.

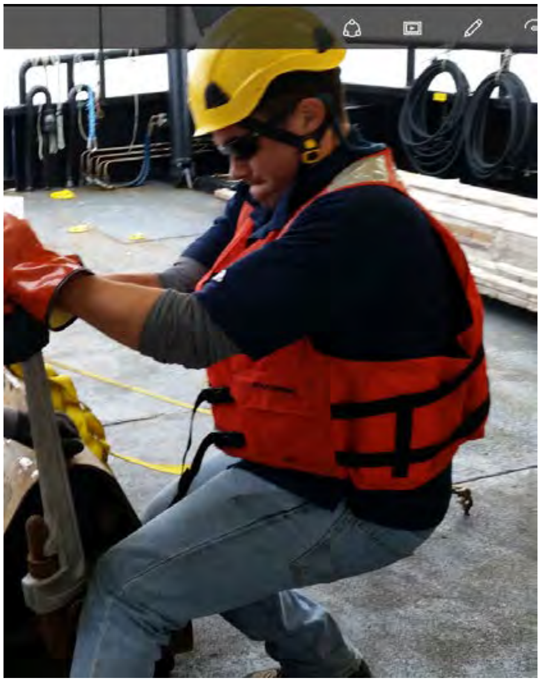


Figure 1: Casey Brokaw (SMU) assisting with preparation of the heat flow probe on deck of the Norseman II.

Robert (Rob) Harris (Oregon State University)

Co-Chief and Professor at Oregon State University specializing in marine heat flow measurement, analysis, and interpretation. Rob manages and runs the OSU heat flow probe—a facility supported in part by NSF—that we used for the cruise.

Figure 2: Rob Harris (OSU) processing incoming data aboard the Norseman II.

Matthew (Matt) Hornbach (SMU)

Co-Chief, Lead PI, and Professor of Geophysics at SMU with a background in seismic imaging, fluid/heat flow, and methane hydrate stability.

Figure 3: Matt Hornbach (SMU) overlooking Cook Inlet near Anchorage, AK.

Madeline (Madie) Jones (SMU)

Second year graduate student, Southern Methodist University, specializing in slope stability analysis, using seismic data and wave modeling methods.

Figure 4: Maddie Jones (SMU) overlooking Cook Inlet near Anchorage, AK.

Benjamin (Ben) Phrampus (formerly SMU, now Oregon State University)

1st year postdoctoral research at Oregon State University, studying methane hydrate stability on continental margins. Ben completed his Ph.D. at SMU and wrote a key paper in JGR in 2014 demonstrating how ocean temperature change in the U.S. Beaufort is likely causing methane hydrate destabilization along the margin.

Figure 5: Ben Phrampus (OSU) in the science lab aboard the Norseman II.

ii. Norseman II Crew

Mike Hastings – Captain. Master, Norseman Maritime

Wayne Peterson – 1st Mate. Chief Officer, Norseman Maritime

Marlin Carey – Cook

Darrin Hallman – Asst. Cook.

Luke Johnston – Tech.

Jorin Watson – AB

Austin Church – AB

Jim Wells – Boson

Kevin Worthington - Engineer

iii. Land-Based Logistics Personnel

Cathy Chickering-Pace
SMU Geothermal Lab Project Specialist

Sheyna Wisdom, primary contract and land-based ship coordinator for Norseman Maritime

Scott Hameister, 1st Mate at Norseman Maritime
Casey Pape, logistics for Norseman Maritime

VI. Data Collection Methods and Tools

The Primary tools used for data collection were (1) Oregon State University's 3.5-m heat flow probe, and (2) SMU's 12 kHz Knudsen Engineering 12 kHz Chirp sub-bottom profiler. Additional data include sea surface temperature and salinity readings provided by the ship's data loggers, ocean temperature measurements provided by placing the OSU heat flow probe at different ocean temperature depths in the water column during transit between sites, and sediment samples obtained when marine muds stuck to the heat flow probe following penetration and recovery. Post-cruise, we later used SMU's needle-probe heat flow tool for additional thermal conductivity measurements made on mud samples collected at sea. Below we describe the tools and deployment methods used for each of the data types collected at sea.

i. Heat flow probe data collection and data reduction

All heat flow measurements were collected using a multipenetration heat flow (MPHF) probe (Figure 9). The MPHF probe consists of a 3.5-m, 11-thermistor, violin-bow heat flow system maintained at Oregon State University. The MPHF probe operations were run from the aft A-frame using spectra line. The probe weighs 0.52 tons in water. The design of the MPHF probe provides both the mechanical robustness to withstand repeated insertions and withdrawals from the sediment, and sensitivity needed to make highly accurate measurements. Repeated insertions of the probe allow multiple heat flow measurements to be made with a single transit through the water column increasing measurement efficiency. Temperature time series used for both the determination of the thermal gradient and thermal conductivity are logged into solid-state memory in a data logger located in the probe weight stand. Other parameters logged by the system include time, pressure (depth), water temperature, tilt, and a stable reference resistance. Acoustic telemetry during surveys relays temperature data and tilt to the surface so that instrument performance can be monitored in real time (For more information, see Oregon State Universities website discussing the heat flow probe). The data logger and tilt meter transmit data to the surface via an acoustic pinger that sends pings to the Knudsen 12 kHz receiver listening in passive mode. Information provided to the ship from the heat flow probe include (1) pinger depth (a constant, longer-time interval, sent every 10 seconds), a tilt meter ping (a shorter pulse that is transmitted later in time when tilt increases), and three temperature pings for three thermistors (located at the top, middle, and bottom) of the probe. Temperature pings occur later as temperature increases (see daily log report for example pictures of these pings). These pings are transmitted every ~10 seconds, but vary at the millisecond level to supply tilt, temperature, and depth information. The pings therefore allowed researchers aboard the ship to determine real-time whether the probe penetrated the subsurface, if, and to what approximate depth frictional heat occurred, the amount of probe penetration, and the relative thermal gradient and subsurface temperature with depth by noting whether the thermistors converged on higher or colder temperatures for each penetration. Internal power allows stations to run 20-30 measurements when fully charged.

Heat flow sites were maintained by the ship by putting the stern into the wind. In general measurement locations were maintained to within 20-30 m. In the relatively shallow water we allowed the probe to swing into position for approximately 10-15 minutes after the ship had stabilized at the measurement location. This stabilization period was long enough to make an adequate bottom water temperature prior to penetration and generally yielded low tilt from vertical

(<5 deg). Heat flow measurements began by lowering the probe into sediments. Early penetrations suffered from the probe not penetrating at a constant rate or quickly enough for full probe penetration into the subsurface. This condition manifested itself in the data via poor frictional heating at each thermistor, with none often at the shallowest thermistors, but was remedied by decreasing winch breaking, allowing the probe to fall at 100m per minute or greater. The top of the large steel housing unit that holds the data logger and pinger on the probe also acts as the connection point for the ship cable. Usually, an additional 12 kHz acoustic pinger is attached approximately 50 meters above the probe along the cable. This probe acts as an important tool for determining when the probe hits bottom, since the pinger signal from 50 m above the probe and the pinger on the probe will converge in time once the probe is inserted and is no longer dropping (however, the line will keep dropping during pay-out). For this survey, the cable pinger located 50 m above the line (which we rented from the University of Washington), failed to produce an easily detectable signal at water depth of a few hundred meters. As a result, we relied on the probe pinger to provide evidence for insertion into the seafloor (primarily the frictional heating spike and the tilt meter, combined with knowing the approximate depth of the bottom using the chirp/shipboard depth sounder, and the wench payout counter). Since the second pinger was non-functioning, but an important tool for determining depth as well as possible boat drift, we had to pay special attention to keep the ship on-station. This was done by paying out typically an additional 30 m of line, and making sure the ship was never more than ~20 m outside of the drop position. This approach worked surprisingly well, with perhaps only one instance (when sea state was poor and winds were high) where we saw evidence of post insertion stress on the probe before probe recovery. Indeed, the penetration success rate was over 97%, with proper seating at 113 out of 116 deployments.

Because a tensiometer was not available, insertion was determined by watching for the spectra line to lose tension. Following the insertion of the probe 20-30 m of line was let slack. Temperatures were interrogated every 10 seconds for 7 minutes via data logger pings to the ship. During this period thermistors approach thermal equilibrium with the surrounding sediment and this temperature-time series is used to compute the thermal gradient. Following this initial 7-minute period a calibrated heat pulse is generated along a heating wire within the thermistor tube. The temperature decay of this heat pulse is monitored to determine in-situ thermal conductivity. The probe was pulled out of the sediment at 10-20 m/min while the ship backed into the measurement point to ensure that the probe was pulled vertically out of the sediment. To determine when the probe was out of the bottom we monitored the acoustic pings looking for the time when the temperatures increased from frictional heating and converged back to bottom water temperature once exposed to ocean water again. We also monitored the tilt meter, looking to see when it went back to its pre-insertion value. The probe was then raised to approximately 100 m above the seafloor while the ship transited at 1-2 kts to the next site.

MPHF probe data were converted to ascii text (heatpro.exe), parsed into individual penetration files (pro51.exe) and processed using SlugHeat, a MATLAB® based program (A. Fisher, written communications, 2005). Thermistors are calibrated and set equal to each other by hanging the probe just above the bottom and assuming that over the 3.5 m probe length the bottom water temperature is constant.

All heat flow measurements are listed in the final table of the cruise report. Their locations and depths are also provided in this table and shown in several Figures. Additional analysis will be required to finalize the heat flow values listed in this report, but values are unlikely to change by more than a few percent as a result of reanalysis. In total, 116 heat flow stations consisting of 1244 temperature measurements were attempted. Of these, 97 % of all probe deployments were successful. No corrections have been applied for the influence of changing bottom water temperature, sedimentation, or local topography. For more information about probe design, method, or data, please contact PI Rob Harris directly.

Data collected with this instrument have-been/will-be processed with custom software based on a processing protocol [Villinger and Davis, 1987] that allows iterative determination of both the local thermal gradient and values of sediment thermal conductivity, and includes a graphical user interface, selective elimination of spurious thermistor readings, and Monte Carlo analysis of variations in thermal conductivity with depth [Stein and Fisher, 2001; Hutnak et al., 2006]. For more detailed descriptions of the data reduction algorithms, see the following references below:

References for Data Reduction Algorithms

Hutnak, M., A. T. Fisher, L. Zühlsdorff, V. Spiess, P. Stauffer, C. W. Gable, Hydrothermal recharge and discharge guided by basement outcrops on 0.7-3.6 Ma seafloor east of the Juan de Fuca Ridge: observations and numerical models, *Geochemistry Geophysics Geosystems (G3)* 7, doi:10.1029/2006GC001242 2006.

Stein, J. S., A. T. Fisher, Multiple scales of hydrothermal circulation in Middle Valley, northern Juan de Fuca Ridge: physical constraints and geologic models, *J. Geophys. Res.* 106, 8563-8580 2001.

Villinger, H., and E. E. Davis (1987), A new reduction algorithm for marine heat flow measurements, *J. Geophys. Res.*, *92*, 12,846-12,856, doi: 10.1029/JB092iB12p12846.

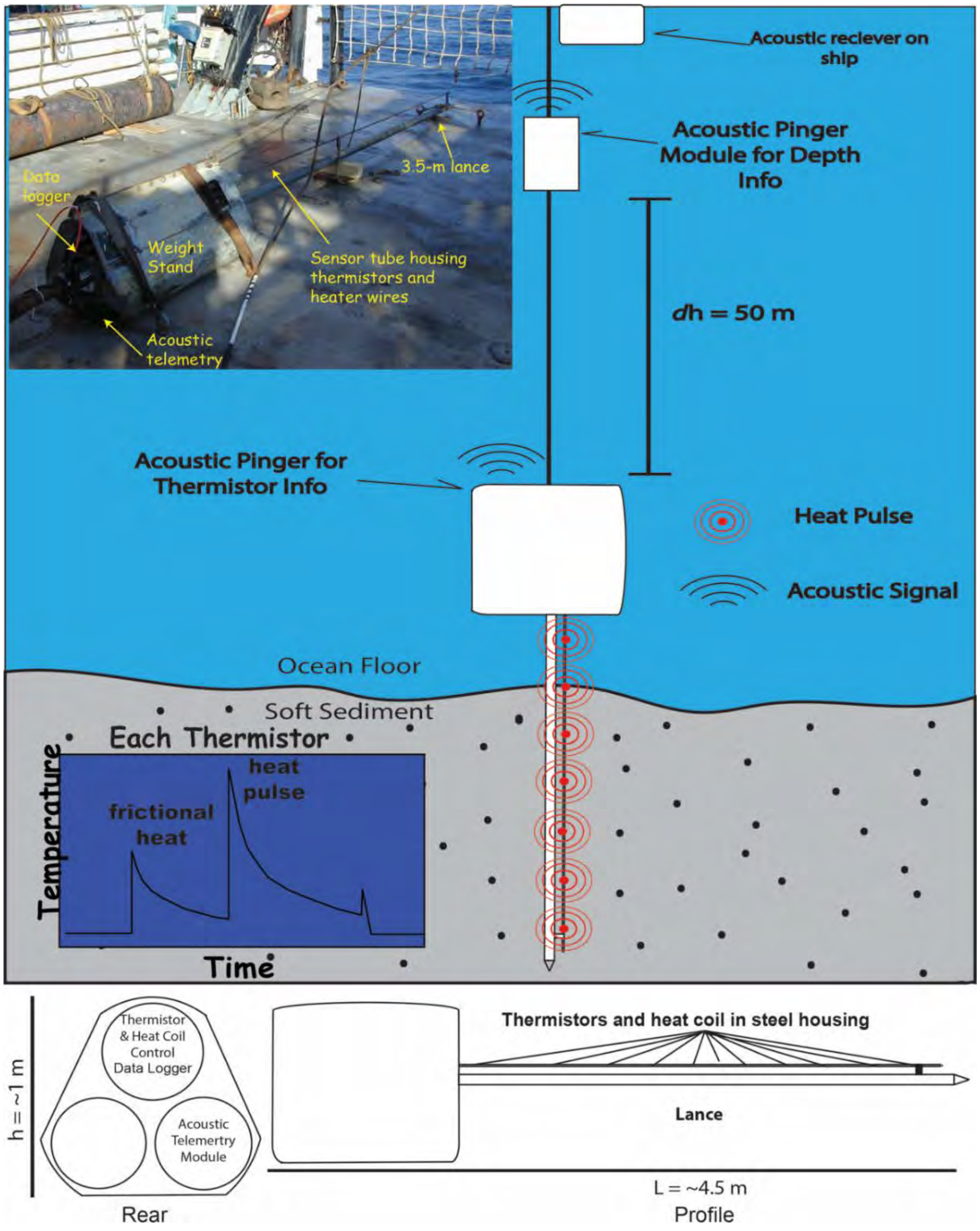


Figure 6: Multipenetration heat flow probe (MPHF). Top left shows probe horizontal on ship deck. Cartoon is exaggerated to illustrate position of lance vertically inserted into ocean sediments through force of gravity of the weight stand above. Eleven thermistors and a heat coil are contained within a 'violin bow' adjacent to the lance. The lance provides strength for repeated insertions and removals, while the sensitive thermistors are separated by sufficient distance to allow measurements of the in situ temperatures of the sediments, apart from the influence of the lance. Thermistor data is stored in the data logger's solid state memory, housed within the weight stand above the lance/violin bow. The weight stand also contains one of two 12 kHz acoustic pingers. The second is attached to the cable ~50 meters above the weight stand. Shipboard equipment receives signals from the pingers used for probe deployment, monitoring, and retrieval. Upon retrieval to the surface, data is downloaded from the logger. The data logger also records time, pressure (depth), water temperature, tilt and a stable reference resistance. The heat coil in the violin bow enables in situ thermal conductivity measurements, however this component was not performing at all penetrations. Fortunately, the seafloor sediments often adhere to the MPHF, allowing for sample collection and laboratory based thermal conductivity measurements.

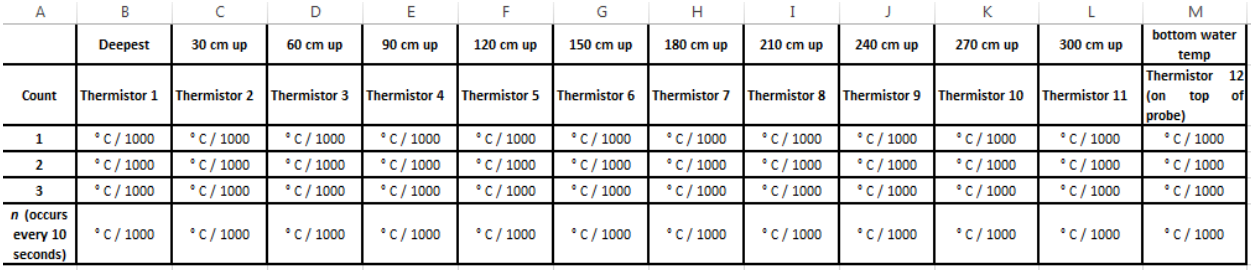
Loading/Reading the Initial Raw Heat Flow Data Penetration Files without SlugHeat02:

All raw heat flow data were converted into *.PEN files (penetration files) that provide time and temperature information for each of the 12 thermistors. These are ASCII files that can be viewed in “notepad” or loaded directly into MATLAB®. To get temperature, the values for each thermistor are divided by 1000 (values in *.PEN files are in milli-deg. C). These files contain 13 columns. The first column on the left in the data is the COUNT, which counts the number of times the clock has ticked 10 seconds, so each count represents a 10 second interval. Columns in the *.Pen file from left to right are from deepest to shallowest, with the shallowest thermistor (number 12) mounted on the probe head, not on the lance (probe 12, column 13 in the *.PEN file, is the water temperature data).

Note that the *.PEN files are only a portion of the data collected during each BHF deployment—they represent only the data from the period when the probe went in and then came out of the bottom sediments for each penetration.

The table below show the column layout for all *.PEN files.

Table 1: Column layout of MPHF Penetrations (.PEN) files. Temperatures for each of 12 thermistors are displayed in millidegrees Centigrade. Thermistor 1 is the deepest recording, on the bottom of the probe’s lance. Thermistor 12 is located on top of the weight stand and records the bottom water temperature. Refer to Figure 9 for a diagram of the MPHF probe.



A	B	C	D	E	F	G	H	I	J	K	L	M
	Deepest	30 cm up	60 cm up	90 cm up	120 cm up	150 cm up	180 cm up	210 cm up	240 cm up	270 cm up	300 cm up	bottom water temp
Count	Thermistor 1	Thermistor 2	Thermistor 3	Thermistor 4	Thermistor 5	Thermistor 6	Thermistor 7	Thermistor 8	Thermistor 9	Thermistor 10	Thermistor 11	Thermistor 12 (on top of probe)
1	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000
2	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000
3	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000
n (occurs every 10 seconds)	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000	° C / 1000

For Complete Temperature Series for an Entire BHF Deployment

As mentioned above, the .PEN files refer to just the portion of the data recorded while the MPHF probe is penetrating the seafloor. The probe is also recording information throughout the time it is deployed, even when not penetrating the seafloor. These data are extremely valuable as they provide additional insight into water column temperatures in the Beaufort Sea at several depth intervals while the ship transited between station locations. This complete series of raw data (NOT cut into small blocks associated with penetration) is provided in a folder called “BHF_ALL_Timeseries”, within ROQ14_BHF*.mat files. These MATLAB data files contain all of the temperature data for each of the thermistors. One can load or view these data simply by opening them in MATLAB. The first 11 thermistors will be labeled as a vector T1, T2, T2,….T11 and the water temperature sensor, T12, is labeled Twater. Also note that the data contains an approximate “depth” value based on the pressure sensor, however, this pressure sensor malfunctioned after the first deployment, so it should not be fully trusted. Instead, use the original data logging sheets (section XII. or the excel spreadsheet with all penetration points, locations, and depths, as these note the depth that we towed the thermistors while transiting in the water column between penetration sites.

ii. 12kHz Chirp sub-bottom profile data collection

To collect sub-bottom profiles and to communicate with the heat flow probe, we used a Knudsen 3212 portable Chirp Dual Channel Echosounder and Transducer system capable of sending and receiving signals in the 12 kHz and 200 kHz range. To collect these data, the transducer was mounted on a pole mount-and -bracket system to a boom on the port side of the Norseman II. The boom also had a side-scan sonar transducer attached directly to the bottom. To avoid damaging the sidescan system, our mount connected to the boom with 2 brackets, 14” off the boom, placing the Chirp transducer 26” below the bottom of the boom and fully below the sidescan sonar transducer. The boom is 20 feet long and when submerged, the Chirp transducer is about 3 feet underneath the hull of the ship, which is about 12-15 feet under the surface of the water (Figure 10). Because the transducer is below the ship and the sonar transducer there was no observable interference or noise caused by the boat itself. Only in very poor sea states, or when moving at speeds in excess of 3 knots did we see any indication of noise associated with air-bubbles or other forms of signal loss.

We kept the boom raised along the upper port deck during higher speed (>3 knot) transits between heat flow profiles, and lowered it during heat flow deployments, chirp surveying, and slow transit between heat flow waypoint sites (Figure 11). The ship cannot generally exceed 3 knots with the boom lowered.

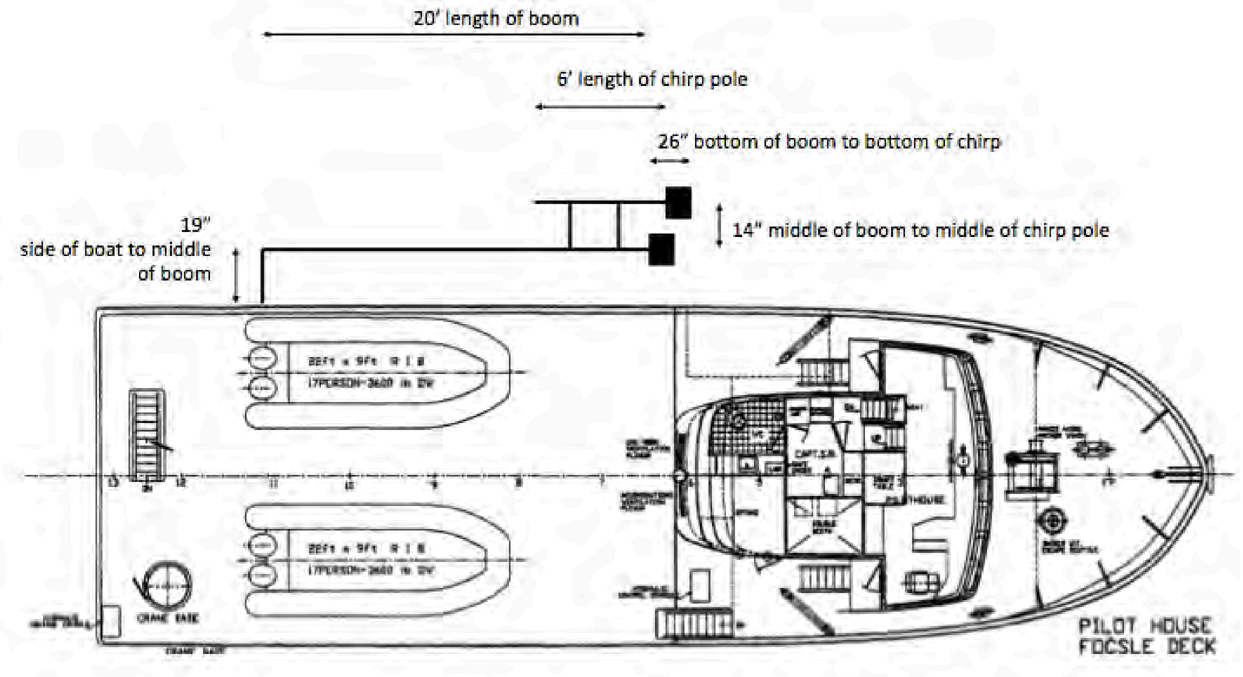


Figure 7: The Knudsen transducer’s 6-foot pole mount is attached by two brackets to the bottom of a 20-foot boom on the ship’s port side. When the boom is lowered into the water, the chirp is 3 feet under the hull of the ship, which is about 12-15 feet under the surface of the water.

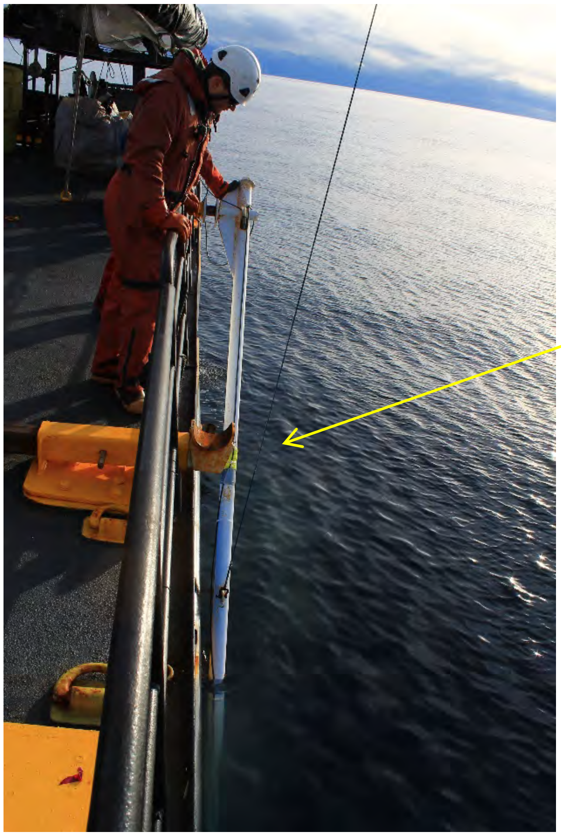
Figure 8: The boom is mounted to the ship's port side during transit, 19 inches away from the side of the deck.

The 40 ft transducer cable was run up the boom and into the science lab, where it connects to the dry end of the Knudsen Echosounder control box. Because of the long cable run (up the deck and down to the pole) and the availability of only 40 feet of transducer cable, we attached the cable to the dry-end of the Knudsen system very close to the cable port in the lab (Figure 12).

Connection between Transducer and Echosounder

Figure 9: Cords from the chirp transducer on the port side of the ship fit through a hole in the science lab, where they connect to the Echosounder and computers for data logging and analysis.

The boom is fully lowered the water line is at the yellow tape, about 4 feet from the top of the boom.



Water line is at yellow tape when the boom is fully lowered.

Figure 10:Science Ccrew oversee the boom as it is raised for transit. When the boom is fully lowered the water line is at the yellow tape, about 4 feet from the top of the boom.

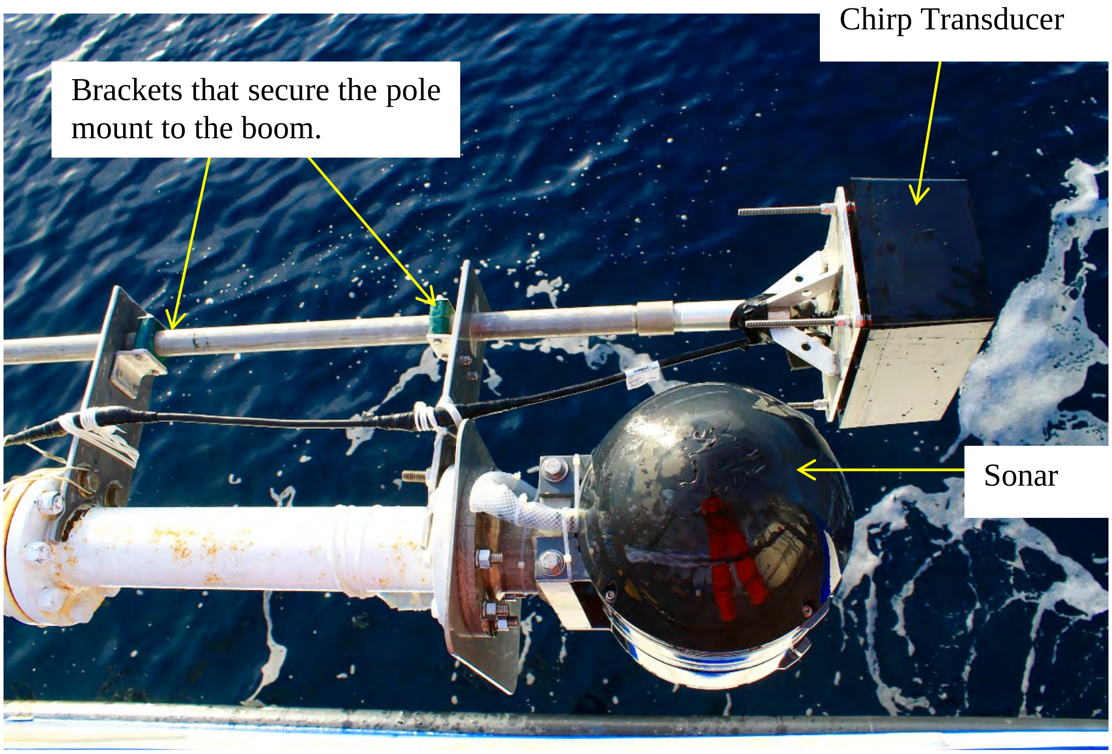


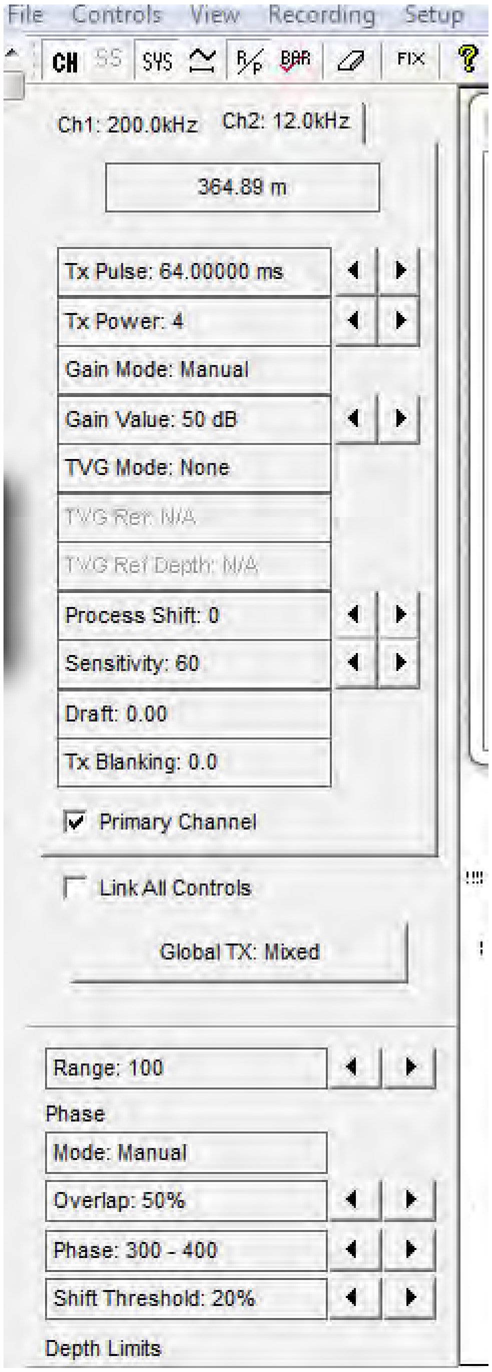
Figure 11: Close-up of transducer and sonar at the end of the boom. Note we added significant amounts of chaffing gear to the cable to reduce the chances of abrasion along the cable.

Knudsen Echosounder Frequencies

The Knudsen 3212 echosounder system is capable of sending and receiving signals in the 12 kHz and 200 kHz range. The heat flow probe, however, communicates only with 12 kHz data. We therefore used 12 kHz data to both listen to signals sent from the heat flow probe and to profile the subbottom. We attempted also to use the 200 kHz system to look below the shallow (upper meter) of the subseafloor and for possible evidence of gas bubbles in the water. The 200 kHz data, however, were very noisy, and we suspect the likely cause was the ship's own depth finder system which transmits at 60 kHz and 170 kHz, resulting in cross-talk and interference between the systems. To allow the ship to maintain high quality depth readings, we disable our 200 kHz system and focused only on 12 kHz data for the cruise. The 12 kHz data is surprisingly high quality, and in many instances (as we show later in the cruise report) was able to clearly image subsurface features to depths of 20 mbsf.

Acquisition Setting for the 12 kHz Knudsen chirp system:

We varied the settings for data acquisition on the chirp depending on the water depth and steepness of the slope. In general, for shallow, low slope settings, we applied no "Process Shift" to the data, and adjusted the db gain only to image deeper horizons. In water depths greater than ~500 m, or where steep slopes exist (or both), once we had exhausted the db gain increase to its maximum value of 96 db, we would then apply a "Process Shift" of 1 or 2, with the higher the number resulting in a greater increase in gain. This shift can sometimes oversaturate the data however, and may increase the noise, so a dance in values often occurs in applying these shifts. Below we show screen-shot images of the settings that generally worked best in shallow vs. deep water.



Ch1: 200.0kHz
Ch2: 12.0kHz

364.89 m

Tx Pulse: 64.00000 ms

Tx Power: 4

Gain Mode: Manual

Gain Value: 50 dB

TVG Mode: None

TVG Rer: N/A

TVG Ref Depth: N/A

Process Shift: 0

Sensitivity: 60

Draft: 0.00

Tx Blanking: 0.0

☑ Primary Channel

☐ Link All Controls

Global TX: Mixed

Range: 100

Phase

Mode: Manual

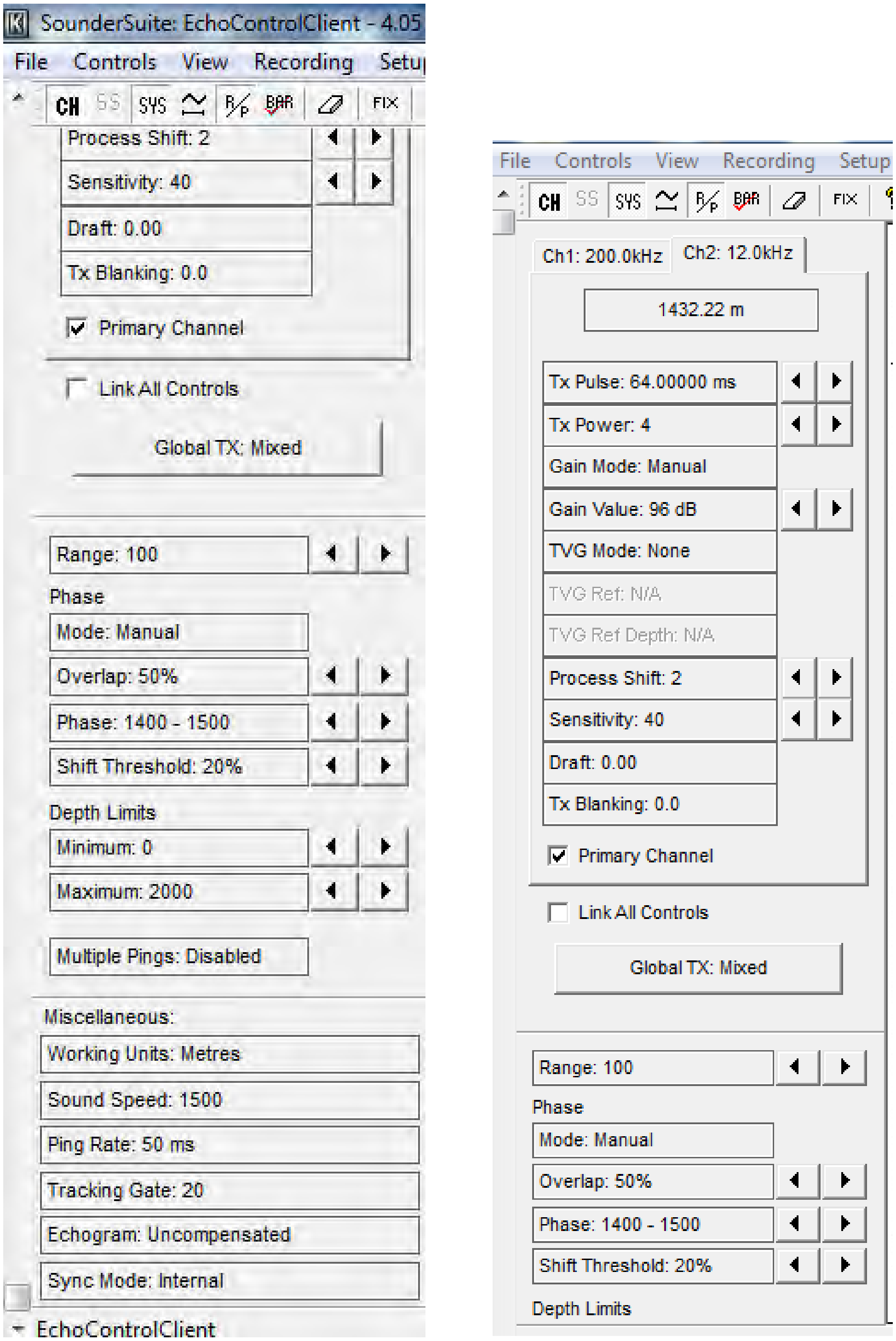
Overlap: 50%

Phase: 300 - 400

Shift Threshold: 20%

Depth Limits

Above: Recommended Setting for Shallow (<500 mbsl) water chirp data acquisition.



Process Shift: 2
Sensitivity: 40
Draft: 0.00
Tx Blanking: 0.0
☑ Primary Channel
☐ Link All Controls
Range: 100
Phase
Mode: Manual
Overlap: 50%
Phase: 1400 - 1500
Shift Threshold: 20%
Depth Limits
Minimum: 0
Maximum: 2000
Multiple Pings: Disabled
Miscellaneous:
Working Units: Metres
Sound Speed: 1500
Ping Rate: 50 ms
Tracking Gate: 20
Echogram: Uncompensated
Sync Mode: Internal

Ch1: 200.0kHz
Ch2: 12.0kHz
1432.22 m
Tx Pulse: 64.00000 ms
Tx Power: 4
Gain Mode: Manual
Gain Value: 96 dB
TVG Mode: None
TVG Ref: N/A
TVG Ref Depth: N/A
Process Shift: 2
Sensitivity: 40
Draft: 0.00
Tx Blanking: 0.0
☑ Primary Channel
☐ Link All Controls
Range: 100
Phase
Mode: Manual
Overlap: 50%
Phase: 1400 - 1500
Shift Threshold: 20%
Depth Limits

Above: Recommended Setting for Deep (>500 m) CHIRP imaging.

iii. Additional Internal Data Collected by the M/V Norseman II

The ship also collected data during the cruise, and these data have been provided to us by Luke Johnston, the technician on the vessel. The data include ship position, sea surface temperature, air temperature, salinity, nitrogen concentrations, ship heading, barometric pressure, wind speed, and ship speed over ground. These data were updated approximately every second. Files containing weather data can be found in the file labeled “WeatherData Norseman2” with files containing ocean chemistry, salinity, temperature found in “SBE21 Norseman2 Data”.

GPS Positioning for the HF Probe and the CHIRP

The ship has two GPS positions available. One is located above the bridge, near the bow of the ship; the second is located on the A-frame on the fantail. We used the GPS on the A-frame for both the Heat Flow probe and chirp location. There is no DGPS on the ship, so uncertainty in position is on the order of ~5 m. Additionally, some minor error in chirp position (a meter or more beyond uncertainty) exists as the pole mounted chirp is located approximately 5-6 m forward of the stern on the port waist of the Norseman II.

VII. Data Collection and Preliminary Analysis at 4 Transects.

Heat Flow and Chirp data were collected along four transects, all of which are coincident with seismic data collected by the USGS in 1977. Transect lengths vary from 10 to more than 20 km, and extend from depths of ~200 mbsl, to depths of 1700 mbsl. Transects begin in the eastern US Beaufort and progress west, with the western most transect (Transect 4) located ~100 km northeast of Barrow, more than 500 km from the Eastern most Transect 1--located near the Alaska-Canada Maritime border. In the following sections, we provide a basic description of each of the transects, their location, where/how data were collected, why they were collected, the conditions and timing of data collection, and preliminary results.

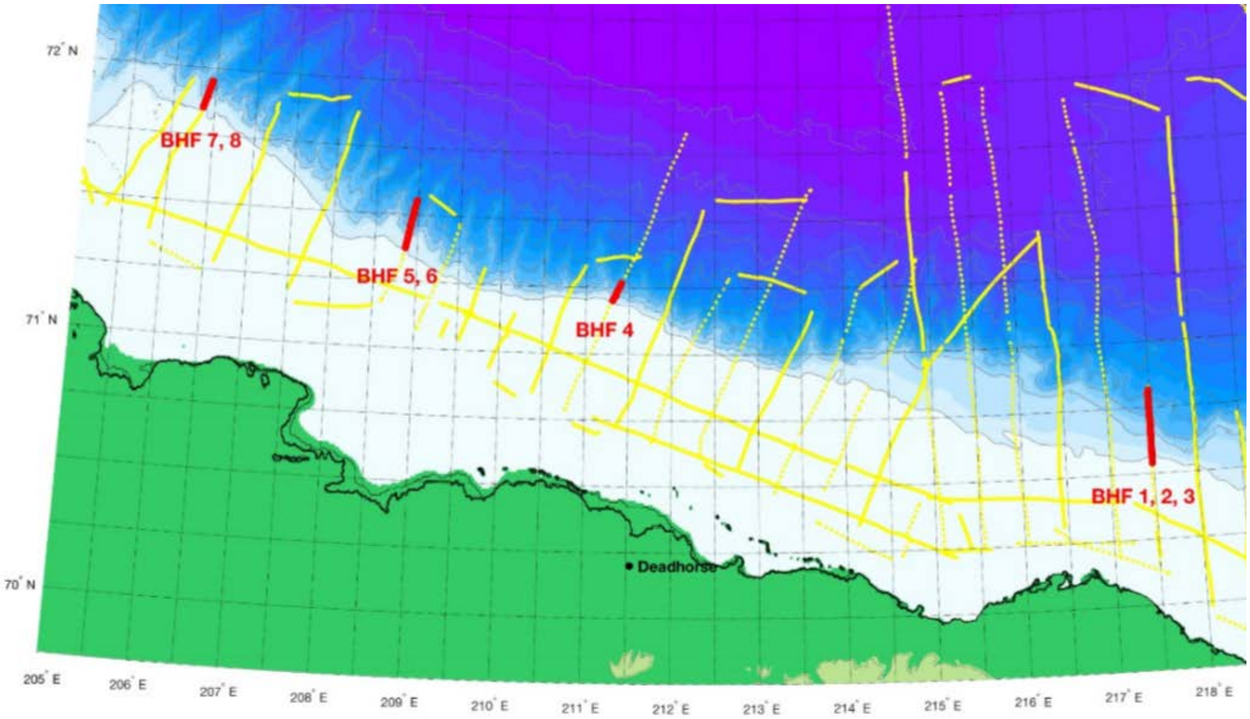


Figure showing the location of the four chirp transects, consisting of 8 total deployments, in red, with each of the deployment site locations labelled.

i. Transect 1: Eastern US Beaufort Margin (Probe Deployments BHF1, BHF2, BHF3) (Coincident with USGS 1977 Seismic Line 730)

Objective of Transect 1

The objective of data collected along this transect is to determine the regional heat flow from the lower edge of the Beaufort margin up and just beyond the feather edge of methane hydrate stability, near the shelf edge, with particular interest in determining the potential heat flow in regions where BSRs exist below the subsurface and where methane hydrates may be dissociating along the upper feather edge of the continental margin (at depths of 400-250 mbsl). The data will be used to determine where methane hydrates are in steady-state equilibrium versus where they may be dissociating, as predicted by recent publications (e.g. Phrampus et al., 2015).

Location of Transect 1

This transect follows the approximate track of USGS Seismic line 730, collected in 1977 in the Beaufort Sea, and highlighted in Pat Hart's Ph.D. thesis. This line extends approximately north-south, from the Beaufort shelf towards the base of the margin, and is located along a North-South profiles parallel to -142.52° W, from 70.52° to 70.82° N (See Figure).

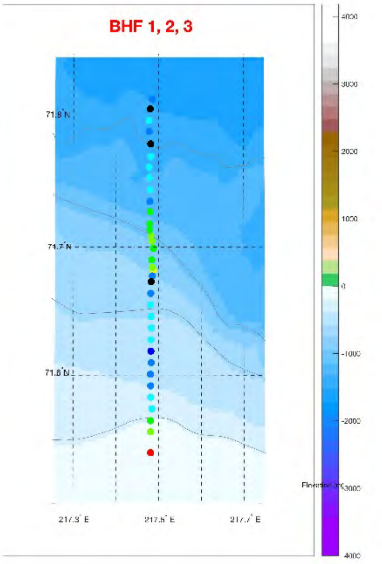


Figure 12: Location of HF probe deployments on Transect 1, which consisted of three total deployments (BHF1, BHF2, BHF3). Colors for the probe deployments provide a rough qualitative value for the HF values at each of the sites with warmer values representing high heat flow. Black values represent zones where the probe either fell over, or may not have usable data. Contour interval is 400 meters.

Timing

Data collection along this transect occurred during the first three days of the survey. Total survey time took approximately 53 hours of round-the-clock deployments and recoveries. The survey started at approximately noon local (Alaska) time September 12th and ended in the late afternoon (approximately 4:50 pm Alaska time) September 14th.

Predominant Current/Wind

The wind direction was highly variable, however, ocean surface current direction typically flowed from northeast to southwest, and the ship would often be pushed in this direction while trying to hold station, although when winds were greater than ~15 knots, it was the driving factor in how the ship drifted on station.

Sea State/Ice Conditions During Data Collection

During the first two days on site, sea state was rather poor, with 4-6 ft swells, and winds of 15-20 knts. Despite less than ideal conditions, we were able to still collect high quality temperature, conductivity, and heat flow data. During the 3rd and final day, sea state was much improved, with a high pressure system passing through the region dropping wind speeds to under 7 knots, resulting in glassy and exceptionally calm (1ft) seas. The improved weather conditions made data collection and ship station holding for heat flow points much easier for the captain and crew. No sea ice was observed during the entire transect 1 survey; ice was therefore a non-issue for the entire period we collected data along the transect.

HF Probe Deployments Along Transect 1

The probe was deployed 3 times on transect 1; and these deployments are labeled in plots, tables, and charts as BHF1, BHF2, BHF3. BHF1 acquired the deepest (northern most) measurements; BHF2 provided some initial fill of bad data collected during BHF1 as well a few shallower penetrations points. BHF3 acquired the shallower measurements (See Figure 15). The probe heat pulse sensor stopped functioning after BHF1, so as a result, we were only able to collect real-time conductivity measurements for the 16 penetrations during this deployment. Additional thermal conductivity measurements, however, were acquired on sediments collected from the probe back in the lab at SMU.

Data types acquired along BHF transect 1

(1) Thermal conductivity (deployment BHF 1 only) (16 penetrations, with ~160 temperature measurements)
(2) Heat flow measurements/estimates from regional K along the margin. (BHF1,2,3) (32 of 35 deployments)
(3) Temperature gradients near anomalous values down slope, and fill (BHF2).
(4) Temperature gradients along the upper feather edge of the margin (BHF3).
(5) Mud samples along the upper feather edge of the margin (BHF3, last site), removed from HF probe when it was buried in sediment. These will be used for additional thermal conductivity analysis (approximately 2 cups from final deployment site at (BHF3).
(6) Chirp (12 kHz) seismic data used to both communicate with the heat flow probe (in passive mode) and to image good spots for probe deployment (softer sediment environments), with an additional line extending up across the hydrate stability zone (approximately 100 km, with depth penetration exceeding 20 m in several locations).

BHF Transect 1 Preliminary Results

Heat Flow Probe Penetration Success Rate

We had a success rate of 91% in obtaining quality temperature-depth data with the probe along this profile. Of the 35 heat flow probe deployments along the transect, 32 provided usable high quality (at least 10 robust temperature depth readings) temperature measurements, indicating at least 10 of the 12 thermistors had multiple thermistors penetrating the subsurface. The deployments with shallow penetration still produce usable ocean bottom temperature data and after additional processing may still be useful in assessing regional heat flow. We were frankly extremely surprised by this success, especially given that over-compacted hard-bottom seafloor is thought to exist in the region. Sidescan sonar images collected by researchers at the University of New Hampshire conducting law of the sea work (Larry Meyer's group) indicate a relatively hard surface bottom compared to surrounding regions in the Eastern US Beaufort. Both chirp seismic data and mud-cake along the heat flow probe and barrel indicated very little if any sand exists in the region, with the predominant sediments observed on the core consisting of very fine-grained dark brown hemipelagic mud, similar to what we observe in shallow sediments collected at Blake Ridge. For all deployments along the transect, it appears that only in one instance the probe didn't penetrate; chirp data indicate this was likely the result of steep slopes, not significant sand in the subsurface. We generally found that winch speeds of 90-100 m/min helped improved penetration—to the point that we sometimes completely buried the probe in the mud when dropping the probe at this rate (with mud caking reaching almost the top of the probe head). We also usually paid-out an additional 30 m of line after probe insertion into the seafloor to provide a buffer zone on the line that reduced the chance of early HF probe pull-out or probe stress caused by ship heave at the surface.

DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)	SHIP REPORTED DEPTH (M)
13-Sep-16	BHF1	1	1	70.8151	142.5151	1470
13-Sep-16	BHF1	2	2	70.8074	142.5198	1427
13-Sep-16	BHF1	3	3	70.7984	142.5225	1440
13-Sep-16	BHF1	4	4	70.7901	142.5216	1430
13-Sep-16	BHF1	5	5	70.7802	142.5185	1458
13-Sep-16	BHF1	6	6	70.7703	142.5184	1400
13-Sep-16	BHF1	7	7	70.7621	142.5223	1380
13-Sep-16	BHF1	8	8	70.7541	142.5210	1320
13-Sep-16	BHF1	9	9	70.7447	142.5199	1305
13-Sep-16	BHF1	10	10	70.7355	142.5204	1210
13-Sep-16	BHF1	11	11	70.7274	142.5198	1148
13-Sep-16	BHF1	12	12	70.7179	142.5209	1167
13-Sep-16	BHF1	13	13	70.7089	142.5177	1165
13-Sep-16	BHF1	14	14	70.6991	142.5120	1105
13-Sep-16	BHF1	15	15	70.6900	142.5160	1035
13-Sep-16	BHF1	16	16	70.6820	142.5120	936

14-Sep-16	BHF2	1	A	70.7134	142.5206	1100
14-Sep-16	BHF2	2	B	70.7047	142.5153	1107
14-Sep-16	BHF2	3	C	70.6841	142.5144	1031
14-Sep-16	BHF2	4	D	70.6776	142.5146	890
14-Sep-16	BHF2	5	17	70.6730	142.5174	810
14-Sep-16	BHF3	1	18	70.6640	142.5182	726
14-Sep-16	BHF3	2	19	70.6550	142.5184	647
14-Sep-16	BHF3	3	20	70.6460	142.5175	613
14-Sep-16	BHF3	4	21	70.6370	142.5170	526
14-Sep-16	BHF3	5	22	70.6280	142.5180	477
14-Sep-16	BHF3	6	23	70.6190	142.5180	449
14-Sep-16	BHF3	7	24	70.6100	142.5175	424
14-Sep-16	BHF3	8	25	70.6010	142.5190	400
14-Sep-16	BHF3	9	26	70.5920	142.5184	378
14-Sep-16	BHF3	10	27	70.5831	142.5182	360
14-Sep-16	BHF3	11	28	70.5741	142.5156	330
14-Sep-16	BHF3	12	29	70.5649	142.5185	298
14-Sep-16	BHF3	13	30	70.5562	142.5185	271
15-Sep-16	BHF3	14	31	70.5399	142.5186	205

Preliminary (uncorrected) Heat Flow Estimates

Data collected along transect 1 represent, to our knowledge, the first high quality heat flow and thermal conductivity measurements ever collected on the US Beaufort Margin. A total of ~400 subsurface temperature measurements were made along the transect, at 35 station locations. For the few sites that failed to penetrated, we were still able to collect high quality ocean bottom temperature measurements. The Table below shows the approximate latitude and longitude of each station location. Depths are also recorded for each station. Station spacing was initially planned at 1 km intervals, however, we ultimately filled in a few gaps to this line, especially where we observed unusual or anomalous heat flow values across the region. Preliminary heat flow values along the lower edge of the margin are consistent with BSR values (in the 40-50 mW/m^2) (see figure below), however, the discrepancies between BSR-predicted heat flow, and observed values increases as we move up slope. Shallower heat flow measurements (<500 mbsl) require additional processing that includes both terrain correction, and seasonal/ annual ocean temperature corrections to properly determine heat flow. We have begun making these corrections while on the vessel (see section on season ocean temperature effects on heat flow in the region).

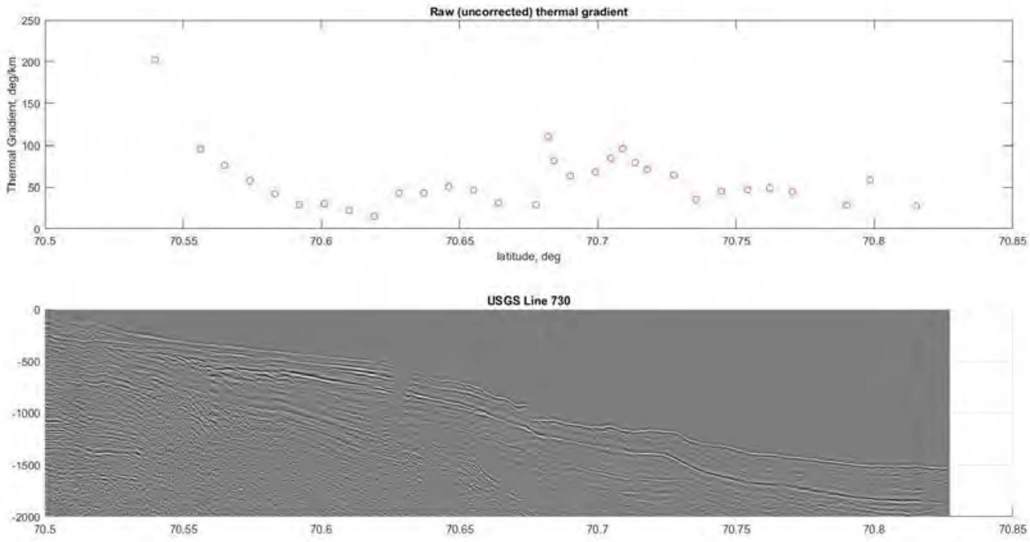
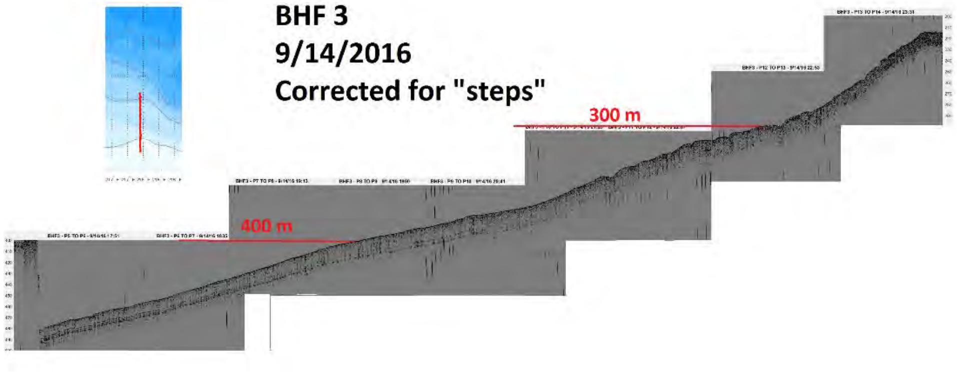


Figure 13: Plot showing USGS Seismic Line 730 and associated uncorrected thermal gradient measurements for ~¾ of the transect. Red circles at top are preliminary thermal gradient measurements. Although the TG values represent rough, first-order estimates (no terrain correction or standard deviation in error assigned yet), they show values remarkably consistent with BSR-derived heat flow (40-50 mW/m^2 on average). The HF measurements also reveal some unusual temperature anomalies, providing evidence for advective fluid flow along a fault at Latitude 70.67, where we observe a sharp increase in heat flow and a step up in the BSR.

12 kHz Chirp Image Preliminary Data Results

While transiting between sites, we collected 12 kHz seismic data. These profiles revealed clear, continuous seismic reflection along the margin edge, however, significant variability and evidence for subsurface disruption of sediment exists at shallow water depths (~300 m) where the hydrate stability zone likely pinches out at the seafloor (see image below). Heat flow data collected on this cruise, combine with ocean temperature data allow us to pinpoint where the hydrate stability zone exists along the margin edge.



Perhaps most notably the area where chaotic sediments appear in the chirp seismic data, are almost exactly where geochemical/geophysical models predict hydrate stability to pinch out into the seafloor (See figure below). This suggest hydrate dissociation is not only an on-going process on this margin, but arguably, based on the deformation of sediments above the hydrate stability zone, have occurred for some time as ocean temperature warming and sea level changes have occurred along the margin edge.

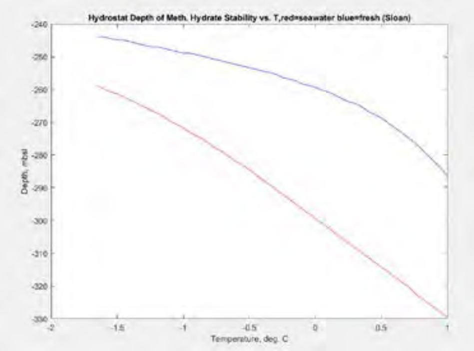


Figure above. Methane Hydrate stability profile for the Beaufort Sea using ocean temperature values matching observations in the Beaufort by Pickart et al., 2008. The phase boundary assumes pure methane hydrate with red values signifying depth of hydrate stability in salt water (34.5%mil), and the blue line signifying end-member fresh water conditions. Values are derived directly from Sloan's model (Sloan, E.D., Clathrate Hydrates of Natural Gases, Marcel Dekker, Inc., New York, 1990) and were generated in matlab script title "Hydrate_stability_depth_vs_temp_plot_using_sloan.m". Note that the depth of hydrate stability, based on temperatures observed in the Beaufort range from -240 to -330 mbsf. This zone also matches the depth interval where we view pockmarks and clear evidence for sediment disruption in the subsurface. Perhaps most notably, the depth intervals of 200-400 m, represent the zones that experience the most significant temperature changes in the Arctic Ocean. It is therefore perhaps not surprising that we see strong evidence for sediment disruption in this zone. Additionally, the fact that we don't see any significant evidence for high heat flow in these regions (but instead anomalously cold heat flow at depths greater than ~200 m) suggests a complex interplay exists between hydrate formation, dissociation, and ocean water temperature at these depth intervals.

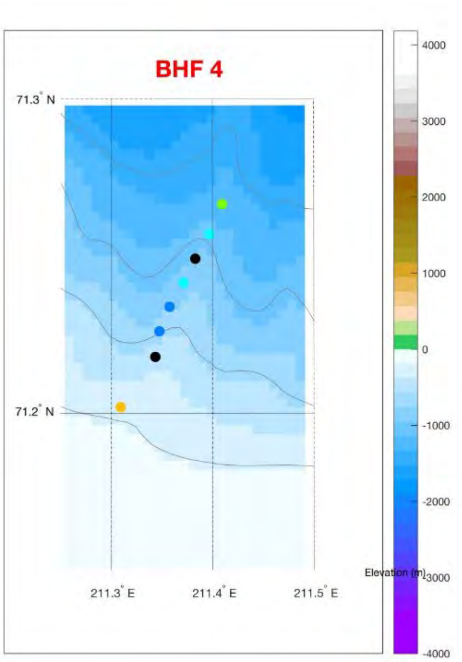
ii. Transect 2: Central U.S. Beaufort Margin (Probe Deployment BHF 4) (Coincident with USGS 1977 Seismic Line 753)

Objective of Transect 2:

The objective of data collected along this transect is similar to Transect 1, and focuses on assessing how heat flow, and the methane hydrate stability zone change along the margin edge. Transect 2, however, is located more than 300 km away from Transect1, so comparison between these two transects will help determine if the temperature/heat flow anomalies we observe in the Beaufort along Transect 1 are localized, or more widespread across the margin. Specifically, we will use HF values along this transect to determine the regional heat flow from the lower edge of the Beaufort margin up and just beyond the feather edge of methane hydrate stability, near the shelf edge, with particular interest in determining the potential heat flow in regions where BSRs exist below the subsurface and where methane hydrates may be dissociating along the upper feather edge of the continental margin (at depths of 400-250 mbsl). The analysis will be used to determine where methane hydrates are in steady-state equilibrium versus where they may be dissociating, as predicted by recent publications (e.g. Phrampus et al., 2015).

Location:

Transect 2 is located approximately 100 km NNW of Prudhoe Bay and follows the approximate track of USGS Seismic line 753, collected in 1977 in the Beaufort Sea. Transect 2 extends approximately north-south along from the Beaufort shelf towards the base of the margin, and is located along a North-South profiles parallel to -148.7° W (211.3 E), from 71.2° to 71.3° N (See figure ***).



Heat Flow (mW/m^2)	
🟥	180+
🟥	160-180
🟧	140-160
🟧	120-140
🟨	100-120
🟩	80-100
🟩	60-80
🟦	40-60
🟦	20-40
🟦	0-20
⬛	<0

Timing:

Data collection along this transect occurred during September 15-16, with total survey time of round-the-clock deployments of approximately 8 hours.

Predominant Current/Wind:

Ocean surface current direction typically flowed from northeast to southwest, and the ship would often be pushed in this direction while trying to hold station. Winds were variable from NE to W, with increased wind from the west towards the survey end. Winds were steady at 15 knots out of west but increasing to 20-25 knots by the time we completed this survey. Ultimately, we ended the survey of this line short due to (1) deteriorating weather conditions and (2) extremely steep slopes resulting in probe tilt and difficulty with probe penetration. As a result of these two factors, we moved west with the hope of passing through the worst of the coming low pressure system during transit and finding a location with flatter seafloor bathymetry.

Sea State/Ice Conditions During Data Collection:

Initial sea state was excellent, as a ridge of high pressure had passed through the day before, but steadily deteriorated during the survey. Swells of initially only 1 ft increased to more than a meter by the survey end, 8 hours later, with winds picking up from the west. No sea ice was observed during the entire transect 2 survey; ice was therefore a non-issue for the entire period we collected data along the transect.

HF Probe Deployments Along Transect 2:

The probe was deployed 1 time on transect 2. Deployment BHF4 was used to collect all data along this transect. With the thermal pulse no longer firing in the sensor, we used the probe to collect thermal gradient data along the profile. Probe penetration spacings were ~1 km.

Data types acquired along BHF transect 2:

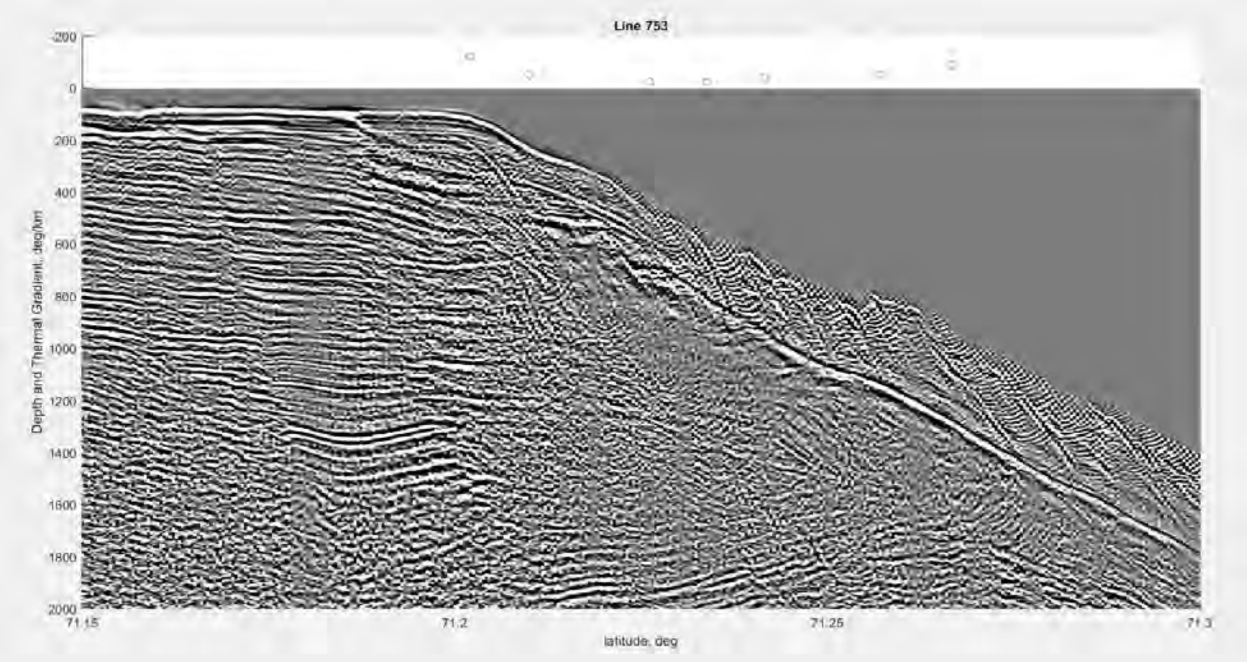
(1) Heat flow measurements/estimates from regional K along the margin.
(2) Temperature gradients along the upper and lower margin.
(3) A small (1/2 cup) mud sample collected off the probe lance upon recovery that will be used as an additional thermal conductivity analysis.
(4) Chirp (12 kHz) seismic data used to both communicate with the heat flow probe (in passive mode) and to image good spots for probe deployment (softer sediment environments), with an additional line extending up across the hydrate stability zone. (approximately 100 km, with depth penetration exceeding 20 m in several locations).
(5) Ocean temperature data collected from the probe being held, and transported within the water column during transits to each deployment site.

BHF Transect 2 Preliminary Results:

Heat Flow Probe Penetration Success Rate

Of the 11 HF probe penetration sites, 9 fully penetrated into the subsurface, producing usable data; a success rate of 82%. The last two sites were unable to penetrate into the subsurface due to steep slopes. Of the two where no data were acquired (penetrations 10, 11) it appears likely that the probe fell over at the bottom due to steep slopes. The Table below shows the approximate latitude and longitude of each station location. Depths are also recorded for each station. Station spacing was initially planned at 1 km intervals.

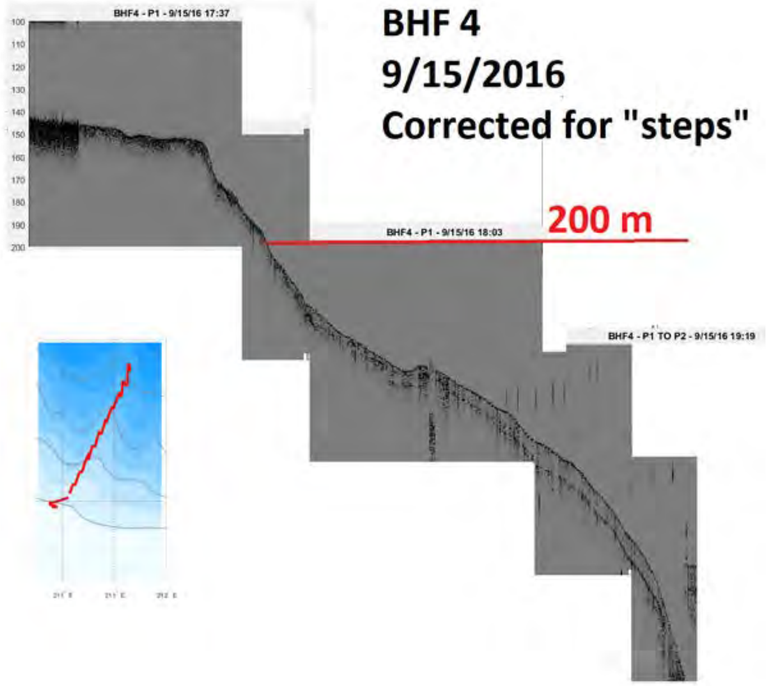
DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)	SHIP REPORTED DEPTH (M)
15-Sep-16	BHF4	1	2	71.2020	148.6907	203
15-Sep-16	BHF4	2	3	71.2100	148.0678	290
15-Sep-16	BHF4	3	4	71.2180	148.6565	400
15-Sep-16	BHF4	4	5	71.2261	148.6526	540
15-Sep-16	BHF4	5	6	71.2339	148.6424	648
15-Sep-16	BHF4	6	7	71.2416	148.6285	783
15-Sep-16	BHF4	7	8	71.2492	148.6170	810
15-Sep-16	BHF4	8	9	71.2571	148.6031	1030
16-Sep-16	BHF4	9	10	71.2666	148.5904	1220
16-Sep-16	BHF4	10	11			1247
16-Sep-16	BHF4	11	12			1321



Plot showing USGS Seismic Line 753 and associated raw heat flow measurements. Red circles at top are preliminary thermal gradient measurements (negative values given so that we could merge the results with seismic data into a quick, but useful plot for comparison). At least two values have HF values nearing zero at depths where seasonal temperature change are not likely impacting data. HF values represent rough, first-order estimates (no terrain correction or standard deviation in error assigned yet). Deeper values however are consistent with expected values derived from BSRs. Anomalously high values are observed closest to shore, which are related directly to seasonal ocean temperature change. This feature appears consistent throughout all transects, as we show later.

Chirp data Collected at Transect 2:

When transiting between stations, we collected chirp seismic data. Along the shelf edge, data are higher quality, revealing structure of the shallow subsurface. Down slope however, data quality are reduced due to steep slopes along the upper edge of the margin. The image below provides some insight into structure at the feather edge of hydrate stability along BHF 4.



12.5 kHz Chirp image along the Beaufort Margin. Note continuous, clear reflectors below ~350 mbsf, with more chaotic deformation above. Based on regional heat flow analysis and newly acquired data, we estimate that the upper edge of the hydrate stability zone is located very near this transition zone.

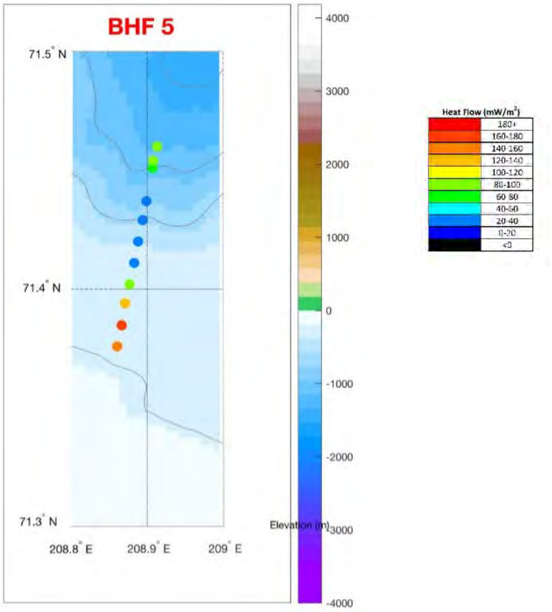
iii. Transect 3: Central-Western U.S. Beaufort Margin (Probe Deployments BHF5 & BHF6) (Following USGS Seismic Line 767)

Objective of Transect 3:

The objective of data collected along this transect is similar to Transect 1, and Transect 2, and focuses on assessing how heat flow, and the methane hydrate stability zone change along the margin. Previous heat flow studies using BSRs (Phrampus et al., 2014) indicate surprisingly high values in this region—higher than typical margin values observed in other areas, such as Blake Ridge or Hydrate Ridge. Data collected along this transect will therefore be used to verify if in fact these higher heat flows exist. Additionally, Transect #3 will collect more data along the shallow upper edge of the margin compared to Transects 1 and 2, and this is because station spacing remains at 1 km or less, but the shelf edge has a more gradational slope at Transect 3, resulting in more measurements for a given seafloor depth change. Transect 3 follows the USGS seismic profile 767, and is located approximately 100 km west of Transect 2 and 400 km west of Transect 1. The analysis of heat flow along this transect, combine with other HF transects along the margin edge will be used to determine where methane hydrates are in steady-state equilibrium versus where they may be dissociating, as predicted by recent publications (e.g. Phrampus et al., 2015).

Location:

Transect 3 is located approximately 200 km ENE of Point Barrow and 200 km WNW of Prudhoe Bay. The transect extends approximately north-south, running perpendicularly to the shelf edge, at a longitude of 208.8 E from 71.38° to 71.47° N (See figure ***).



Location of HF probe deployments on Transect 3, which consisted of two heat flow probe deployments (BHF5, and BHF6—only 5 is shown above). Colors for the probe deployments provide a rough qualitative, uncorrected value for the HF values at each of the sites with warmer values representing high heat flow. Black values represent zones where the probe either didn't penetrate the seafloor, or may not have usable data. Contour interval is 400 m.

Timing:

Data collection along this transect occurred during September 16. By the end of that day however, a major storm developed that ultimately had sustained winds > 30 knots, forcing us to pull up the probe and cease data collection activities. After 2.5 day, the storm passed, and by the early morning of the 20th, we were again collecting data in 12 ft seas that rapidly diminished to 3-5 ft swells within 24 hours.

Predominant Current/Wind and Sea State:

Sea state was poor on the 16th with swell increasing to 6 ft, white-caps, blowing snow, and a confused sea state due to cross current. Strong 20+ knot winds from the WSW combined with ocean cross currents running from NE to SW resulted in a less than ideal sea state for holding station on the 16th. No sea ice however was observed during data collection. We were informed by the Captain that the sea state would only get worse for the next 48 hours, and based on this information, we began deploying the probe more frequently, and at tighter spacing as we moved downslope to reduce time spent transiting. Ultimately we had to cut deployment BHF 5 short due to winds approaching 30 knots, since these winds made holding station problematic. On September 17th and 18th, the winds continued to blow from the SSW, making probe deployment unsafe, with the ship rocking violently. During this period, the ship hove too, riding out the storm, with the sea anchor deployed part of the time, and later, the anchor dropped in shallower waters near shore, at a location near Point Halkut, where we attempted to find lee. Chirp data collection was also seriously hampered and ultimately abandoned during the 2.5 day-long storm because of air bubbles getting below the chirp system wiping out the return signal (the chirp was 2 m below the water line, but still became exposed to air bubbles or the sea surface because of the significant swell. On the morning of September 20th, winds had dropped to ~20 knots out of the west, and we returned to operations with deployment BHF6, despite significant swell. Sea state improved further during this deployment, resulting in rapid data collection.

HF Probe Deployments along the transect:

The probe was deployed 2 time on transect 3 (BHF5 and BHF6) and had a total of 34 penetrations along the profile. With the thermal pulse no longer firing in the sensor, we used the probe to collect thermal gradient data along the profile and used mud samples recovered from the probe to make conductivity measurements back in the lab. Probe penetration spacing was ~1 km for the shallow section, but reduced to 0.5 km spacing for deeper water to reduce transit time and allow for more data collection before having to pull the probe.

Data types acquired along BHF transect 3:

1. Heat flow estimates from regional K along the margin.
2. Temperature gradients along the upper and lower margin derived directly from the probe.
3. Chirp (12 kHz) seismic data used to both communicate with the heat flow probe (in passive mode) and to image good spots for probe deployment (softer sediment environments.
4. Ocean temperature data collected from the probe being held, and transported within the water column during transits to each deployment site.

BHF Transect 3 Preliminary Results:

Heat Flow Probe Penetration Success Rate

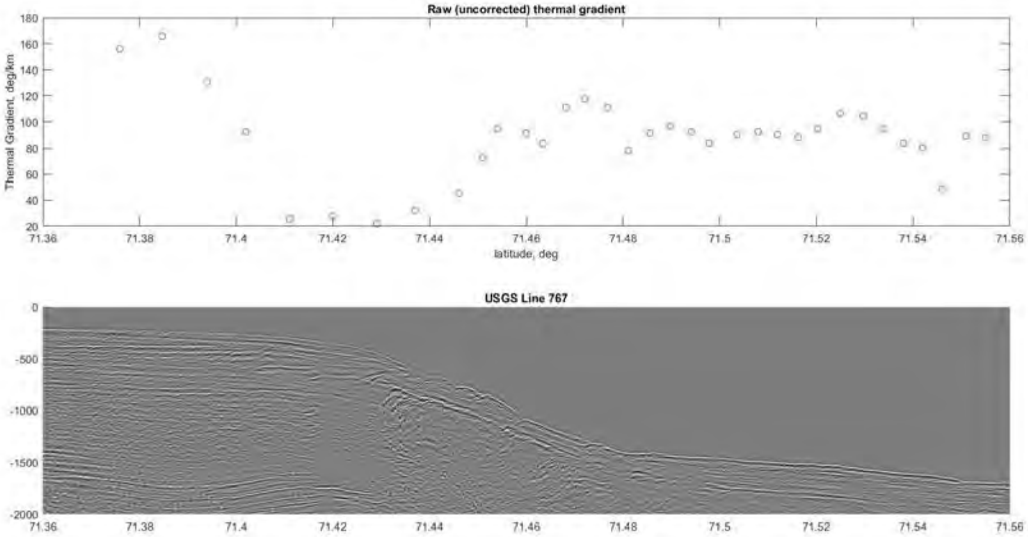
Of the 34 HF probe deployment sites for BHF5 and BHF6 along transect 3, all fully penetrated into the subsurface--a success rate of 100%, despite sometimes steep slopes at several deeper water site locations. We believe part of the success was due to the fact that the sediments appeared finer grained and muddier both in the chirp images and based on the mud samples brought on deck by the probe. Additionally, Chirp data was invaluable at providing insight into the subsurface slope and sediment character, and from this, detecting key locations for probe deployment where slopes were relatively flat. The Table below shows the approximate latitude and longitude of each station location.

OPERATOR	DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)

MJ	16-Sep-16	BHF5	1	1	71.3759	151.1394
MJ	16-Sep-16	BHF5	2	2	71.3847	151.1335
CPB	16-Sep-16	BHF5	3	3	71.394	151.129
CPB	16-Sep-16	BHF5	4	4	71.402	151.123
CPB	16-Sep-16	BHF5	5	5	71.411	151.117
CPB	16-Sep-16	BHF5	6	6	71.42	151.113
CPB	16-Sep-16	BHF5	7	7	71.429	151.106
CPB	16-Sep-16	BHF5	8	8	71.437	151.101
CPB	16-Sep-16	BHF5	9	9	71.446	151.097
CPB	16-Sep-16	BHF5	10	10	71.451	151.093
CPB	16-Sep-16	BHF5	11	11	71.454	151.092
CPB	16-Sep-16	BHF5	12	12	71.46	151.087
BP	20-Sep-16	BHF6	1	13	71.4634	151.0853
BP	20-Sep-16	BHF6	2	14	71.4682	151.083
BP	20-Sep-16	BHF6	3	15	71.4721	151.0802
BP	20-Sep-16	BHF6	4	16	71.4768	151.0775
BP	20-Sep-16	BHF6	5	17	71.4811	151.0748
MJ	20-Sep-16	BHF6	6	18	71.4856	151.0725
MJ	20-Sep-16	BHF6	7	19	71.4898	151.0682
MJ	20-Sep-16	BHF6	8	20	71.4941	151.06514
MJ	20-Sep-16	BHF6	9	21	71.4978	151.0621
MJ	20-Sep-16	BHF6	10	22	71.50361	151.059
MJ	20-Sep-16	BHF6	11	23	71.50795	151.05617
MJ	20-Sep-16	BHF6	12	24	71.51196	151.05286
MJ	20-Sep-16	BHF6	13	25	71.51627	151.05035
MJ	20-Sep-16	BHF6	14	26	71.52025	151.046897
MJ	20-Sep-16	BHF6	15	27	71.52495	151.04422
MJ	20-Sep-16	BHF6	16	28	71.52966	151.04196
MJ	20-Sep-16	BHF6	17	29	71.5338	151.03872
CPB	20-Sep-16	BHF6	18	30	71.538	151.034
CPB	20-Sep-16	BHF6	19	31	71.542	151.031
CPB	20-Sep-16	BHF6	20	32	71.546	151.027
CPB	20-Sep-16	BHF6	21	33	71.551	151.024
CPB	20-Sep-16	BHF6	22	34	71.555	151.02

Initial Thermal Gradient Results

We observe anomalously high apparent thermal gradients at the upper shelf edge, followed by anomalously low values from ~300-900 mbsl. Based on some preliminary 1D HF modeling and CTD/ocean temperature studies in the region, we attribute much of the shallow trends to seasonal/annual temperature changes, revealing significant (1-0.1 deg C) ocean temperature swings in the Beaufort Sea. Preliminary analysis of the data suggests some of the most severe temperature swing in the Beaufort Sea occur at depths where the hydrate stability zone pinches out at the seafloor. At depths greater than 900 mbsl we observe surprisingly high thermal gradient values that are very difficult to attribute to any ocean temperature swings based on mooring and published data in the US Beaufort (See papers by Pickart on this topic, as well as temperature mooring data he has collected in the region).



Plot showing USGS Seismic Line 767 and associated raw heat flow measurements along Transect 3. Red circles at top are preliminary thermal gradient measurements (negative values given so that we could merge the results with seismic data into a quick, but useful plot for comparison). The trend along Transect 3, showing high heat flow upslope, anomalously low apparent heat flow mid-slope followed by higher values again with depth is consistent with what we observe in Transects 1 &2. Importantly, these HF values represent rough, first-order estimates (no terrain correction or standard deviation in error assigned yet). Deeper values however are consistent with expected values derived from BSRs. Anomalously high values are observed closest to shore, which are related directly to seasonal ocean temperature change. This feature appears consistent throughout each transect.

Chirp data:

When transiting between stations, we collected chirp seismic data. Data collected along the upper margin are of high quality. The middle and lower margin chirp data are more difficult to interpret due to moderately steep slopes and out of plane reflections.

12 kHz Chirp Image Preliminary Data Results

We collected chirp data when transiting between HF site locations, and from this, pieced together several high-resolution shallow seismic images of the Beaufort Margin. Data along the upper part of the margin were of higher quality (steep slopes along the margin edge reduced signal return). Below is the combined seismic image for the upper feather edge of the margin for Transect 3. Here, less subsurface disruption of sediment is observed compared to Transects 1 & 2 at depths where the feather edge of the hydrate stability zone should exist.

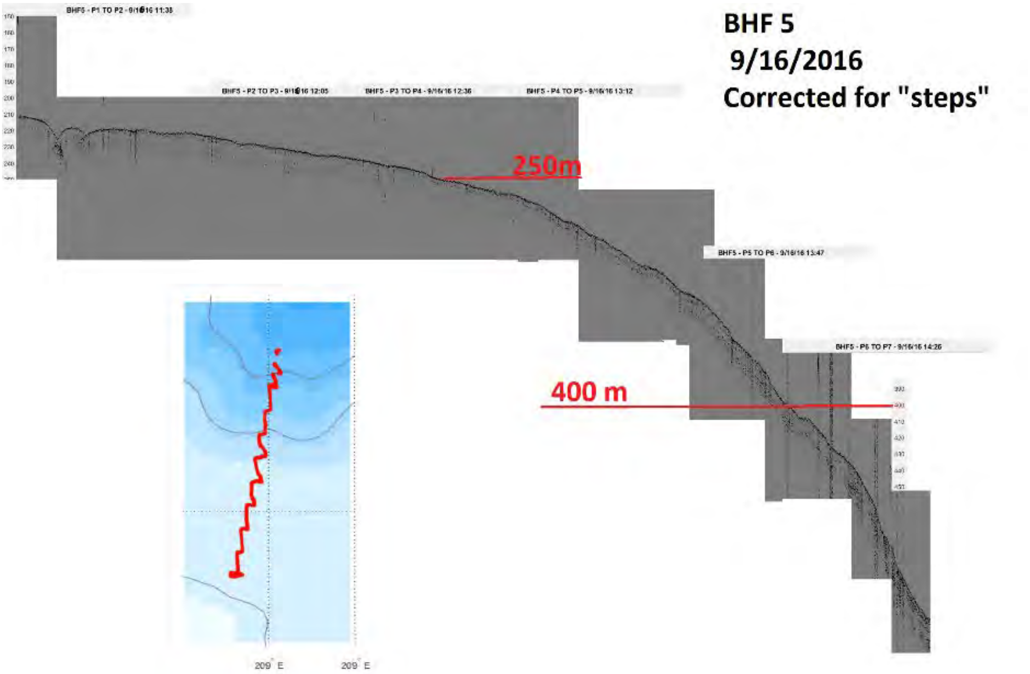


Figure above shows the approximate track line path in mapview (red line). Note that the zig-zag pattern is caused by the ship drifting onto the heat flow probe deployment stations. This drift allowed time for the probe, swinging on the cable below, to dampen out its pendulum-like motion, ensuring the probe dropped nearly vertical into the seafloor below. To correct for this zig-zag. We cut overlapping latitudinal values out of the chirp, and stitched the lines together from data collected between transits to each heat flow probe deployment site. Red depth bars on the chirp section show the approximate region where methane hydrate stability should pinch-out into the seafloor.

iv. Transect 4: Western US Beaufort Margin (Probe Deployments BHF7 & BHF8) (Coincident with USGS Seismic Line 773)

Objective of Transect 4:

The objectives of data collection along this transect are similar to Transects 1,2,3, and focuses on assessing how heat flow, ocean temperatures, and methane hydrate stability change laterally along the margin. Transect 3 reveals anomalously high heat flow values along the lower margin (> 900 mbsf) in the Western US Beaufort Sea. Transect 4 will help determine whether this high heat flow anomaly extends further west and is therefore widespread, or, alternatively, if what we observe in Transect 3 is an isolated, anomalous feature. Additionally, by acquiring closely spaced HF measurements downslope (with 250-500 m spacing at depth variations under 100 m), we hope to ascertain how ocean currents/temperature influence seafloor temperature boundary conditions with space and time at much higher spatial resolution than previous transects. With data collected at Transect 4, the total width of temperature transects will therefore span 500 km of the US Beaufort Margin. The analysis of heat flow along this transect, combined with other HF transects we collected along the margin edge, will be used to help constrain where methane hydrate stability intersects the sea floor.

Location:

Transect 4 follows the deeper northern half of USGS seismic profile 773. Heat Flow measurements from deployments BHF7 and BHF8 extend along a roughly a north-south profile parallel to 153.6 W, from 71.85 to 71.95 N. Transect 4 is approximately 100 km west of Transect 3 and >500 km west of Transect 1. Transect 4 is located approximately 100 km ENE of Point Barrow and 300 km WNW of Prudhoe Bay. Transect 4 is our Western-most Transect, and is located more than 500 km west of Transect 1, our most easterly transect.

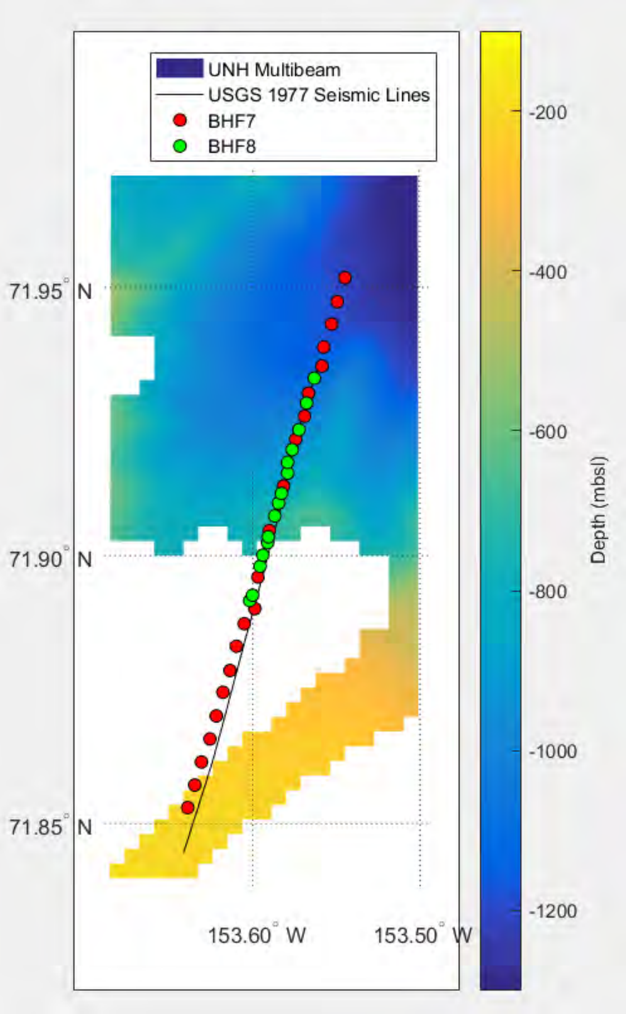


Figure 14: Location of HF probe deployments BHF7 and BHF8 on Transect 4. Black line show the approximate location of USGS Line 773 collected in 1977. Spacing between HF points ranged from 500 to 250 m.

Timing:

Data collection along this transect occurred from mid-day September 20th until approximately midnight on the 22nd local time (when the ship was required to pull gear and start steaming towards Nome), with total survey time for Transect 4 with round-the-clock deployments of approximately 30 hours.

Predominant Current/Wind During Data Collection:

The first few hours of day 1 of data collection at this site (i.e. Start of BHF 7) winds were 15-20 knots out of the SSW with a swell of 10-12 ft. However, the weather improved significantly throughout the day. By the time we completed BHF7, winds were light (<10 knots) with 2-3 ft seas. Sea state remained excellent for BHF8 deployment as well, with almost glass like conditions, light winds, and significant amount of ice on the water towards the end of the survey, reducing all waves to lake-like conditions. This significantly improved the speed and success of probe deployment and recovery.

Sea State/Ice Conditions During Data Collection:

As noted above, sea state continually improved throughout the survey, with the worst conditions at the beginning. Originally, there was concern that it may worsen and we would potentially have to pull the probe, however, weather conditions improved over the next day. By the time we deployed the system for the last time on Transect 4 (BHF8) at the site, we were starting to encounter significant amounts of first year and a little bit of second year (blue) ice scattered about (but nothing the ship couldn't maneuver easily around—no significant pack ice—just small amounts of floating ice—maybe 15-20% of the water covered with it). This ice greatly reduced the swell, damping all waves so that we had lake-like conditions for virtually all of the BHF8 deployment.

HF Probe Deployments Along Transect 4:

The probe was deployed 2 time on transect 4 (BHF 7 and BHF 8). BHF 7 provides regional HF coverage. We first collected BHF 7 with penetration station locations of 0.5 km, however, initial concerns about possibly developing wind and weather resulted in several penetrations of 1 km spacing, in an attempt to get broader coverage before weather shut-down operations. BHF 8, collected one day after BHF7, filled in gaps along the transect and allowed us to focus on locations of specific interest based on what we observed in data from BHF 7. HF penetration points on this line have the highest spatial resolution of the survey, with several penetration points at 250m spacing. BHF 7 has a total of 21 penetration points, and BHF 8 has a total of 15. Analysis of the data indicate the probe penetrated the seafloor at all 36 sites along Transect 4, a 100% success rate. This is again likely due to relatively soft sediment at this site compared to transects further east, as well as the fact that slopes were not as steep at this site compared to some of our eastern transects.

Data types acquired along BHF transect 4:

(1) Heat flow measurements/estimates from regional K along the margin.
(2) Temperature gradients along the upper and lower margin.
(3) Chirp (12 kHz) seismic data used to both communicate with the heat flow probe (in passive mode) and to image good spots for probe deployment (softer sediment environments), with an additional line extending up across the hydrate stability zone. (approximately 100 km, with depth penetration exceeding 20 m in several locations).
(4) Ocean temperature data collected from the probe being held, and transported within the water column during transits to each deployment site.
(5) Significant amounts of sediment recovery (4 cups for BHF 8 recovery, and ~2 cups for BHF 7) that will be used for XRD/thermal conductivity analysis.

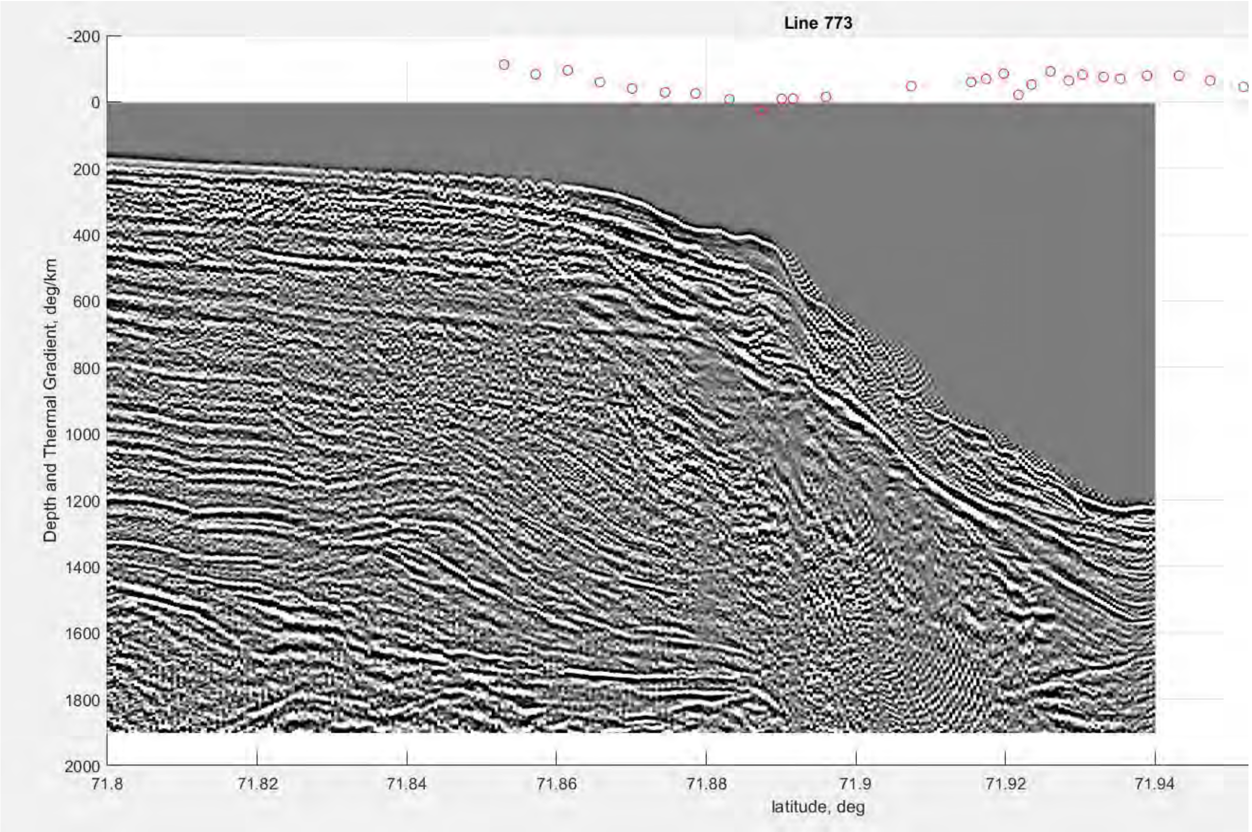
Transect 4 Preliminary Results:

Heat Flow Probe Penetration Location and Success Rate

Of the 36 HF probe penetration sites, all fully penetrated into the subsurface, providing usable data--a success rate of 100%, despite a few locations with very steep slopes. The Table below shows the approximate latitude and longitude of each station location. Depths are also reported for each station.

Date	BHF	Sites		Lat	Lon
20-Sep-16	BHF7	1	1	71.853	153.639

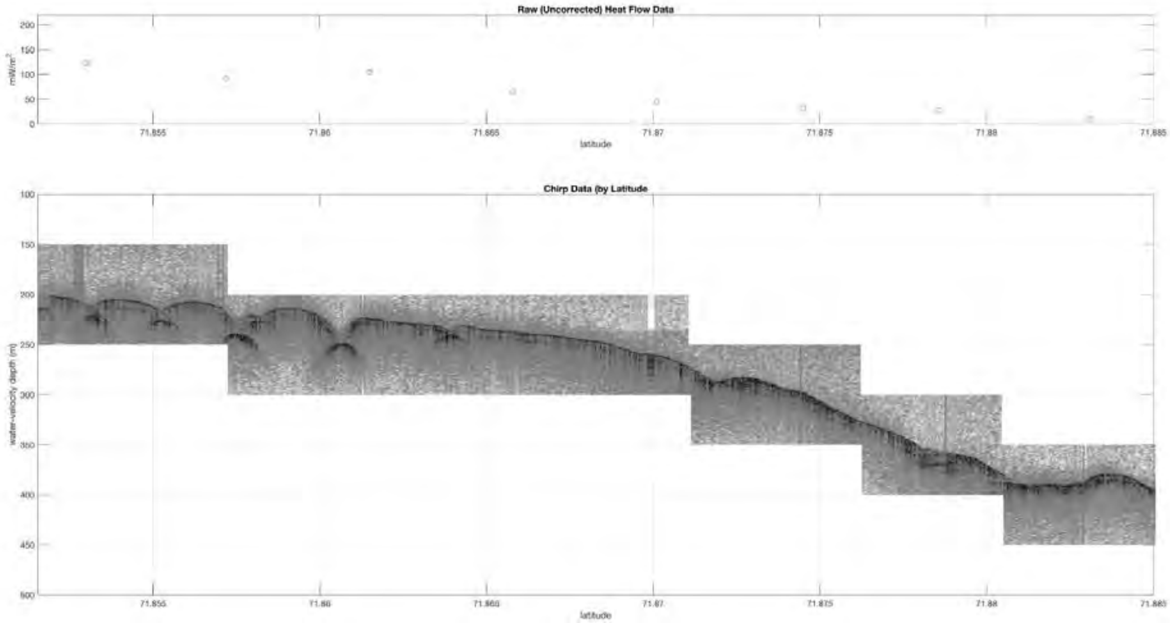
20-Sep-16	BHF7	2	2	71.8572	153.6348
21-Sep-16	BHF7	3	3	71.8615	153.6308
21-Sep-16	BHF7	4	4	71.8658	153.6257
21-Sep-16	BHF7	5	5	71.8701	153.6219
21-Sep-16	BHF7	6	6	71.8745	153.6179
21-Sep-16	BHF7	7	7	71.87857	153.61371
21-Sep-16	BHF7	8	8	71.8831	153.6099
21-Sep-16	BHF7	9	9	71.8873	153.6052
21-Sep-16	BHF7	10	10	71.89602	153.59699
21-Sep-16	BHF7	11	A	71.8901	153.59883
21-Sep-16	BHF7	12	11	71.90467	153.590107
21-Sep-16	BHF7	13	12	71.91297	153.581673
21-Sep-16	BHF7	14	13	71.92173	153.574285
21-Sep-16	BHF7	15	14	71.93028	153.566597
21-Sep-16	BHF7	16	15	71.9389	153.5575
21-Sep-16	BHF7	17	16	71.94318	153.552763
21-Sep-16	BHF7	18	17	71.94735	153.54933
21-Sep-16	BHF7	19	18	71.9518	153.544668
21-Sep-16	BHF7	20	19	71.93534	153.55851
21-Sep-16	BHF7	21	20	71.926	153.569
21-Sep-16	BHF8	1	2	71.8916	153.6019
21-Sep-16	BHF8	2	3	71.8926	153.6002
21-Sep-16	BHF8	3	4	71.898	153.5957
22-Sep-16	BHF8	4	5	71.9001	153.5941
22-Sep-16	BHF8	5	6	71.9024	153.5912
22-Sep-16	BHF8	6	7	71.9035	153.5908
22-Sep-16	BHF8	7	8	71.9074	153.5869
22-Sep-16	BHF8	8	9	71.9098	153.5846
22-Sep-16	BHF8	9	10	71.9116	153.5829
22-Sep-16	BHF8	10	11	71.9154	153.5792
22-Sep-16	BHF8	11	12	71.9174	153.5792
22-Sep-16	BHF8	12	13	71.91975	153.576417
22-Sep-16	BHF8	13	14	71.92347	153.57237
22-Sep-16	BHF8	14	15	71.92844	153.567812
22-Sep-16	BHF8	15	16	71.9331	153.56315



Plot showing USGS Seismic Line 773 and several associated raw heat flow measurements along Transect 4. Red circles at top are preliminary thermal gradient measurements (negative values given so that we could merge the results with seismic data into a quick, but useful plot for comparison). The trend along Transect 4 showing high heat flow upslope, anomalously low apparent heat flow mid-slope followed by higher values again with depth is consistent with what we observe in Transects 1 &2 & 3. Importantly, these HF values represent rough, first-order estimates (no terrain correction or standard deviation in error assigned yet). Deeper values however are consistent with expected values derived from BSRs. Anomalously high values are observed closest to shore, which are likely associated with seasonal ocean temperature change. This feature appears consistent throughout each transect.

Chirp data:

When transiting between stations, we collected 12 kHz chirp data. By stitching the images together between transits, we have been able to make shallowly penetrating seismic profiles along the Transect. The 12 kHz data did a remarkably good job penetrating into the subsurface, and often provided subsurface seismic reflections at depths of ~20 mbsf. The chirp was invaluable at showing where soft sediments likely exist in the subsurface, and the steepness of the slopes at locations where we considered probe deployment. The slope at 773 were generally less steep compared to several other sites (especially Transect 2), however, there is clear evidence for slumping, slope failure, and the accumulation and ponding of sedimentary drape in the subsurface along the profile. There is also clear evidence for pockmarks or faulting in the shallowest sections of the profile.



Raw (uncorrected) heat flow values (top) near the pinch-out of hydrate stability, with raw (unfiltered, no-traces-killed) chirp data running parallel to USGS line 773.

VIII. Daily Cruise Log

All times local (AKDT) unless otherwise noted.

Tuesday, September 6th, 2016

Brokaw, Jones, Hornbach depart at 3:15 pm CDT from DFW airport to Anchorage on American Airlines flight 2571, and arrive at approx. 7 pm Anchorage time. Harris and Phrampus arrive earlier from Portland. To save on room/board costs, we rented dorm rooms at Alaska Pacific University, approximately 5 miles east of downtown Anchorage. Weather in Anchorage is nice—55 deg. F, partly cloudy—we'll need similar weather or better to make the flight to Wainwright, where we will board the ship in another day. The ship we will use for this study, the M/V Norseman II, is currently steaming from Nome, Alaska--where it loaded heat flow probe and chirp gear--toward Wainwright, Alaska, where we will mobilize and board on Thursday, weather permitting.

Wednesday, September, 7th, 2016

8:30 pick up from Casey Pape, who drove the science party to Fairweather Science to walk through the flight plan for tomorrow to Wainwright, safety procedures on the ship, and plan of action for deployment and recovery of all scientific instruments on the vessel. The meeting lasted for approximately 7 hours and involved collection, fitting, and preparing of all mustang suits, hard-hats, gloves, boots, and other safety equipment outfitting (discussion of wet-weather tools and exterior protection needed for deploying gear). Last minute items were purchased for going to sea. The plan tomorrow is to leave for the airport at 6 am, and take a 2.5 hour flight to Wainwright with all 5 of the science part as well as two from Fairweather science (Casey and Sheyna). Once in Wainwright, depending on the wind direction, we will board a transfer vessel either in the lagoon east of Wainwright (west wind), or along the beachhead east of Wainwright (east wind). We will spend the first 2-3 hours either in a calm bay, or find a nearby protected bay to unload, construct and mobilize the heat flow and chirp gear. Once completed, we will begin steaming to towards our first waypoint north of Barrow. Day 1 of the 10 day science cruise therefore begins the morning of Friday, September 9th.

Shifts were outlined today during dinner. All students/postdocs have staggered 8 hour shifts; Rob and Matt have 12 hour shifts. The student
8 hour shifts consist of the following:

- Madie--8 pm to 4 am
- Casey--4 am to 12 pm
- Ben-- 12 pm to 8 pm.

Rob and Matt's shift has yet to be decided, but it will require someone (ideally both) available for morning meetings with crew and land.

Thursday, September 8th, 2016

The day began with a 5 am wake-up this morning to prepare for flight. Case Pape met us at 6 am with the Fairweather Truck to take us to the airport. We arrived at the airport by 6:45, and began calling into the ship and ground personnel in Wainwright to determine if seas were steady and landing was clear.

Initial discussion on the phone with personnel in Wainwright indicated the weather was poor with low visibility, light drizzle, and significant fog. Additionally, the sea state was poor, with breakers on the beach east of Wainwright making a beach landing for a transport boat almost impossible. Wainwright has no protected harbor, however, the town is on a spit with a lagoon to the east and the open Arctic to the west. If a strong westerly wind exists, the lagoon can fill and can therefore be used as a safe location to board a transport vessel to the Norseman II. Unfortunately, the wind not out of the west, resulting in only a few inches of water in the lagoon, so no lagoon transport would be possible. After waiting at the airport for a couple hours and observing only further degradation in weather conditions, we (Hornbach and Harris, and Fairweather science staff, Casey and Sheyna) agreed it would be best to wait a day and hope for improved weather conditions instead of risking a potentially unsafe landing or boat transport in Wainwright. In hindsight, this was a good decision, as web cams located in Wainwright combined with continuing discussions with shipboard officers revealed that the weather only further deteriorated during the day, with sustained 20 knot winds that would have made any beach landing for a transport vessel impossible.

With the flight delayed a day, we spent much of the rest of the day working through heat flow probe station timing and logistics. We have now organized and estimate steam-times to our first heat flow transect, and outlined all of the site locations using the limited sidescan sonar data for the region, made available from UNH's Law of the Sea data collected in the Arctic during the past few years (Larry Meyer's group). These data indicate that the Barrow Canyon is likely very hard bottomed and should be avoided, so we set our first transect line just east of this Canyon, working from ~1700 mbsf up to ~200 mbsf, in a region an area where seafloor pockmarks are observed at water depths above ~350 mbsf. We have also used the backscatter data to determine which transect locations are likely to have the softest bottom, which should help increase the chances of probe penetration into the seafloor. In general, the areas in the western half of the Beaufort have less back scatter than to the east, suggesting softer sediment in the west, however, there is some evidence that this may also be the result of more topography along some of the canyons in the east (resulting in more scatter and signal loss, and therefore, not necessarily an indicator of bottom strength). Based on these observations, after we complete transect 1 located west of the Barrow canyon and through the pockmarks, we intend to collect heat flow data
~40 km east, near seismic lines 773 and 767, where backscatter is low and BSRs are clearly visible in seismic lines.

Tomorrow morning we have a planned conference call beginning at 6:30 in the morning to determine if weather conditions have improved in Wainwright and if we can therefore proceed to the ship.

(Note: See also Blog Post 1 by Madie Jones dated Sept. 8)

Friday, September 9th, 2016

The 6:30 am conference call was held with the ship's Captain, ground support in Wainwright, Fairweather personnel in Anchorage, and the science party. Initial discussions and webcam images of the runway confirmed that visibility was still very poor in Wainwright (less than a quarter mile visibility with heavy fog).

Additionally, sea state was still too rough for a beach landing to transport scientists and gear onto the ship. We decided to reconvene at 8:30 and check for additional updates. The 8:30 call proved much the same, with no clear improvement in weather. We remained on call until noon, when we held a 3rd conference call discussing weather and options. The weather by noon had still not improved in Wainwright; furthermore the forecast was now calling for snow and continued heavy seas, making any aircraft or beach landing problematic. In fact, the dirt runway at Wainwright had been closed for the past two days now, and weather predictions suggested this may be the case for the next several days. With no clear change in the weather in sight, we began discussions with the possibility of moving the ship to a different port call location where there would be less uncertainty in boarding the boat or landing the aircraft. By 6 pm, logistics had been worked out that the Norseman II would sail to Prudhoe Bay, with arrangements for possible boat transfer and the possibility of commercial air traffic to Prudhoe that would be more reliable for landing even in bad weather as they have radar/instrument landing capabilities. By 8 pm, we had secured a transfer vessel that would be available to transfer the science party to the ship (which has to moor offshore due to shallow water). The ship has begun steaming to Prudhoe and will arrive by Sunday afternoon/evening. Fairweather is currently in the process of booking flights on Alaska Airlines for Sunday morning.

Saturday, September 10th, 2016

The ship has nearly reached Prudhoe Bay, and Sheyna spent the morning purchasing tickets so that we now fly out tomorrow on a morning flight to Prudhoe around 7:45 am. As we will now sail out of Prudhoe, much of the morning was spent reorganizing the transect timing and locations to start with the eastern-most lines and progress westward, with the plan to finish up just north of Barrow along a pockmark field near the shelf edge. The first line scheduled for surveying is a transect along USGS seismic line 730, where we have ~30 station points planned. Steam time to the first transect line is approximately 12-13 hours from Prudhoe bay, assuming ship speed of ~9 knots.

After reorganizing the ship track in the morning, we spent the afternoon washing laundry and cleaning gear, in preparation for our departure to the ship. The facilities at Alaska Pacific have been a bit Spartan (empty doom rooms upon which we threw our sleeping bags kindly provided by Fairweather), but have been convenient and very inexpensive ($30 per person per night). In the late afternoon, Jones, Phrampus, and Hornbach went for a 5 hour hike up Wolverine Mountain, and then returned back to town for dinner and to pack up for the early (5 am wake-up) morning departure for the airport.

Sunday, September 11th, 2016

Water Depth:	4.2 m
Latitude:	70 26.275’ N
Longitude:	148 32.476’ W
Wind: NE	~9 knots

Today we boarded the vessel. The day started with a 5 am wake-up, followed by a trip to the airport. We flew on Alaskan Airlines flight 55, leaving at 7:45 am, and arriving at Prudhoe at ~9:10 am. Flight was nice and easy, and despite heavy cloud cover most of the way, we were able to see the Brooks Range near the end of the flight. Once in Prudhoe, we travelled via company truck to a launch boat. The Norseman II was heaved to ~2.7 miles north of Prudhoe Bay, so we took a launch to the ship at approximately 10:30 am, arriving on the vessel at 11 am. Once aboard, we went through safety protocols, quickly ate lunch and then began unloading and securing gear. Given that the ship's crane needed to be used to secure both the Chirp and the heat flow probe, we decided to keep the anchor down until all equipment had been pieced together.

Some concerns raised on the ship in the first few hours regarding heat flow measurements:

(1) The line for deploying the heat flow is made of Kevlar (Spectra), however, we are concerned that it or the chirp probe system attached above the heat flow probe (rented from the University of Washington) will chafe the line easily. One possible solution was to add a 100 ft leader to the Spectra line, however, this was quickly nixed due to the block over the A-frame being specifically designed for the line, with a metal wire potentially scraping the block, and therefore scraping the Spectra. The alternative solution we will try first is to attached the heat flow probe directly to the Spectra, and add a loop with chafing gear 50 m above the heat flow probe so that we can also attach the UW 12 kHz pinger.

(2) The winch doesn't have a high precision tensiometer available, making it difficult for us to determine when the probe has hit bottom. We ran several tests with the winch where we monitored the hydraulic pressure on the winch to determine if any spikes occurred during bottom contact or pull-up. We found that that there is a clearly detectable increase in hydraulic pressure when the winch is pulling a weight off the bottom and that a small (but apparently perceptible) increase in pressure occurs when we hit bottom, as the pneumatic winch applies back pressure to the wheel when the weight drops. The hope is that we will be able to detect this change in pressure clearly, even if it is subtle, in deep water.

(3) The pinger sent by UW requires 16 D cells, however, they only supplied 12, and two of these were broken in shipping. The ship luckily had purchased more so that we could continue to use the pinger. It appears the ship has an additional box of D cells as well in case the pinger goes down—very lucky, and we're glad the crew noticed this problem.

We have mounted the chirp system to a steel pole running along the port side of the vessel. Fugro currently has a sidescan sonar system mounted on this pole, so the chief and bosun have used some ingenuity to build a very nice side brace that allows us to mount the our 6 ft long, 2" diameter, chirp pole and mount system onto the 4-inch diameter pipe. This pipe is levered out of the water during transit, but can be deployed by swinging the entire pipe downward by lowering it form the crane. The chirp was secured to this pole with stainless steel bolts, with rubberized chaffing gear applied to locations where the chirp might rub against any sharp edge on the pole. Because we were in shallow water, we were unable to deploy the chirp pole, and will do so once we are at our first heat flow site. We did however test the chirp, and it is function properly. Tonight we sail to our first waypoint on heat flow transect 1, located at the seaward end of seismic line 730: Latitude 70.816 N, Longitude 142.515 W.

For senior level shifts, Rob will work 8 am to 8 pm, Matt will work from 8 pm to 8 am.

Based on discussions and email with Sheyna and folks, the research clock for the 10 day science cruise begins tomorrow (September 12). Expected arrival time on site is ~12:30 pm tomorrow. The first transect will follow USGS seismic line 730.

Figure 15: Jim Wells, the Bosun, Securing the 12/200 kHz Knudsen Chirp system to pole on the port beam. This pole was then lowered into the water, where the chirp system could listen in passive mode to the heat flow probe transmitting temperature, location, and tilt information via different pinger signals.

(Note: See also Blog Post 2 by Madie Jones dated Sept. 11)

Monday, September 12th, 2016. (Day 1 of science)

Morning readings
Water depth= ~1500
Wind= ~15-20 knts, from NE.
Seas= 4-6 ft

8:00 am

8 am science and safety meeting held, where we discussed procedures for deployment once on site around noon. Went through some of the waypoints given to the bridge yesterday and described procedures for deployment. Initial waypoints provided below. All are along seismic line 730.

Table 2: Initial waypoints. All are along seismic line 730.

Latitude	Longitude	Waypoint Number
70.816	-142.515	1
70.8070475	-142.5151475	2
70.798095	-142.5152951	3
70.7891425	-142.5154426	4
70.78019001	-142.5155901	5
70.77123751	-142.5157377	6
70.76228501	-142.5158852	7
70.75333251	-142.5160327	8
70.74438001	-142.5161803	9
70.73542751	-142.5163278	10

70.72647501	-142.5164753	11
70.71752252	-142.5166228	12
70.70857002	-142.5167704	13
70.69961752	-142.5169179	14
70.69066502	-142.5170654	15
70.68171252	-142.517213	16
70.67276002	-142.5173605	17
70.66380752	-142.517508	18
70.65485503	-142.5176556	19
70.64590253	-142.5178031	20
70.63695003	-142.5179506	21
70.62799753	-142.5180982	22
70.61904503	-142.5182457	23
70.61009253	-142.5183932	24
70.60114003	-142.5185408	25
70.59218753	-142.5186883	26
70.58323504	-142.5188358	27
70.57428254	-142.5189834	28
70.56533004	-142.5191309	29
70.55637754	-142.5192784	30

12:00 pm

Deployed chirp in the water at noon local in ~1490 m water depth. Chirp could detect sea bottom with 12 kHz very well.

2:50 pm

Heat flow probe deployed at 2:50 pm local with 12 kHz UW pinger located 50 m above the line. First Transect line is called BHF1. Dropped probe to 100 m off the bottom and looked for pinger signal and seafloor reflection using passive mode for the Knudsen. We found that the UW pinger signal was especially weak. We could see the direct arrival of the UW pinger, but not the reflection off the bottom. As a result, we wouldn’t know for sure if we had hit bottom unless the pinger also hit bottom as well, since the line is only neutrally buoyant when it feels no weight. As a result, we decided to retrieve the pinger and remove it from the line, since it couldn’t be used to detect bottom and could impact the probe if we pay out too much line. Instead, we intend to drop line until we see that the probe temperature spikes (which it transmits every 10 seconds) and to pay close attention to the buoyancy on the line. During the rest of the day, we averaged 1 HF point an hour, and had completed the 6 deepest measurements along the first transect line.

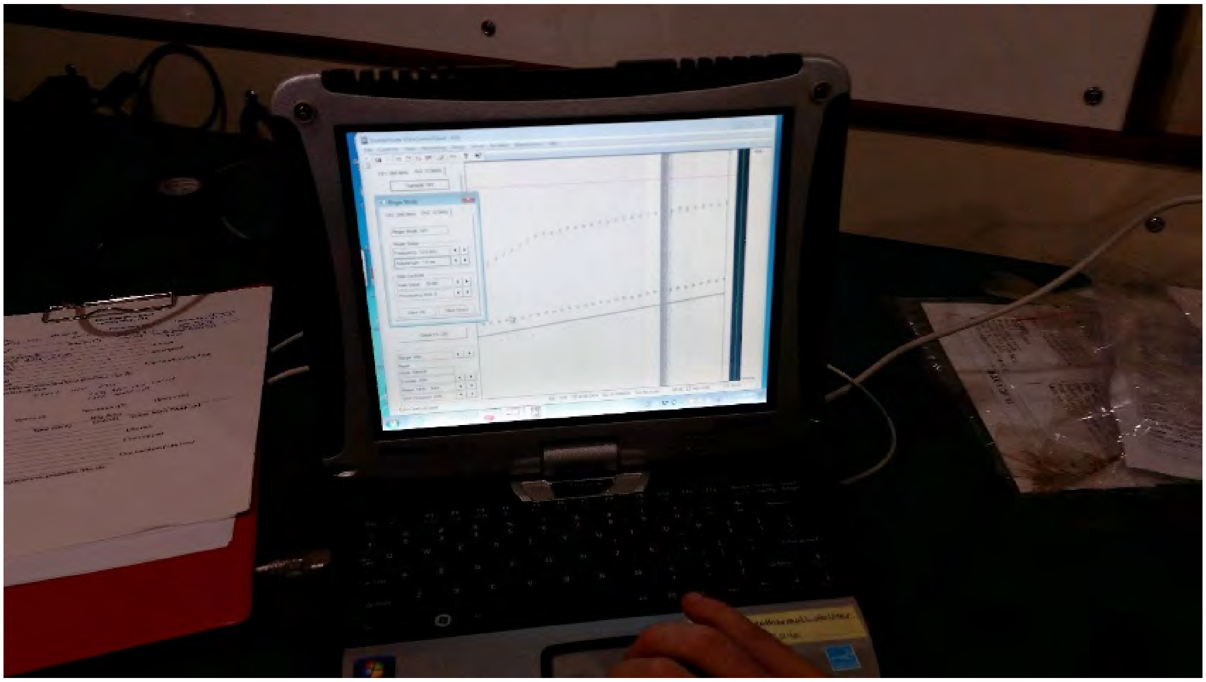


Figure 16: In picture above, the solid line getting shallower from left to right is the UW pinger signal. For some reason this signal was too weak to observe at depths shallower than a few hundred meters, so we removed this pinger and used the pinger on the HF probe as a tool to detect probe location and depth.

Tuesday, September 13, 2016 (Day 2 of science)

12:00 pm

Noon readings
Water depth = ~1000 m
Wind= ~18 knots, from ENE.
Seas= 4-6 ft.
Latitude: 70 40.183' N
Longitude: 142 15.413' W
Seismic line following: USGS 1977 line 730

11:40 am – 2:00 pm

Pulled probe up after collecting BHF1 no. 16. Probe was on deck by 11:40 am, with recharge of system starting soon after (well need 8 hours for full recharge). Data were downloaded with preliminary heat flow and temperatures estimated made by 2 pm. Values range from 30 mW/m^2 to 95 mW/m^2, with higher values generally landward.

3:00 pm

At 3 pm local we surveyed briefly an odd seafloor feature between BHF1 14 and BHF1 15. It initially looked like a methane seep, but later appeared to be side-swipe associated with a deep channel incision. After this, we pulled up the chirp to eliminate some of the rattling on the line, and began to steam towards BHF1 16, where we obtained our last HF value.

4:00 pm

We moved back along the line south, towards, BHF1 no. 16, where we redeployed the chirp, with the goal of collecting chirp seismic data along the rest of profiles with less ship and heat flow probe chirper noise.

5:00 pm

We checked the charge on the heat flow probe and found that the apparent voltage was dropping instead of increasing. We tested the charger cable and the pin head on probe and found the voltage at 3.9 V instead of the expected 6 volts. The charger unit was supplying the right voltage, so the issue has something to do with the probe. We decided to reconnect the charger for 1 more hour since the connection may have been loose (however, why it might drain the probe voltage is unclear). During that hour we extended the chirp profile up slope so that we had a complete line running up to the shelf. Chirp 12 kHz data were surprisingly high quality, with depth penetration of more than 20 m. We saw continuous strata from about 600 to 400 m, however at depths of ~350 m or more, subsurface sediments appear heavily disturbed and disrupted, and deformation beginning very close to our estimated depth of hydrate stability of ~270 m.

6:30 pm

We extended the chirp line another ~10 km landward, so that we could give more time to charge the heat flow probe. The chirp line extends to the shelf, and was ended around 70 m water depth. We cut this line short because Rob was able to determine that the batteries on the heat flow probe were in fact properly charged—he did this by removing the data logger from the heat flow probe and testing the voltage directly on the battery, which showed it was fully charged). This is a strange observation, since the voltage across the pinout for the probe suggests much lower voltage, yet the batter clearly has higher potential. Our current hypothesis is that the charging pin on the heat flow probe, or the cable connecting it, has a loose connection, or is perhaps bare and touching another element in the connection, resulting in a wonky read. For now, however, our plan is to simply remove the data logger each time we need to recharge, to make sure we are properly charging the battery to its full potential between each heat flow probe deployment. With direct voltage measurements on the battery indicating it is fully charged, we set course for our next heat flow point location, we pulled in the chirp, and set course to fill gaps in heat flow where we observed anomalously high values based on the BHF1 results.

8:30 pm

Steaming began at 8:30 pm local. Next deployment of the probe is along BHF2, station #1, located at 70.7134 N, 142. 5193. This deployment will fill gaps in some of the data collected and initially analyzed on deck.

10:08 pm

Arrived on station for BHF2, insertion point 1, at 10:08 pm.

11:20 pm

HF Probe dropped to bottom at 11:20 pm. The probe is currently unable to fire a heat pulse. We tested the pressure trigger before launching and the heat pulse was non-functional before deployment. This means we will be able to collect temperature data, but will not be able to collect thermal conductivity at each site until we bring the probe back up and fix the problem. The good news is that the thermal conductivity measured at the other sites appears nearly constant, hovering between 1.1-1.3mW/mK—values consistent with weighted average equations for sediments collected in the Beaufort, and from what Ben derived for his initial heat flow model.

12:00 am (September 14)

At midnight, the seas dropped significantly, with winds of only 9 knots, making station holding much better, and allowing for much more consistent line payout (where the drivers payout line between 60-100 m/min, but must break it during free-fall to achieve this, since the winch cannot payout faster than 44 m/min without allowing controlled freefall. High pressure is forecast for tomorrow, before winds start to pick up again after. Our hope is to fully complete this line and be in transit by the end of tomorrow before the weather picks-up.

Wednesday, September 14, 2016 (Day 3 of science)

12:00 am

At 12 am, Winds dropping nicely holding around 7 knots, with pressure rising.
Water depths ~900 m.
Seas down to 2 ft.
Heading to first drop of BHF2.

Continuing to collect data on seismic line 730 with fill-in and shallower depths the key targets.

4:00 am

Pinger stops working on 5th site of deployment for BHF2. Appears to have penetrated mud when we lost signal. Once recovery began, and we pulled it out of the mud, however, signal returned. This signal then faded and disappeared later when we arrived at the 5th site. We brought up the probe to the surface and heard no pinging, so we then decided to bring it on deck to check pinger batteries. Voltage was at 4.6 along the battery string when it should have been at 6. Once on deck, we replaced all pinger batteries on the HF probe.

5:00 am

Preparing for redeployment, we noticed a fray in the line for deploying the pinger: approximately 5 feet above the pinger, several strands of line appeared frayed. Close inspection shows that 3 of the 13 strands had been lost on the HF probe deployment line. We immediately decided that we needed to remove the damaged line and splice a new loop into the line above the fray. It is unclear how the fray occurred. Possibilities include rubbing of the line against the fantail during deployment or recovery, rubbing of the line against the probe during recovery, or perhaps those working on the deck stepping on the line. Regardless, we have worked to identify any locations on the probe where rough edges might fray the line if it were to contact it. We also noted the important of keeping line off the stern, and minimizing the chances that the line comes into contact with stern of the vessel during deployment. The line is quite strong but also appears very easy to cut and fray, and there remains concerns about this.

6:05 am

We deployed the probe for the 3rd time (BHF3) on the transect following seismic line 730, at the site of original waypoint 17. Continue to collect heat flow minus the thermal conductivity measurement.

8:00 am

We discussed water depths for ending heat flow probes for this track (~250 m, just above the hydrate stability zone), and also discussed the location of the next profile given some of the delays and the likely onset of poor weather in the coming days. We determined that the best course of action was to drop two other profiles where we might collect data and instead, move further west to ensure we had better broader basin-wide coverage of regional heat flow.

3:00 pm

Nearly complete with line. Water depths of 279, nearly on top of fresh-water hydrate stability zone for the margin edge. Seas are glassy, wind 1.8 knots. HF probe pinger functioning well minus thermal conductivity tool. ~34 measurements made, of which ~30 appear usable.

Waypoints for the next line are below. We have canceled two other lines. Additionally, the margin is steeper in this area, so we anticipate collecting few measurements (~12). Ideally, if we continue at the same rate with no other snafus, we suspect the line should only take about 14 hours to complete. Steam time is ~13 hours, but of course depends on current and wind.

Table 3: Next set of Waypoints following seismic line 753 (the next profile)

Latitude	Longitude	Waypoint (# may be flipped depending on current)
71.194	-148.702	1
71.20201	-148.69	2
71.21003	-148.677	3
71.21804	-148.665	4
71.22605	-148.652	5
71.23406	-148.64	6
71.24208	-148.628	7
71.25009	-148.615	8
71.2581	-148.603	9
71.26612	-148.59	10
71.27413	-148.578	11
71.28214	-148.565	12

4:40 pm

Heat flow probe on deck. Probe is coated in mud so that water couldn't leak out of the top of the probe (mud was a virtually perfect seal. Appears we may have buried it on our very last (shallowest) deployment on BHF3, penetration 14, waypoint 31, at a depth of 205-215 mbsl. Significant mud was collected along the probe edge that we saved and put in the reefer. The mud was extremely fine grained (like potting clay). We preserved at least 2 cups of it in a Ziploc bag, and should be able to use the mud as an additional reference for shallow thermal conductivity, by applying a needle probe to it back at SMU.

4:50 pm

The pinger used for chirp listening and mounted on the pole was pulled up and secured.

4:55 pm

All data collection on our first transect complete (USGS line 730). We are steaming for the start of the next transect line (USGS line 753), with an ETA of ~12 hours (7 am on Thursday). We will have a brief man overboard drill scheduled for 8 pm local during the shift change, so there will be a brief stop during transit.

5:30 pm

Removed the data recorder from the HF probe and tried to reevaluate why the battery charger is non-functional. After reconnecting all of the power supply plugs both inside and outside the data recorder, the charger appeared to be working normally, suggesting a looks connection somewhere between one of the power supply lines. After performing a wire test where we supplied power externally and tracked each connection internally within the data logger, we were unable to determine where the loose connection existed, but it appears gone (for now).

We also worked through the connections on the pressure detector, which Rob had recently replaced (the older one had also broken). After testing all of the power supply lines, we determined that the problem with the pressure sensor was not a loose connection, but instead appeared related to either the pressure detector itself not sending data, or the computer card associated with the pressure detector, as the power supply wires seemed to work properly, and the data lines running from the board out through the data logger and into the pressure detector, when we measured resistance across them, appeared to also function properly. The key conclusion from this analysis is that the pressure detector (which supplies the timing for when the heat pulse fires) will likely be non-function for the rest of the cruise, and therefore, we will not likely have any additional measurements for thermal conductivity. The good news, however, is that of the measurements we did have for thermal conductivity, all were nearly constant. Furthermore, the conductivity values obtained from the probe are virtually identical to those estimated using both empirical relationships and theoretical values derived from the geometric mean of the sediment mineralogy. Additionally, by collecting mud samples from the logger, there are ways for us to estimate additional thermal conductivity by simply looking at sediment mineralogy back home or measuring it with the needle probe.

7:30 pm

While breaking down the data logger, we had Maddie and Ben start working through the chirp reflections, organizing and backing up all data collected for the last profile. Casey has completed a write-up and diagram for the Heat flow Probe system, including the basic explanation of how the system works.

7:40 pm

Conducted man overboard drill. The ship comes about surprisingly well, when needed. Fun to watch the crew in action on this.

8:00 pm

Man overboard drill completed and underway again for transect 2.

8:30 pm

Discuss with Captain Mike the path forward given the uncertainty in weather. We both agree that if things work smoothly, we should be able to complete 12 stations on the next transect before sea states likely become too poor for deployment or recovery. We will play by ear, however.

9:00 pm

Finished rebuilding the data logger and reconnected it to the thermistor string. Brought the thermistor string on deck, and reconnected it to the heat flow probe.

9:10 pm

Connected charger to the data logger batteries. Data log battery charge was at 5.7 V. Full charge is 6 V. Charge should be complete in 8 hours (5 am tomorrow).

10:00 pm

Downloaded and viewed initial cut of all HF data on the line. Some big surprises! Data are quite high quality, even in the upper few hundred meters. Probe penetration was excellent. Some of the data show clear seasonal bottom water changes that we need to account for. Shallowest measurement shows exceptionally high heat flow—very strange….

11: 55 pm

Darren, the assistant cook, provides the lab with some really damn good home-made burritos, as we process/reduce the data from first transect, and complete writing initial draft of cruise report for first profile.

Thursday, September 15, 2016 (Day 4 of science)

12:00 am

At 12 am, Winds strengthening to 10 knots.
Water depths ~240 m.
Seas at 3 ft.
Heading to second transect on line 753, BHF4.

4:00 am

Developed script with Madie showing transect one HF deployment locations and chirp profiles along the transect that will be used for final cruise report. Casey nearly complete with HF probe description and spec sheet for report.

8:00 am

Morning meeting and weather briefing. Poor conditions predicted by late weekend that could possible halt data collection. Will begin deployment of probe in approximately 1.5 hours for transect 2 that has 12 site locations. Without the pressure detector functional, we can take temperature depth reading only, and this will reduce bottom-hole time to ~7 minutes instead of 15, so this should help accelerate measurements. Will work to recover mud samples off core if probe comes on deck. As conductivity changes appear marginal, temperature depth values should still be quite valuable for heat flow estimation.

8:15 am

Short on battery charger for data logger appears back, with 4.7 V noted on the charger despite knowing the interval voltage is at least 5.7 V from yesterday's readings. For now, we are leaving as is, since we know from yesterday evening that the system was charging normally and holding a voltage of at least 5.7 V.

8:45 am

Passed over waypoint 1 and decided no deployment here as it was too shallow (~100 m); progressed to next waypoint.

9:00 am

Probe deployed in water at 1800 UTM, deployment begin for waypoint 2 of transect 2.

12:00 pm

Running smoothly, with evidence for good probe penetration based on chirp pings sent back to ship, and this despite steeper slopes than the previous line.

5:00 pm

Completed ~10 stations along transect 2. Making excellent time, and starting to make up for lost time during first 2 days.

5:30 pm

Provided the bridge with next set of HF probe waystations, all located along seismic line 767, which will be our 3rd transect. Currently, the transect has 19 proposed HF waypoints, at ~1 km spacing. Proposed station locations for transect 3 are listed below.

Table 4: Proposed Transect 3 stations (for deployment BHF5)

Latitude	Longitude	Station
71.37586	-151.14	1
71.38463	-151.134	2
71.39341	-151.129	3
71.40218	-151.123	4
71.41095	-151.117	5
71.41972	-151.113	6
71.4285	-151.106	7

71.43727	-151.101	8
71.44604	-151.095	9
71.45481	-151.089	10
71.46359	-151.084	11
71.47236	-151.078	12
71.48113	-151.073	13
71.4899	-151.067	14
71.49868	-151.061	15
71.50745	-151.056	16
71.51622	-151.05	17
71.52499	-151.044	18
71.53377	-151.039	19

6:00 pm

Probe at HF Station 11 on BHF4 likely tipped over, so we pulled the probe off the bottom (lost pinger communication with probe), and moved to last station. For station 11, we suspect the probe likely tipped over as the seafloor is exceedingly steep in this area, and both the ship's sounder, and the chirp sounder show very steep, chaotic bottom reflections. Based on observations of seismic line 753, the deeper section of Transect 2 may be over a slide feature. So it will be valuable to compare how the BSR HF compares with the surface heat flow, as this could provide some insight into recent dynamics on the margin at this site.

6:45 pm

Probe tipped over on last deployment. Slope still steep. Probe indicates if tipped over at final site location showing no temperature change and a loss in tilt meter sensor. Pulling up the probe to the surface as this was the last waypoint for this transect. Equipment will be on deck shortly.

7:45 pm

Probe on deck, pinger removed from the probe. Tranducer Pole with chirp coming up along the port waste. A quick look over of the heat flow probe indicates all features look good. The thermistor string is looser than when we deployed it. There was very little mud on the probe. Total mud recovery was from the side of the probe lance, consisting of very fine, dense mud. Small sample (1/4 cup) taken from the probe, and labelled "Transect 2" BHF4 sample. Some minor chaffing on the spectra line approximately 2 ft above its connection to the probe. To help further avoid additional chaffing, we are adding a heavy 2-foot section of braided cable leader that we will attach to the HF probe so that there is less of chance of chaffing between the braided spectra line and the HF prove. Crew has done a nice job of recovering the probe efficiently and safely.

7:55 pm

Steaming towards transect 3, where USGS seismic line 767 was shot.

8:00 pm

Changing out pinger batteries in HF probe, as the voltage has started to drop along the battery pack again. Could probably get away with not removing them given voltage drop is small, but will do so anyway to stay safe.

8:15 pm

All back deck work complete, steaming towards next waypoint which is the start of the next transect located near the south end of USGS line 767. ETA is ~2 am local.

Friday, September 16, 2016 (Day 5 of science)

12:20 am

Weather conditions holding steady, with wind out of NE at 11 knots and intermittent light flurries. Sea state remains favorable for now, with small white caps, 2-4 ft seas. Continuing to transit to 3rd transect that shadows USGS seismic line 767. New maps have been created by Madie showing data collected on each of the lines. During the night we have been overlaying preliminary heat flow data onto seismic lines to look for possible correlation/explanation of some of our anomalous heat flow values. We see evidence for higher heat flow values coincident with areas where large submarine faults or submarine slides exist, suggesting upward fluid flow along these faults, or recent exposure of submarine slide debris along Transect 1. Ben and I have also developed and run a 1D time dependent heat flow model that accounts for seasonal ocean temperature change. Results indicate some of the most significant anomalies observed in shallow water are likely in part due to ocean warming, especially at depths of ~200 m or greater, where Pickart et al. suggest significant temperature swings. Our results confirm observation by Pickart that ~1 degree temperature swings occur at these depth intervals at the time frame he predicts (the model closely matches our observations for the heat flow probe at these depths), implying these annual ocean temperature swings in the Beaufort are widespread (we see clear evidence for it at both transects, despite a separation of at least 300 km along the margin).

2:00 am

Approaching first station for transect 3 (deployment BHF5). Re-attached pinger and turned on. Data logger disconnected from power charger. Added additional chaffing gear to the spectra line (rapped the upper 10 meters of the line in fire hose).

3:00 am

Probe in water.

3:20 am

First HF point at BHF5 collected at 207 m of water. Temperature trend is nearly identical to the two other transects at this water depth, consistent with ocean seasonal ocean temperature effects.

7:30 am

Completed 8 stations on transect 3, BHF5. Very steep slopes encountered deeper than 300 m water depths, but probes still appears to have penetrated.

8:00 am

Morning meeting with crew and science party held. Discussed options and timing of data collection in the next few hours and days as weather is poor and likely to continue to deteriorate, with sustained 30 knot winds by Sunday. Currently, winds are sustained at ~20 knots, with seas of 3-5 feet. The next survey line will be west of our location, north of Barrow, however, the worst weather is predicted for this region in the next 24-48 hours, and there are few places for the ship to tuck into a lee near Barrow. After discussions with the Captain, we agreed it would be best to focus more efforts on our current line for the next 12-24 hours as weather predictions are better for this area during that time frame. If weather forecasts stay accurate, we will likely swing south towards Harrison Bay, and heave to until the worst of the low pressure passes, and then work towards Barrow to complete the last two transects on Monday/Tuesday/Wednesday.

10:22 am

After consultation with the Captain and Bosun, we began pulling up probe after completing 12 HF stations for transect 3 (deployment BHF5). Sea State has deteriorated significantly, making work on the fantail potentially dangerous. Winds are sustained above 22 knots out of the NE and continuing to increase. Sea state is sloppy, with swells at 6 ft and steadily rising with significant chop. Surface weather has also deteriorated with surface temps below freezing the past ~24 hours mixed with occasional driving snow. Weather predictions suggest sustained 30 knot winds through Sunday with gusts up to 40 knots and 12 foot seas.

~11:00 am

Gear secured on deck. Steaming toward Harrison Bay, just south of Transect 3 where we will download all additional data collected during transect 3, recharge/replace batteries for pinger and data recorder, resecure thermistor string which has loosened, and determine the best location to collect data based on our initial findings once storm weakens.

8:10 pm

Dropped anchor ~3 km east of Cape Halkett to ride-out gale. Winds sustained above 20 knts gusting near 30 out of southwest at Cape Halkett and worse offshore. Snow continues to fall. Casey has completed HF Probe write-up; Madie writing Transect 3 deployment script for producing different chirp images and waypoint maps. Ben is integrating HF data with seismic line placement for the current three transects.

Figure 17: Working in the science lab with 30 knot winds and 12ft seas developing outside. Things are moving around a lot more than the still-frame suggests!

Saturday, September 17, 2016 (Day 6 of science)

12:00 am

Pressure at 990 bars.
Wind out of West, 18 knots.
3 ft seas in Harrison Bay.

We remain anchored waiting for improved weather that will allow probe deployment. Jones stringing together chirp seismic lines into a single continuous profile for each transect. Phrampus has generated a script plotting thermal gradient above each of the three seismic transects. Analysis reveals a couple of unusual (and exciting trends). First, chirp seismic data shows a clear break in subsurface coherency where we model the predicted location of the gas hydrate stability zone, indicative of subsurface disturbance at these depths. Second, Heat flow measurements suggest anomalously low temperatures and low heat flow compared to expected values in regions where hydrate may be destabilizing. Multiple reasons for this might exist, including (1) recent (annual to decadal-scale) ocean temperature warming at these depths which result in reduced shallow thermal gradients, or (2) the dissociation of hydrate cooling the subsurface via latent heat energy absorption. If either case are correct, both would support the hypothesis that methane hydrates on the margin are destabilizing. Results from our data, however, provides a well-defined depth range for where active dissociation may actually occur. Other possibilities for explaining these anomalously low heat flow values include (3) downward advection of fluid, which is highly unlikely base on multiple models of fluid flow along continental margins (e.g. Dugan and Flemings, Fredrick and Buffett, etc.), or (4) naturally existing lower heat flow values as we approach the margin edge—something that seems highly unlikely as the heat flow values we are observing are well less than half expected values for oceanic or continental HF values. Ocean temperature change, or hydrate dissociation (or both) currently provide the simplest explanation for these observations, however, seasonal changes at depth should also be analyzed to see if they could also play a role (and if so, what magnitude this role would play in HF variability). Additional transect will also help confirm/build-upon some of these preliminary findings.

4:30 am

Provided the 1st Mate, Wayne, with waypoints for next set of transect lines. One line follows USG 773, the other set crosses a series of pockmarks along the Beaufort margin just east of Barrow Canyon in water depths where hydrates may be destabilizing based on hydrate stability models. There is also the possibility of us forgoing Line 773 and instead extending line at 767 as this line projects into deeper water than 773, providing a longer heat flow profile. Rob and I will discuss this at 8 am during the next weather briefing.

8:00 am

Winds at 17 knts. Pressure at 989 mb. There was a brief reduction in wind in the early morning, but it has since picking up again, with pressure still dropping. Captain indicates 30 knot winds will continue to build, but will be reduced after Sunday night. Looking into options of possibly collecting chirp profiles and slowly moving to next site location once pressure begins to rise.

12:00 pm

Checked charge on data cable for probe. Values appear ok, but data logger casing is frozen to the probe due to ice/freezing rain. Should be a non-issue once probe is dropped in Salty water during deployment.

5:00 pm

Compared combined HF values for three Transects with mean ocean temperature values and show a negative correlation. Implications are ocean temperature changes have an impact on HF in several areas. Upper section (within 250 m) appears season based on Pickart's work, but lower section is less clear. We are working to compare values with standard deviations from XBT/CTD casts for the last 40 years. The Trend would be consistent with bottom water warming at depth of at least 1000 m. Looking at measurements from the world ocean database now.

7:30 pm

25 knot sustained winds with gusts to 30, pressure 993 mbars. Discussed with captain the current weather reports and the possibility of collecting HF data North of Point Barrow first if the weather window improves there earlier. Current forecasts don't show a clear difference in weather from east to west between point Barrow and Prudhoe for the next 24 hours however.

11:00 pm

Developed processing script that corrects headers in Chirp Segy data so that all depths are properly shifted or compensated with read into SEGYMat. We've begun hydrate stability modeling on the upper feather edge using chirp data and heat flow values.

11:30 pm

Pressure rising to 996mb, and sky clearing. Winds 23 knots out west. Rising moon, just past full, with impressive trail of dancing northern lights running almost east west across the sky—fantastic.

Sunday, September 18, 2016 (Day 7 of science)

12:30 am

Sustained Wind 28 knots from SW.
Pressure at 996 mbars.
Clearing.

We remain anchored just west of Cape Halkett. Sea state is poor despite some lee protection from Cape Halkett coast, with 3-6 ft swells and freezing spray. With pressure rising, the hope is to weigh anchor this evening and steam the vessel toward our most recent transect (#3, following USGS seismic line 767) to complete the heat flow survey along this profile.

3:00 am

Wind at 32 knots from WSW.
Pressure 997 mbars.
Clear.

Ship pitching and heaving heavily with wind and waves. All chirp subbottom profile .SGY files have been merged with proper depth corrections. A mean ocean temperature-depth model for the US Beaufort integrating several hundred CTD casts from the world ocean database has been generated by Ben for use in the revised hydrate stability model. The data indicate standard deviations in annual ocean temperature at depths of 1000 m are less than 0.07 deg C, suggesting anomalous heat flow values observed in data at these depths are likely not a function of ocean temperature changes. We reach this conclusion by noting that even if we collect the data during a period where the temperature swing is most extreme in the annual cycle, the difference (or false signal) in probe temperature with depth over 3 m probe length is <= .04 deg. C assuming standard diffusion parameters derived from the probe's thermal conductivity measurements. At depths of 3mbsf (the probe length) such a temperature swing would generate a maximum anomalous thermal gradient of ~13 deg/km, or only 10% of the high values we observe at ~1000m (see "*oneD_timevarying_diff_heatflow_w_annualchange.m*" in cruise report computer folder —a script demonstrating the impact of potential ocean temperature swings, to use this same approach at different depths). This suggest that the high values we observe along the margin at these depths are not likely the result of bottom water temperature variation. Noting this, we continue developing scripts for a series of hydrate stability models integrating chirp data and HF that will more accurately predict hydrate stability along the margin.

3:20 am

Wind speed 31 knots from SW. Pressure 998 mbar. 1st Mate (Wayne) is moving the vessel further southeast into Harrison bay in an attempt to reduce the stress on the anchor and anchor line due to wind and wave action. Currently, the ship jerks sharply back to the anchor point when large swells pass below. My understanding is they are trying to find better anchorage that reduces this stress.

4:15 am

Spectacular northern lights-- green and red dancing ribbons of light extending from east to west, passing through the zenith.

6:15 am

Anchor Dropped at 70 35.5 N, 151 23.5 W. Powered down.

8:00 am

Wind WSW at 24 knots.
Pressure 1001 mbars.
Morning meeting held to discuss next site location. The primary target will be to first to finish off measurements along Transect 3. Based on weather reports, the plan is to start a slow approach out tonight hugging the lee before transiting out to the end of Transect 3. This will depend however on weather conditions improving in the next 12-18 hours.

5:00 pm

Winds WSW at 25 knots.
Pressure 1005 mbars.

10:00 pm

Adding locations of HF points to chirp lines for subsurface temperature contouring. Preliminary hydrate stability models completed. We see major variability in the hydrate stability zone at the pinch-out edge of the margin depending on the HF/thermal gradients exist. In particular, HF values between 25 and 45 mW/m^2 result is large (tens to hundreds of meters) changes in hydrate stability on the margin edge, that are not initially intuitive. Much of these swings are a direct result of the ocean temperature inversion that exists at shallow (~200mbsl) depths. Initial plots showing these results have been added to the cruise report.

Monday, September 19, 2016 (Day 8 of science)

12:20 am

Weighing anchor in Harrison Bay and making our way to Transect 3 to complete line. Winds WSW at 23 knots, but steadily dropping in the last 3 hours. Swells 3-5 ft in Harrison Bay. Pressure 1008 mbars. Expected to arrive on transect and deploy probe by noon.

4:30 am

Changed waypoint to southern end of transect 3, as the data show increasing heat flow up slope right at end of hydrate stability zone, with a potential pockmark feature. We hope drop the HF probe near this feature and collect better chirp over this site.

5:00 am

Wind WSW 25 knots, pressure 1008. Taking good rolls now that we’ve cleared the cape. Seas 12-14ft.

6:00 am

Gear flying around in lab due to heavy seas and large, low frequency swell. All lab chairs and gear dogged down. Speed reduced from 7 to 4 knots.

12:00 pm

WSW wind calming to 20 knots. Approaching transect 3. Discussed with Rob and crew next several days. Plan is to complete Transect 3 by first collecting chirp at the front of the line, and filling in the end with 16 HF waypoint at 0.5 km spacing, then move to the final short transect west of Barrow canyon. At midnight on Wednesday (beginning of Thursday), we begin course for Nome to disembark.

1:45 pm

Pinger lowered into water, beginning transect3 survey for upper 5 stations. Ship speed for survey is 3 knot. With strong swell, running parallel to ship track, some pings show bubble washout. Winds WSW 17 knts.

3:30 pm

Chirp survey completed to depth of ~450m. Ready for HF probe deployment, however, seas are still too rough for deployment of the probe (10ft waves, and lots of ship motion). We therefore continue to collect chirp as we slowly approach next HF waypoint site.

4:00 pm

Prepping the probe for deployment.

4:30 pm

Probe in water. Probe going to 1100mbsl with target depth of seafloor at ~1270m.

7:30 pm

Completed 4 HF measurements and moving to 5th station of day. Preliminary HF values from probe appear higher than other areas.

9:00 pm

Passed over 100 m ridge. Very steep. HF values obtained on each side are high. Entire line so far appears to have anomalously high HF.

11:00 pm

At BHF6, no. 9. Heat flow still high but appears lower than further upslope. May be seeing effects of southward dipping sediments associated with the barrow arch outcropping along the margin edge (as suggested by Demming papers).

11:45 pm

Just collected BHF6 in 1480m water depth. HF high but appears to be dropping steadily.

Tuesday, September 20, 2016 (Day 9 of science)

1:00 am

Winds SSE at 13 knots
Pressure 1002 mbars.
Light snow/rain.

Waves 3-6 ft.
Current/wind change is shifting boat direction upon waypoint approach—conducting drift test following data collection on BHF6, no. 15. Delivered to the Bridge 7 more waypoints at 0.5 km spacing that extend to very end of line 767 with the plan of pulling up gear at 8 am and steaming to next transect.
Waypoint extension for transect 3, USGS line 767:

Table 5: Waypoint extension for transect 3, USGS line 767

Latitude N	Longitude W	Waypoint or Station
71.5338	-151.039	
71.53813	-151.035	
71.54246	-151.032	
71.54679	-151.028	
71.55113	-151.025	
71.55545	-151.021	
71.55978	-151.017	

7:15 am.

Completed Transect 3. Greatest depth ~1700 mbsl. Probe coming on deck for data dump and recharge, while we transit to Transect 4 (USGS seismic line 773). Should surface at 8 am.

8:15 am

HF probe on deck. Recovered ~1 cup of sediment for extra conductivity measurement. Sediments appeared less dense, finer, and less consolidated than previous recoveries (almost a slurry), this is perhaps due to the site of last deployment being the deepest yet.

8:20 am

In transit to shallow end of Transect 4.

3:15 pm

Pinger and probe going into water at beginning of Transect 4.

3:30 pm

BHF7, site 1 hits bottom.

4:40 pm

Finished loading and giving preliminary analysis of Transect 3. Data quality are excellent. Heat flows along the margin edge are exceptionally high (~100 mW/m^2!!?). Data are consistent, and trends robust. Very unusual. Possible groundwater flow laterally here. Based on Discussions with Bosun Jim, we should contact Dan Holiday at BOEM, Anchorage, as they have some complimentary data on groundwater in the region that may be of additional value.

7:45 pm

Wind coming up out of SW at 16 knots.
Pressure at 992 mbars.
Expect peak wind near midnight with gusts up to 30 knots. Seas 2-4, but may build by tonight and captain wants to pull gear in if sustained winds exceed 25 knots. To ensure we obtain some deep data points, we will begin collecting data at 1 km spacing starting after BHF7 station 9.

9:00 pm

Backtracked one station to collect BHF7, station 11, which targeted potential fault on the upper slope. First pass show it being exceptionally cold. Should be very close to hydrate stability zone. Dissociation could drop the subsurface temperature.

11:55 pm

Nearing end of Transect 4. Will turn around and fill line upon completion of next waypoint. Unbelievable Northern Lights outshining moon on fantail.

Wednesday, Sept. 21, 2016. (Day 10 of Science)

(Near North end of Transect 4, possibly more fill at top after data dump).

12:30 am

Went back to 500 m spacing as we are making good time on transect 4. Last three measurements in deeper water will all be at 500 m spacing.

2:15 am

Reached end of transect 4 (USGS 773). Turning back to fill in 500 m gaps in the line to the south.

4:30 am

Completed two more station back to south as fill. Pulling up probe for transit to crossline transects at possible hydrate pockmark field west of Barrow Canyon.

5:15 am

Probe safely on deck. Data for Transect 4 (BHF7) dumped and saved. Pinger power shut down until next deployment. Recovered approximately 2 cups of sediment from the probe, likely from the last deployment at ~1000 mbsl penetration depth. Sediment was more dense than transect 3. We’ve now collected more than 1200 temperature measurements from the U.S. Beaufort Sea from over 100 probe deployments. 100% penetration on last line, with all penetrations showing usable data.

11:00 am

Checked potential pockmark zone imaged with UNH multibeam near Barrow channel via multiple chirp line runs. In chirp, these features appear as shallow scour marks adjacent to, and associated with the Barrow channel, and not hydrate-related features or pockmarks. Bottom also appears hard with clear signs of scour into the channel. Instead of potentially collecting in an area of unlikely fluid flow and potentially poor penetration (where we see scour and may damage the probe), we’ve decided to add additional high quality fill to Transect #4 so that the Heat Flow spacing is consistently 500m or greater. Begin transit to gaps in Transect #4.

11:45 am

Finished uploading all transect 4 preliminary data. Several negative temperature inversions near the hydrate stability zone—very unusual. Possible explanations are significant, severe ocean bottom temperature changes, or dissociation of hydrate. Will try to address this with additional measurements in the area of hydrate stability pinchout with closer spacing, while filling in gaps of 1 km or greater.

2:00 pm

Scattered clumps of house-size multi-year (blue) ice encountered nearing probe deployment site.

2:20 pm

Probe in water and collecting data at first site for BHF8. Moved first probe site location ~250m down line due to first site having Polar Bear and two cubs swimming up next to boat!!!

5:30 pm

Continuing to collect HF Fill-in on Transect4. Spacing after integrating with other measurements will near 250m.

8:30 pm

Some slight diversions in the line to avoid ice. Some waypoints sites very slightly off axis because of this.

10:02 pm

Just pulled last heat flow measurement BHF8 no. 15 out of mud at 1095mbsf. Beginning equipment recovery, chirp pole mount pull-up, and ~1 hour cable haul-in.

10:50 pm

Probe on deck. Significant recovery of sediment with clear evidence for full probe penetration (70% of probe head had mud cake on it). Recovered approximately 4 cups of very fine low permeability mud (we know low k because water was held in the probe data wells after lifting it out of water and suspending from the A-frame. Approximately 4 cups of sediment recovered from BHF8 recovery.

11:30 pm

Data logger removed from HF probe, data dumped, and thermistor string removed and secured for transit. All secured to deck. Bridge turning ship towards Nome for Transit. Grand total of 117 stations, 1287 temperature measurements spanning more than 500 km of the US Beaufort Margin. Of those, only three had no penetration—a 97% success rate. Much better than expected or predicted. With careful planning and use of chirp imaging to pinpoint softer targets and avoid steep slopes, Coring/APC drilling clearly feasible in the region.

Thursday, September 22nd, 2016 (Transit to Nome)

1:00 am

Encountering significant sea ice, resulting in diversion to SE toward Prudhoe, with hope that less sea ice exists towards land. Will then cut back towards Point Barrow.

6:00 am

Nearing Point Barrow. Significant sea ice, slowing ship speed to 4-5 knots.

8:00 am—12:00 pm

Data from Transect 4 BHF 8 processed. All data above ~900m show significant curvature indicative perhaps of recent bottom water warming or advective flow. Below this, we see anomalously high heat flow values.

12:00 pm

Diverted North of Barrow due to whalers (Whaling season just began for indigenous people in Barrow). Encountering significant sea ice still, hampering speed. Heat Flow probe packed and ready for shipment out of Seward.

5:00 pm

12 kHz Chirp system packed in Pelican cases and ready for shipment. Two items total (pelican case with packing list inside and pole mount). Need to discuss with Sheyna how we might ship sediment samples.

Friday, September 23rd, 2016 (Transit to Nome)

Continuing Transit to Nome. Writing Cruise Report. Saw three walruses within 20 yards of ship just north of Spectacled Eider bird sanctuary in Eastern Chukchi Sea.

Saturday, September 24th, 2016 (Transit to Nome)

Continuing Transit to Nome. Completing Cruise Report. Observed whale breach and splash ~100 m from ship while on bridge today.

Sunday, September 25th, 2016 (Transit/arrive to Nome)

7:00 pm

Arrive at Nome harbor in rough seas. Disembark from vessel.

IX. Understanding/applying ocean temperature corrections/models to HF data.

Ocean Temperature studies in the U.S. Beaufort suggest the most significant seasonal swings occur at depths of 200 m or less (E.G. Pickart 2004, 2008, 2013), where seasonal swings can be on the order of ~1 deg. C (peak to peak). Below ~200 m, however, the seasonality temperature changes appear significantly reduced. Our ocean temperature analysis not only confirms the analysis of Pickart, but demonstrates that such severe ocean temperature swings are widespread along virtually the entire U.S. Beaufort Margin, with clear evidence that these temperature swings extend at least 500 km along the upper margin of the US Beaufort.

On transect 1, our shallowest deployment was 205 m, with HF of ~184 mW/m^2. Similarly, we found an anomalously high heat flow on transect 2 at our shallowest point of 203 m, and HF of ~122 mW/m^2. Perhaps surprisingly, the temperature gradient on these probes was nearly linear. One therefore must question if what we are observing is truly high heat flow values or ocean temperature changes at these shallow depths.

To test this, we ran a simple 1-D time dependent HF model that subjects the seafloor to an annual sinusoidal temperature change of -0.5 to 0.5 deg. C... According the Pickart's work, Peak warming at 200 m water depths occurs in the late winter to mid spring, and peak cooling occurs in late summer to early fall (i.e. the time period when we collected this data). Thus, just from these observations alone (and recognizing that temperature diffusion should extend out no more than ~15 m into the subsurface during the year based on rough estimates of thermal diffusion), we should observe anomalously high heat flow in these zones because the seafloor 4 months ago was exposed to the warmest bottom water, followed by current exposure of the coldest bottom water, with warming likely to start again soon (October).

Model Results below show how the temperature should change with depth during the course of a year assuming a thermal diffusivity of 2.6x10^-7.

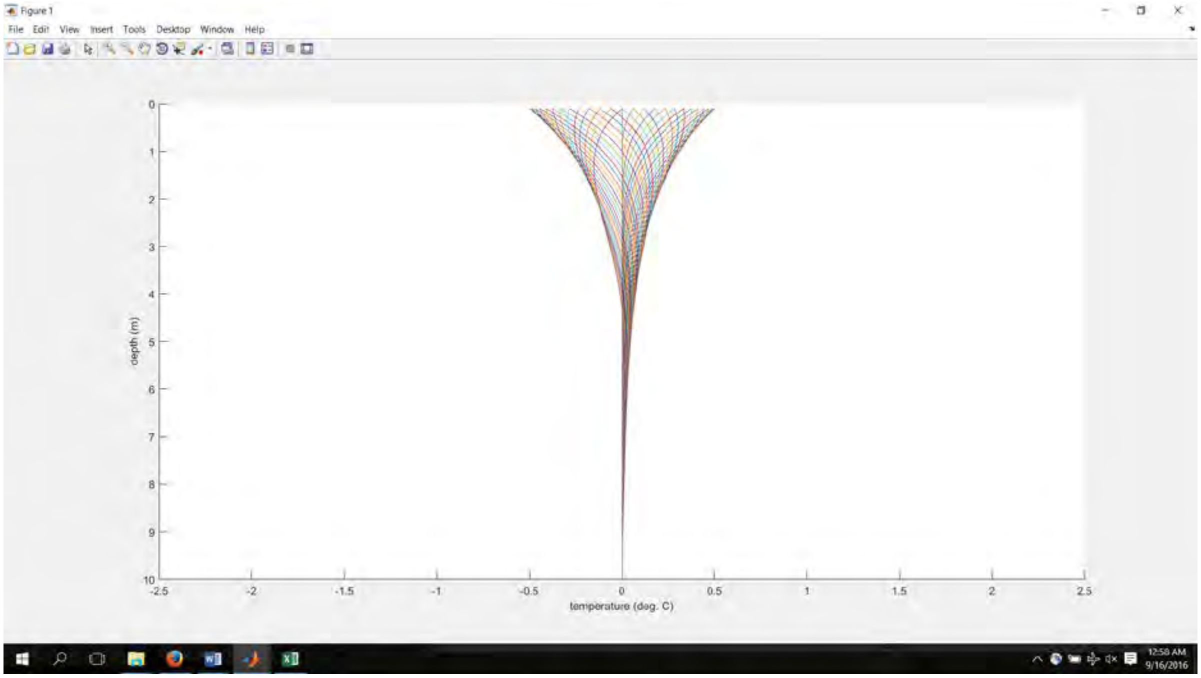


Figure 18: Model results indicating how the temperature should change with depth during the course of a year assuming a thermal diffusivity of 2.6x10^-7.

Annual temperature change in the shallow subsurface in the Beaufort Sea, assuming a ~1 temperature change occurs with time at a depth of 200 mbsl.

If we just show what the profile should look like for the September time frame (i.e. The time at which we collected our heat flow data at these depths), we observe a trend that nearly perfectly fits what our model predictions show, with temperature increasing by ~.4 deg. C at 3 m depth at the 200 mbsl contour (see figure below).

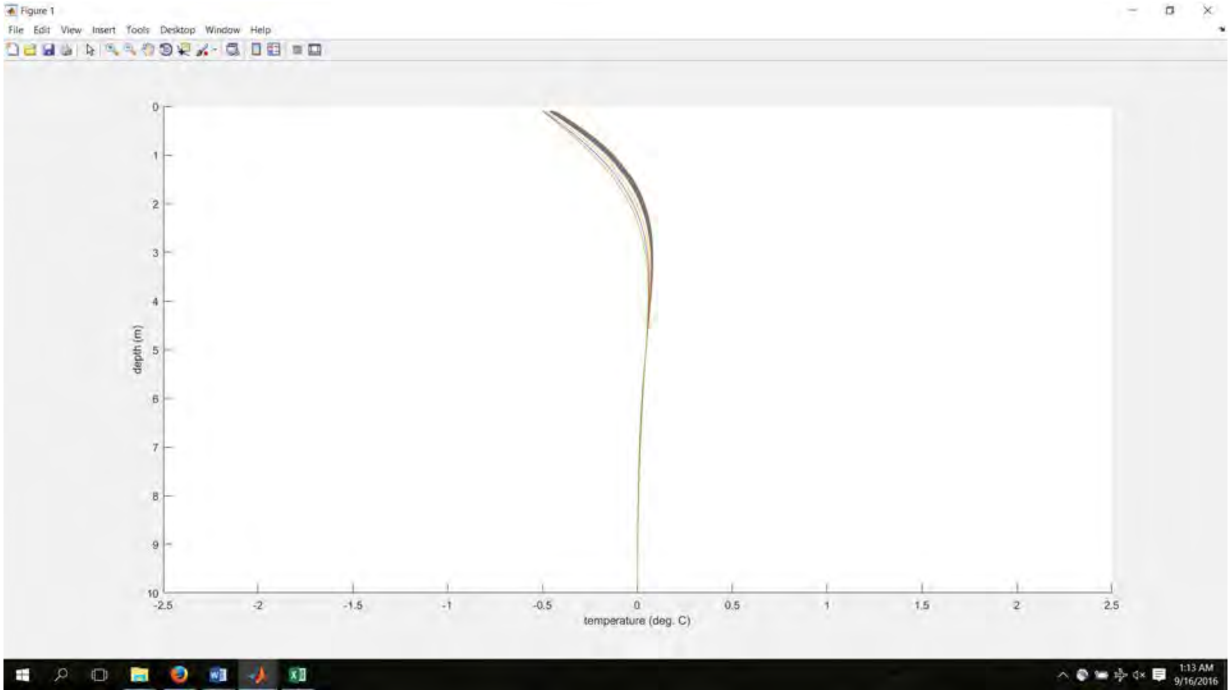


Figure 19: Model predictions for September. If we just show what the profile should look like for the September time frame (i.e. The time at which we collected our heat flow data at these depths), we observe a trend that nearly perfectly fits what our model predictions show, with temperature increasing by ~4 ° C at 3 m depth at the 200 mbsl contour.

Expected temperature-depth profiles each day in the Beaufort for the month of September at 200 m depth, assuming ocean temperature trends match those of Pickart's studies. The "Apparent" thermal gradient is ~0.43 at three meters, but is caused by seasonal ocean temperature swings at this depth. We observe 0.36 deg C. increase at 3 meters at 200 mbsf for transect 2, at a depth of 203 m.

The time varying nature of BWT has been resolved in a number of studies. In the Denmark Strait, temperature profiles measured in sediments indicate BWT fluctuations on the order of 0.4° C [*Lachenbruch and Marshall*, 1968]. Along the Reykjanes Ridge [*Sclater and Crowe*, 1979], temperature profiles are apparently linear between 7.5 and 12.5 mbsf (the base of their measurements), but show a sharp decrease in temperatures (~0.4° C) in the upper 5 m, consistent with a yearly BWT fluctuation. Other studies documenting BWT variations based on sediment temperature-depth profiles include: the Canadian Beaufort Shelf [*Taylor and Allen*, 1987], Bermuda Rise [*Galson and Von Herzen*, 1981], the Bay of Biscay [*Foucher and Sibuet*, 1980], the Gulf of Mexico [*Cathles and Nunns*, 1991] and the Scotia Sea [*Barker and Lawver*, 2000]. Across the Norwegian margin at shallow depths of 600 - 800 mbsl, *Vogt and Sundvor* [1996] attributed curvature in thermal gradients to the upward movement of pore fluids, although they could not rule out BWT variations. Where oceanic BWT time series are available, two of these studies [*Lachenbruch and Marshall*, 1968; *Cathles and Nunns*, 1991] successfully model perturbations in temperature-depth profiles in terms of deep water movements. Below, we provide a useful starting point of references that discuss BWT variation and its influence on shallow heat flow measurements.

References of BWT variation and influence on shallow heat flow measurements

Cathles, L. M. and A. G. Nunns, 1991, A temperature probe survey on the Louisiana Shelf: effects of bottom-water temperature variations, *AAPG, 75*, 180-186.

Foucher, J. P. and J. C. Sibuet, 1980, Thermal regime of the northern Bay of Biscay continental margin in the vicinity of the DSDP sites 400-402, *Phil. Trans. R. Soc. A, 294*, 157-167.

Galson D. A. and R. P. Von Herzen, 1981, A heat flow survey on anomaly MO south of Bermuda Rise, *Earth Planet. Sci. Lett., 53*, 296-306.

Lachenbruch A. H. and B. V. Marshall, 1968, Heat flow and water temperature fluctuations in the Denmark Strait, *J. Geophys. Res., 73*, 5829-5842.

Sclater, J. G. and J. Crowe, 1979, A heat flow survey at anomaly 13 on the Reykjanes Ridge: a critical test of the relation between heat flow and age, *J. Geophys. Res., 84*, 1593-1602.

Taylor, A. E., and V. Allen, 1987, Shallow sediment temperature perturbations and sediment thermal conductivities, Canadian Beaufort Shelf, *Can. J. Earth Sci, 24*, 2223-2234.

Vogt, P. R., and E. Sundvor, 1996, Heat flow highs on the Norwegian-Barents-Svalbard continental slope: Deep crustal fractures, dewatering, or 'memory in the mud'?, *Geophys. Res. Lett., 34*, 3571-3574.

X. Methane Hydrate Stability (2D, steady state) Modeling MATLAB Scripts for the Beaufort Sea using Chirp/seismic data

Directions for running a 2D Hydrate Stability model (steady-state) on Beaufort Sea Chirp/seismic data from scratch with MATLAB scripts developed aboard the Norseman II in September of 2016:

1. Select and run one of three scripts to read in the seismic data and produce an output of sea-bottom depths (or seafloor picks) and step size in the x direction in m (dx). Note the output file of all three is the same: "SN_SFdepth.asc"

    a). Run "***Convert_time_to_depth_pick_sf.m***", or, alternatively, skip to (1.b) or (1.c), below and run a version that accounts for variable shot spacing with time (good for Knudsen data). For this script, you need to supply the seismic line for which you want to run a thermal conductivity model on. Currently, this script is designed to load Knudsen 12 kHz seismic data (sample rate will need to be changed for other types of seismic data). This script reads in the seismic data, converts it to depth, and then asks the user to pick the seafloor horizon, which is needed so that the model can determine where to assign thermal conductivity values for the sediments. It outputs all of your pick values as depths and trace/shot numbers (in future versions, this could be adjusted to latitude or longitude however). The output is a file containing the sea-bottom depths for a given trace number or position, called "**SN_SFdepth.asc**".

b). To plots the traces with respect to latitude, and calculate an average dx to use based on the latitudinal length of the line divided by the number of traces, use "**convert_time_to_depth_trace21lat_pick_sf.m**". This approach will generally be more accurate for chirp data, since ship speed can change significantly, and chirp shoots on time, not distance. As with the former script, at the end of the program it returns a value for dx to use in the model. Output file is "**SN_SFdepth.asc**".

c). If you have several Knudsen segy files that you want to merge together to conduct this analysis, use the script entitled, "***merge_knudsen_segy_conv2D_convLat_pick_sf.m***". This script allows you to merge up to 3 Knudsen files (but more could be added if needed), and plots the traces with respect to latitude instead of trace number. This script was used frequently due to the ability to stitch together multiple Knudsen files. The output file is the same as the two above (**SN_SFdepth.asc**)

2. Run "***Create_conductivity_model.m***". This program loads in your seafloor picks from step 1 and assigns thermal conductivity values for all of the sediments below the seafloor (and puts in zero values where water exists). The results from this are used to determine where the seafloor temperature is located, and therefore where water temperature boundary conditions should be applied. The program will output a conductivity grid that defines the shape of your model called "**conductivity_grid.asc**"

   Furthermore, this script is used to define the dimensions of your heat flow model. You will want to set dx (step size in the x direction in m) and dy (the vertical scale of the model in the y direction) to values that generally fits your data. For chirp data, you can do this approximately by noting the speed at which chirp was collected and ping rate, or alternatively, the approximate total length of the chirp line divided by the number of traces. Or, you can reformat the data to latitude and longitude and redefine the trace spacing. For our initial analysis, we simply assumed an average trace spacing value of 10 m (dx), and a vertical resolution for the model of 1 m (dy), since chirp has a resolution at or below a meter vertically, and we collected traces every ~10 m based on average ship speed.

   Note that the smaller the dx, the bigger the model, and the slower the heat flow model will run, so to help alleviate this, we also provide a means of reducing the resolution of the model via interpolation in the x direction. Check the interpolation at the end of the script (line 57), and adjust if you think the spacing of the data in the x direction is too tight (or you are worried about the model running too slowly). If no interpolation is needed, just set the interpolation value to 1, so that the program reads in every dx value assigned.
   Important: NOTE THE GRID SIZE CREATED for the model (numcells_x, numcells_y and numcells_z in conductivity_grid.asc output file), AS YOU WILL NEED THIS FOR YOUR NEXT STEPS.

3. Run "***Make_Ocean_temp_depth_profile_for_model.m***". This model fits an ocean-temperature versus depth profile to the heat flow model so that the temperature at the seafloor has the correct boundary condition for a given depth. Note: you will not need to run this model every time. Only when you change the grid size (since changes in grid size require a change in the depth interval of the ocean temperature grid). When you run it, you will need to supply:

    a. A “**mod_dz**” value—the model dz value that you intend to use for the model run, and
    b. The total number of vertical cells “**numcells_z**” in the heat flow model you will run.

Currently, this file uses a mean temperature-depth profile based on average values from several hundred CTD cast in the Beaufort (called “**Beaufort_sea_mean_T_vs_D.xlsx**”), however the temperature depth profile can be changed to incorporate different seasonal or regional temperature effects as needed. Data to make the mean value model were compiled by Ben Phrampus. This program outputs a file containing ocean temperature-depth information that is fed into the thermal refraction model. The file it produces is called **SFT4model.asc**.

4. Run “***Calculate_thermal_refraction_SS_varSFT.m***”. This program is the workhorse that calculates the seafloor and subsurface temperature regime by running a 2D diffusive heat flow model for thousands of time steps until the temperatures converge to steady state in the subsurface. Depending upon the scale of the model and dx and dz values used, this model may take a long time to run. For this model you will need to input
    a. the number of cells in the y direction (**numcells_y**), as defined by your conductivity model,
    b. the vertical cell size used for the model (**dz**) in meters,
    c. the number of cells in the x-direction for the model (**numcells_x**), the cell spacing in the x-direction (dx), and
    d. the thermal gradient (**TG**) that the sediments in the model generally experience in the region of interest.
    e. Also, you will need to determine how long you want to run the model to allow it to relax to a steady state solution (**max_time**).

    After running the model, the file produces a final temperature matrix for the model, called **temp_matrix_varSFT**.

5. Run “***hydrostatic_prediction_of_hydrate_stability_AND_instability.m***”. This program uses Sloan’s data to run through the model depths, pressures, and temperatures, and from this, determines where hydrates is stable (and unstable) in the subsurface. It generates a picture that you can save with a file name of your choice and overlay on seismic data for comparison. In this program, you need to make sure that the depth step (**d**z) fits the step value used in the model.

References for MATLAB Scripts

Sloan, E.D., Clathrate Hydrates of Natural Gases, Marcel Dekker, Inc., New York (1990)

XI. Equipment and Packing

The equipment manifest included items owned or leased by SMU and OSU, including a pinger rented from University of Washington. Details on the packing approach for the SMU Pelican box (SMU 1) appears below the manifest chart. It does not include any personal luggage items, equipment owned by Norseman Marine, or equipment owned by Olgoonik-Fairweather – most notably nearly all personal safety equipment.

Equipment Manifest

OWNER & Item #	Description Including estimates of size (L-W- H in “), weight (lbs.), and value (US$)

WashU 1	University of Washington owned. Crated Pinger. Model Benthos 2216 12 kHz. (98 lbs. 33.25” x 14.25” x 8.75”; value $11,166). Sent to AK as FedEx Tracking # 8088 6291 0075
SMU 1	Large deck box (~140 lbs. 32” x 24” x 20”; value $35,000) containing: • 1 Knudsen KEL571-12/200 Dual Frequency Transducer (44 lbs), • 1 Knudsen 3212 Portable Dual Channel Echosounder (in its own smaller deck box along with several associated Power Cords), (26 lbs) • 1 surge protector, • 1 transducer mount with 4 small threaded poles for securing mount to long pole. • 1 toolbox containing a box of nuts, bolts, locknuts and washers, 8 bungee cords, 5 wrenches, and string. • GPS 16x HVS Receiver. • May include 2 additional GPS 18x units and hard drives, etc. for return trip. Sent to AK as FedEx Tracking # 8063 0545 2156
SMU 2	Long cardboard box containing 6’ long x 2” diameter pole for mounting transducer to deck. (15 lbs., Value not specified) Sent to AK as FedEx Tracking # 8063 0545 2134
OSU 1	Pelican Case 1 (140 lbs. 40” x 28” x 15 Value $1,500) containing 3 tool boxes: • Wrenches, pliers, screwdrivers • Electrical and soldering supplies • Office supplies Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 1 of 11)
OSU 2	Pelican Case 2 (165 lbs. 46” x 17” x 15” Value $11,250) containing Thermistor Nose Cone Assembly and Tools: • 36” pipe wrench • 24” crescent wrench • Heavy-duty strap wrench Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 2 of 11)
OSU 3	Pelican Case 3 (165 lbs. 40” x 28” x 15” Value $8,250) containing Electronics and Communications equipment: • Power and communications cables • Digiquartz Depth Sensor, Paroscientific Inc. Model #8b7000-2 • Temperature Sensors • PowerSonic Sealed Lead Acid Battery Chargers • Heat Flow Manuals Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 3 of 11)
OSU 4	Pelican Case 4 (125 lbs. 40” x 28” x 15” Value $9,250) containing Electronics and Spares: • Logger Case (PVS) and stands • Batteries, O-rings, nuts, bolts, and keys

	Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 4 of 11)
OSU 5	Pelican Case 5 (75 lbs. 46” x 17” x 15” Value $30,000) containing Data Logger, Serial # 5301 by Richard Brancker Research Ltd. Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 5 of 11)
OSU 6	Pelican Case 6 (75 lbs. 46” x 17” x 15” Value$30,000) containing Data Logger, Serial # 5302 by Richard Brancker Research Ltd. Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 6 of 11)
OSU 7	Pelican Case 7 (30 lbs. 34” x 24” x 15” Value $5,000) containing electronics, including circuit boards and Dell laptop. (No information on how sent to AK. Perhaps brought with personal items.)
OSU 8	Pelican Case 8 (95 lbs. 46” x 17” x 15” Value $25,000) containing High Power Bottom-Finding Acoustic Pinger, DataSonic Model BFP-312 by Benthos, Inc. Sent to AK as FedEx Tracking # 676326217618
OSU 9	Box #9 (1,240 lbs. 41” x 32” x 31” Value $9,000) containing Weight Stand and Pressure Case. Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 7 of 11)
OSU 10	Box #10 (360 lbs. 205” x 10.5” x 8” Value $5,000) containing Heat Probe Strength Member. Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 8 of 11)
OSU 11	Box #11 (160 lbs. 164” x 14” x 11.5” Value $31,000) containing Two (2) Thermistor Strings by YSI Inc. Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 9 of 11)
OSU 12	Box #12 (160 lbs. 164” x 14” x 11.5” Value $31,000) containing Two (2) Thermistor Strings by YSI Inc. Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 10 of 11)
OSU 13	Box #13 (125 lbs. 32” x 20” x 17” Value $1,000) containing shipping, labeling and miscellaneous supplies. Sent to AK as ACS_ref7056 or NAC Airbill Number: 23020476 (part 11 of 11)
Approximate weight of all 15 items listed above is 3,168 lbs., Value of $242,416: • 1 to Wash U 98 lbs. Value $11,166 • 2 to SMU 155 lbs. Value $34,000 13 to OSU 2,915 lbs. Value $197,250	
In addition to personal luggage items, SMU brought printed documentation and literature, 12 HOBO temperature loggers, 5 laptop computers, 2 SSD external hard drives, and 2 Garmin 18x GPS units with them in carry on cases.	

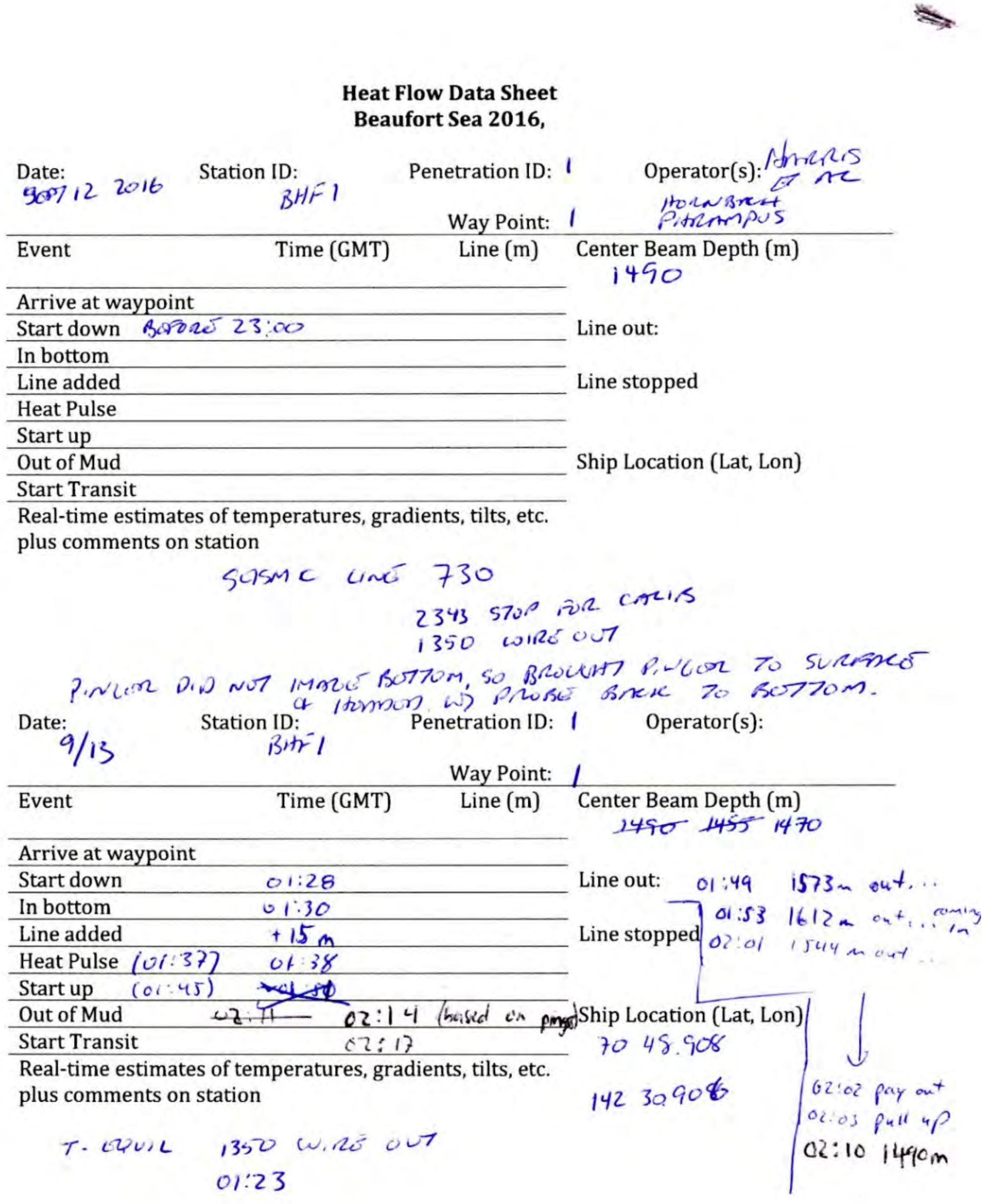
Packing Instructions for SMU 1 Pelican Box containing Chirp System

Large deck box (~140 lbs. 32” x 24” x 20”; value $35,000) contained:

- 1 Knudsen KEL571-12/200 Dual Frequency Transducer (44 lbs),
- 1 Knudsen 3212 Portable Dual Channel Echosounder in its own smaller deck box, (26 lbs)
  - Plus 3 power cords (1 for 110V, 2 for 12 V battery connections).
  - Plus 2 USB cords for data reading or connection to GPS.
  - Plus 1 extra power cable connection.
- 1 surge protector,
- 1 transducer mount with 4 small threaded poles for securing mount to long pole.
- 1 toolbox containing:
  - extra nuts and bolts for mount.
  - 8 bungee cords for holding down unit.
  - 5 crescent wrenches and socket wrenches of correct size.
  - extra line for tie-down.
- GPS 16x HVS Receiver. Additional Garmin 18x units carried in personal luggage.

XII. Original, Scanned, Hand Written, HF Data Logs (In Order of collection, BHF 1 thru BHF 8)

BHF 1 -September 12-13, 2016. 16 Penetrations.



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: SEPT 12 2016
Station ID: BHF 1
Penetration ID: 1
Operator(s): HARRIS & ME HORNBACH PITRAMPUS
Way Point: 1

Event	Time (GMT)	Line (m)
Arrive at waypoint		
Start down	BEFORE 23:00	
In bottom		
Line added		
Heat Pulse		
Start up		
Out of Mud		
Start Transit		

Center Beam Depth (m): 1490
Line out:
Line stopped
Ship Location (Lat, Lon)

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

SEISMIC LINE 730
2343 STOP FOR CALLS
1350 WIRE OUT
PINGER DID NOT IMAGE BOTTOM, SO BROUGHT PINGER TO SURFACE & [illegible] W/ PROBE BACK TO BOTTOM.

Date: 9/13
Station ID: BHF 1
Penetration ID: 1
Operator(s):
Way Point: 1

Event	Time (GMT)	Line (m)
Arrive at waypoint		
Start down	01:28	
In bottom	01:30	
Line added	+15 m	
Heat Pulse (01:37)	01:38	
Start up (01:45)	~~01:50~~	
Out of Mud	~~02:11~~ 02:14 (based on pings)	
Start Transit	02:17	

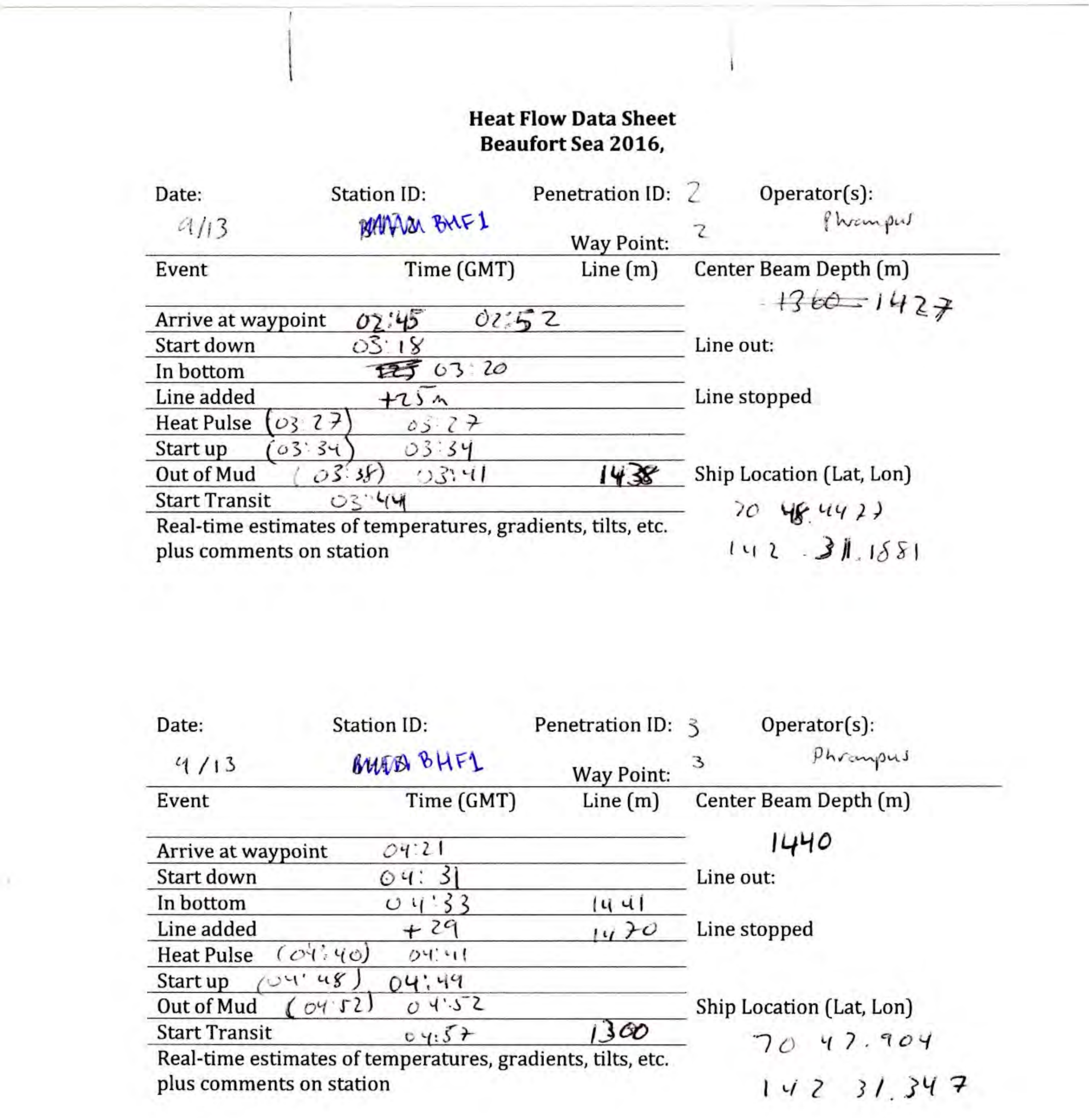
Center Beam Depth (m): ~~1490~~ ~~1455~~ 1470

Line out: 01:49 1573m out...
01:53 1612m out... coming in
Line stopped 02:01 1544 m out...
02:02 pay out
02:03 pull up
02:10 1490m

Ship Location (Lat, Lon)
70 48.908
142 30.908

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

T-EQUIL 1350 WIRE OUT
01:23



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/13
Station ID: BHF1
Penetration ID: 2
Way Point: 2
Operator(s): Phrampus

Event	Time (GMT)		Line (m)
Arrive at waypoint	02:45	02:52	
Start down	03:18		
In bottom	03:20		
Line added	+25m		
Heat Pulse	(03:27)	03:27	
Start up	(03:34)	03:34	
Out of Mud	(03:38)	03:41	1438
Start Transit	03:44		

Center Beam Depth (m): ~~1360~~ 1427

Line out:

Line stopped

Ship Location (Lat, Lon)
70 48.4427
142 31.1881

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9/13
Station ID: BHF1
Penetration ID: 3
Way Point: 3
Operator(s): Phrampus

Event	Time (GMT)		Line (m)
Arrive at waypoint		04:21	
Start down		04:31	
In bottom		04:33	1441
Line added		+29	1470
Heat Pulse	(04:40)	04:41	
Start up	(04:48)	04:49	
Out of Mud	(04:52)	04:52	
Start Transit		04:57	1300

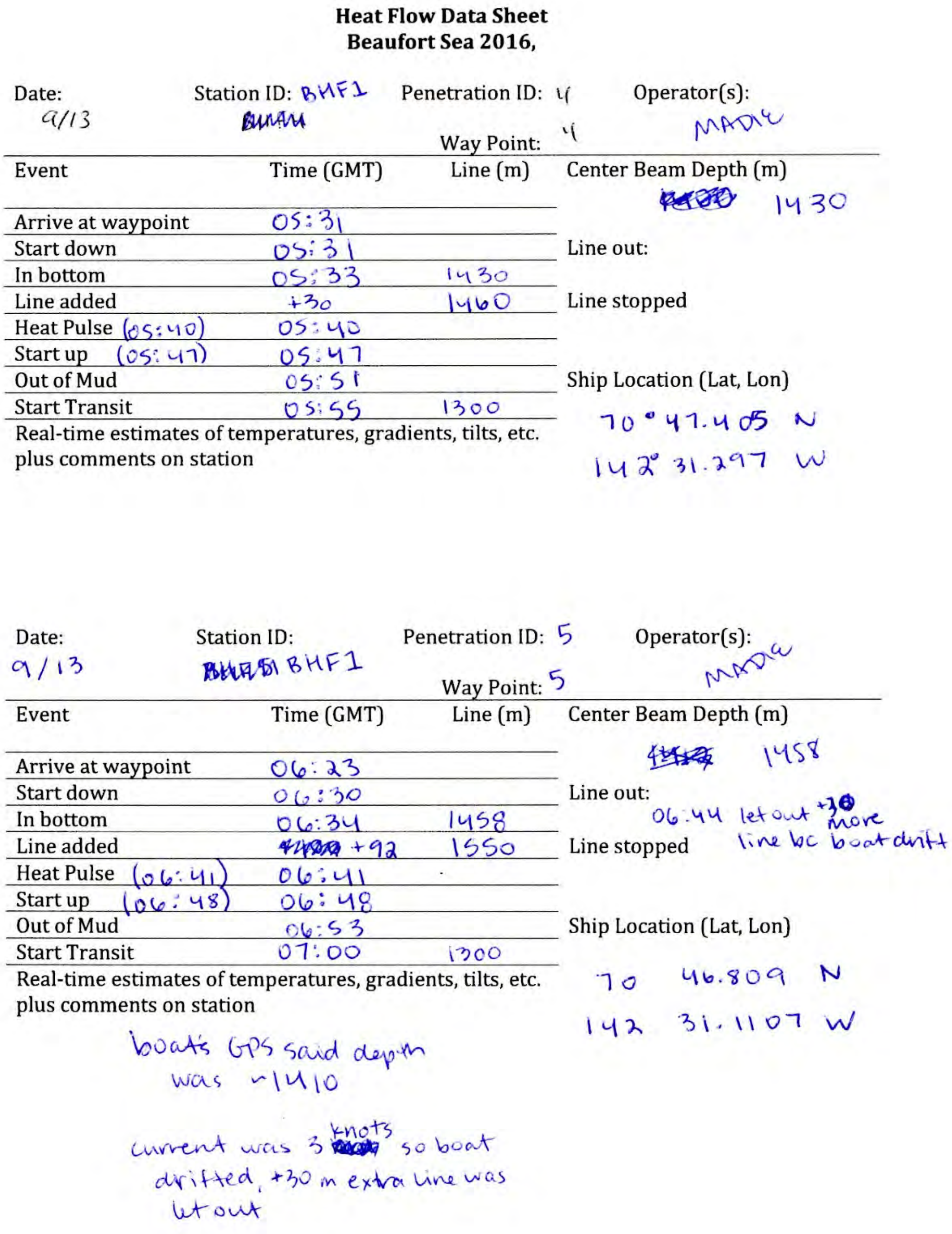
Center Beam Depth (m): 1440

Line out:

Line stopped

Ship Location (Lat, Lon)
70 47.904
142 31.347

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/13
Station ID: BHF1 [illegible]
Penetration ID: 4
Way Point: 4
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	05:31	
Start down	05:31	
In bottom	05:33	1430
Line added	+30	1460
Heat Pulse (05:40)	05:40	
Start up (05:47)	05:47	
Out of Mud	05:51	
Start Transit	05:55	1300

Center Beam Depth (m) [illegible] 1430

Line out:

Line stopped

Ship Location (Lat, Lon)

70° 47.405 N
142° 31.297 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9/13
Station ID: [illegible] BHF1
Penetration ID: 5
Way Point: 5
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	06:23	
Start down	06:30	
In bottom	06:34	1458
Line added	[illegible] +92	1550
Heat Pulse (06:41)	06:41	
Start up (06:48)	06:48	
Out of Mud	06:53	
Start Transit	07:00	1300

Center Beam Depth (m) [illegible] 1458

Line out:
06:44 let out +30 more line bc boat drift

Line stopped

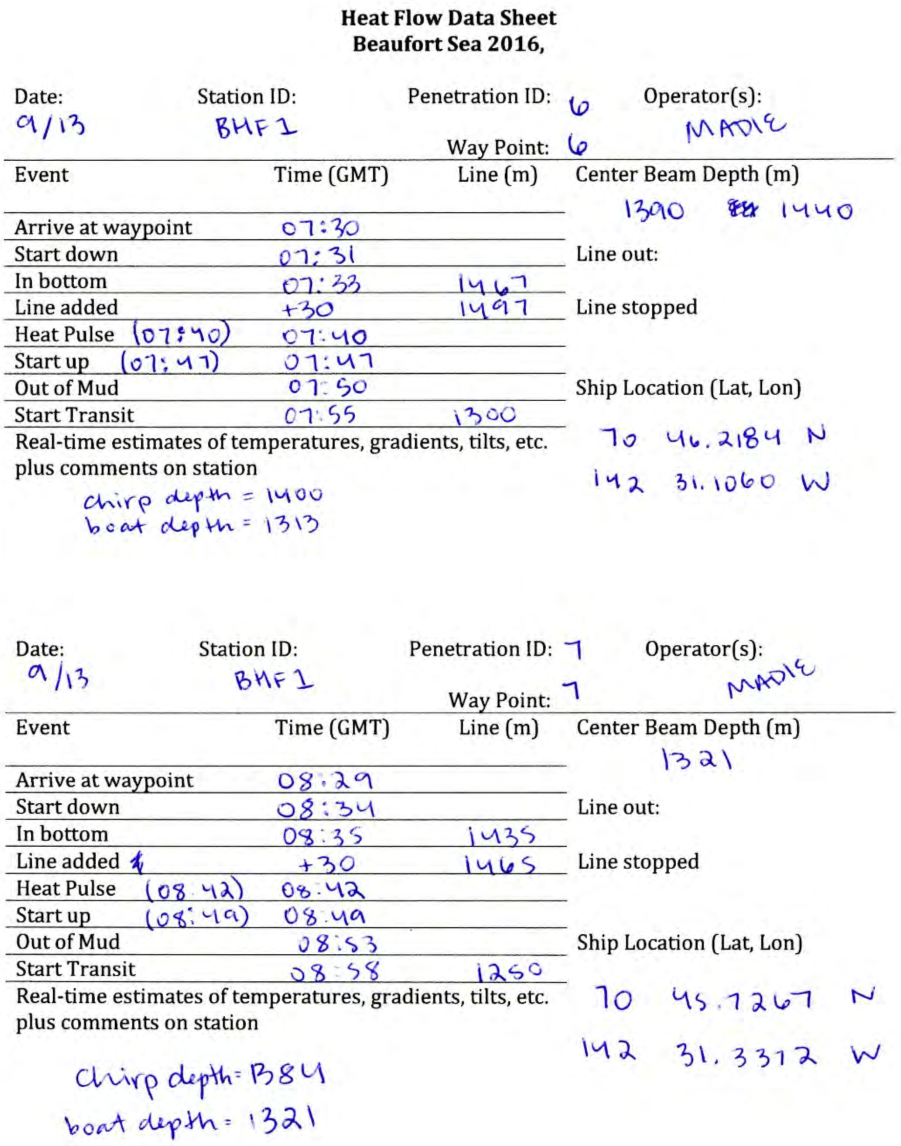
Ship Location (Lat, Lon)

70 46.809 N
142 31.1107 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

boat's GPS said depth was ~1410

current was 3 knots so boat drifted, +30 m extra line was let out



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/13
Station ID: BHF1
Penetration ID: 6
Way Point: 6
Operator(s): MADIE

Event		Time (GMT)	Line (m)
Arrive at waypoint		07:30	
Start down		07:31	
In bottom		07:33	1467
Line added		+30	1497
Heat Pulse	(07:40)	07:40	
Start up	(07:47)	07:47	
Out of Mud		07:50	
Start Transit		07:55	1300

Center Beam Depth (m)
1390 1440

Line out:

Line stopped

Ship Location (Lat, Lon)
70 46.2184 N
142 31.1060 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp depth = 1400
boat depth = 1313

Date: 9/13
Station ID: BHF1
Penetration ID: 7
Way Point: 7
Operator(s): MADIE

Event		Time (GMT)	Line (m)
Arrive at waypoint		08:29	
Start down		08:34	
In bottom		08:35	1435
Line added		+30	1465
Heat Pulse	(08:42)	08:42	
Start up	(08:49)	08:49	
Out of Mud		08:53	
Start Transit		08:58	1250

Center Beam Depth (m)
1321

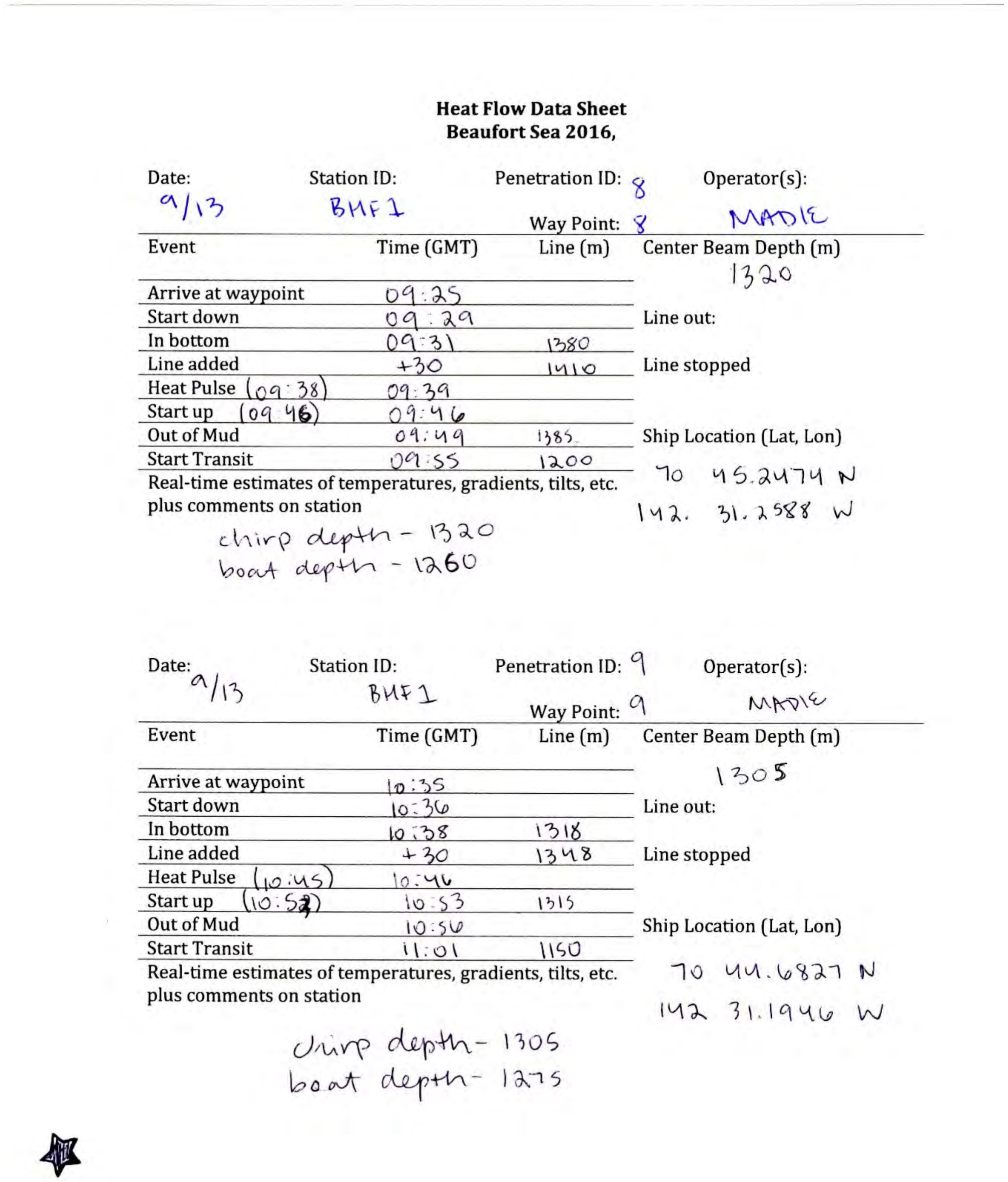
Line out:

Line stopped

Ship Location (Lat, Lon)
70 45.7267 N
142 31.3312 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Chirp depth = 1384
boat depth = 1321



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/13
Station ID: BHF1
Penetration ID: 8
Way Point: 8
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	09:25	
Start down	09:29	
In bottom	09:31	1380
Line added	+30	1410
Heat Pulse (09:38)	09:39	
Start up (09 46)	09:46	
Out of Mud	09:49	1385
Start Transit	09:55	1200

Center Beam Depth (m): 1320

Line out:

Line stopped

Ship Location (Lat, Lon)
70 45.2474 N
142. 31.2588 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp depth - 1320
boat depth - 1260

Date: 9/13
Station ID: BHF1
Penetration ID: 9
Way Point: 9
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	10:35	
Start down	10:36	
In bottom	10:38	1318
Line added	+30	1348
Heat Pulse (10:45)	10:46	
Start up (10:53)	10:53	1315
Out of Mud	10:56	
Start Transit	11:01	1150

Center Beam Depth (m): 1305

Line out:

Line stopped

Ship Location (Lat, Lon)
70 44.6827 N
142 31.1946 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp depth - 1305
boat depth - 1275

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/13
Station ID: BMF1
Penetration ID: 10
Way Point: 10
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	11:33	
Start down	11:38	
In bottom	11:41	1288 [illegible]
Line added	+30	1318
Heat Pulse (11:48)	11:48	
Start up (11:55)	11:55	
Out of Mud	11:58	1273
Start Transit	12:05	1050

Center Beam Depth (m): 1210

Line out:

Line stopped

Ship Location (Lat, Lon)
70 44.1296 N
142 31.2222 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp depth = 1210
boat depth = 1162

* signal from pinger is very hard to see, maybe low battery? weak signal

---

Date: 9/13
Station ID: BMF1
Penetration ID: 11
Way Point: 11
Operator(s):

Event	Time (GMT)	Line (m)
Arrive at waypoint	[illegible] ~~13:28~~	~~1000~~
Start down	~~13:31~~	
In bottom		
Line added		
Heat Pulse		
Start up		
Out of Mud		
Start Transit		

Center Beam Depth (m)

Line out:

Line stopped

Ship Location (Lat, Lon)

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

See next page for 11

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/13/2016
Station ID: BHF1
Penetration ID: 11
Way Point: 11
Operator(s): Casey B

Event	Time (GMT)	Line (m)
Arrive at waypoint	12:36	
Start down	12:41	
In bottom	12:44	1142
Line added	+30	+30(1172 paid out
Heat Pulse	(12:51) 12:50	
Start up	12:58	
Out of Mud	12:59	1148
Start Transit	13:04	1000

Center Beam Depth (m) 1148
Line out: 1
Line stopped
Ship Location (Lat, Lon)
70° 43.641'
70.7274
142° 31.213
142.5199

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Good signal, appears all thermistors in mud.

Chirp depth 1151 m

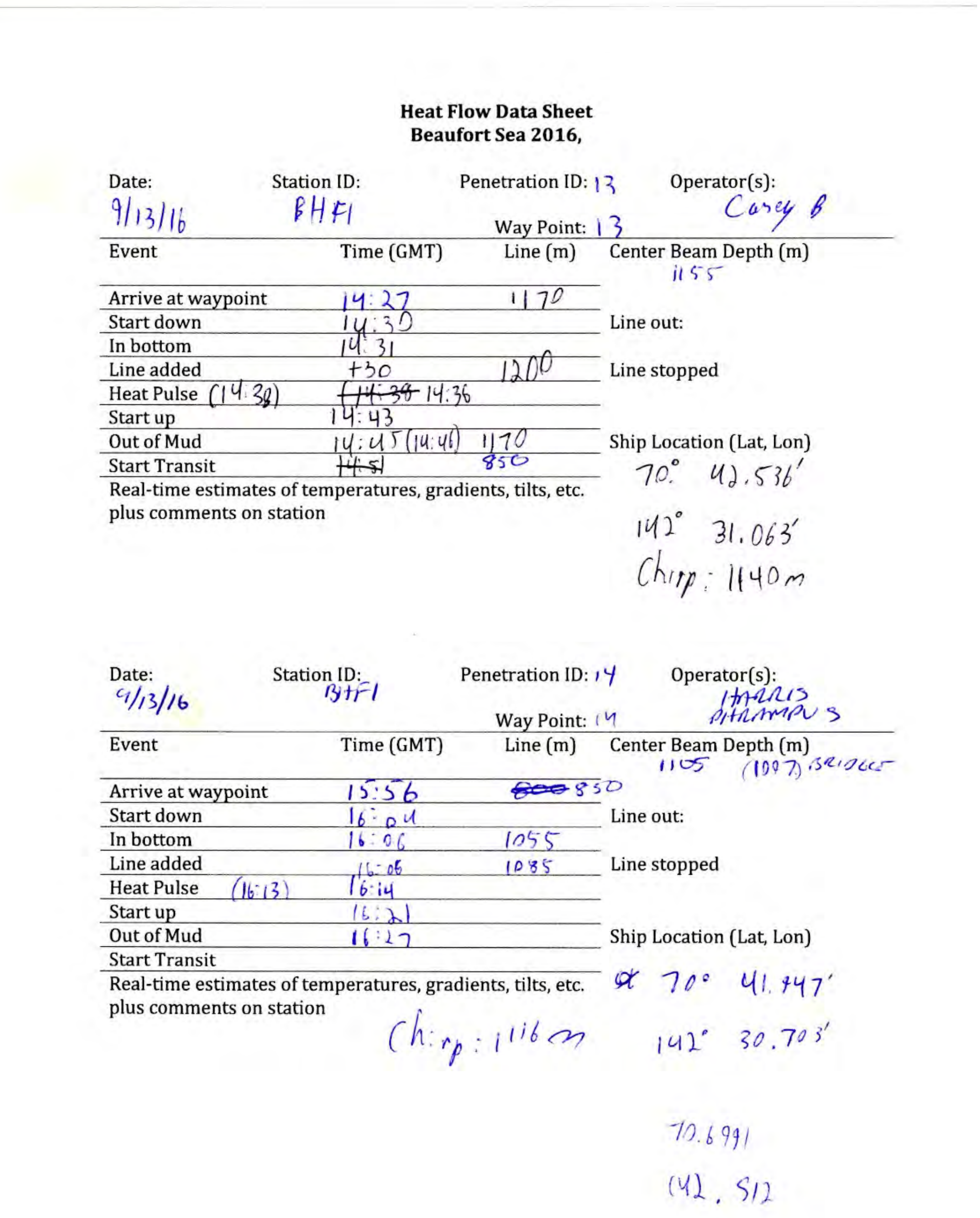
Date: 9/13/16
Station ID: BHF1
Penetration ID: 12
Way Point: 12
Operator(s): Casey B

Event	Time (GMT)	Line (m)
Arrive at waypoint	13:28	1000 m
Start down	13:31	
In bottom	13:34	1166
Line added		+30 1196
Heat Pulse	(13:41) 13:41	
Start up	13:50	
Out of Mud	13:52	1157
Start Transit	13:58	w 1000m

Center Beam Depth (m) 1157
Line out:
Line stopped
Ship Location (Lat, Lon)
70° 43.075'
70.7179
142° 31.242'
142.5209

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

~~Ranger~~
Chirp depth 1149m



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/13/16
Station ID: BHF1
Penetration ID: 13
Way Point: 13
Operator(s): Casey B

Event	Time (GMT)	Line (m)	Center Beam Depth (m) 1155
Arrive at waypoint	14:27	1170	
Start down	14:30		Line out:
In bottom	14:31		
Line added	+30	1200	Line stopped
Heat Pulse (14:38)	~~14:39~~ 14:36		
Start up	14:43		
Out of Mud	14:45 (14:46)	1170	Ship Location (Lat, Lon)
Start Transit	~~14:51~~	850	

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

70° 42.536'
142° 31.063'
Chirp: 1140 m

Date: 9/13/16
Station ID: BHF1
Penetration ID: 14
Way Point: 14
Operator(s): HARRIS DITRAMPUS

Event	Time (GMT)	Line (m)	Center Beam Depth (m) 1105 (1097) BRIDGE
Arrive at waypoint	15:56	~~800~~ 850	
Start down	16:04		Line out:
In bottom	16:06	1055	
Line added	16:08	1085	Line stopped
Heat Pulse (16:13)	16:14		
Start up	16:21		
Out of Mud	16:27		Ship Location (Lat, Lon)
Start Transit			

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Chirp: 1116 m

70° 41.447'
142° 30.703'

70.6991
142.512

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/13/16
Station ID: BHF1
Penetration ID: 15
Way Point: 15
Operator(s): Casey B + Robert Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	17:10 on site	850
Start down	17:22	
In bottom	17:24	1002
Line added		+30 1032
Heat Pulse	(17:31) 17:32	
Start up	(17:38) 17:38	
Out of Mud	17:44 wire out 988	
Start Transit	~~17:50~~ 17:49	850

Center Beam Depth (m) 1035m

Line out: 1032 total

Line stopped

Ship Location (Lat, Lon)

Stabilized time: 17:21

70° 41.4001′ 70.69
142° 30.7337′ 142.516

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Chirp depth: 1060.9m
Waited approx. 10 min for probe to stabilize

Date: 9/13/16
Station ID: BHF1
Penetration ID: 16
Way Point: 16
Operator(s): Casey B

Event	Time (GMT)	Line (m)
Arrive at waypoint	18:13	850
Start down	~~18:15~~ 18:23	
In bottom	18:25	990
Line added		+20 1010
Heat Pulse	(18:3[illegible]) 18:32	
Start up	(18:39) 18:39	
Out of Mud	16:43	
Start Transit	going to surface	

Center Beam Depth (m) 936m

Line out: 1010 total

Line stopped

Ship Location (Lat, Lon)

70° 40.908′ 70.682
142° 30.8541′

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

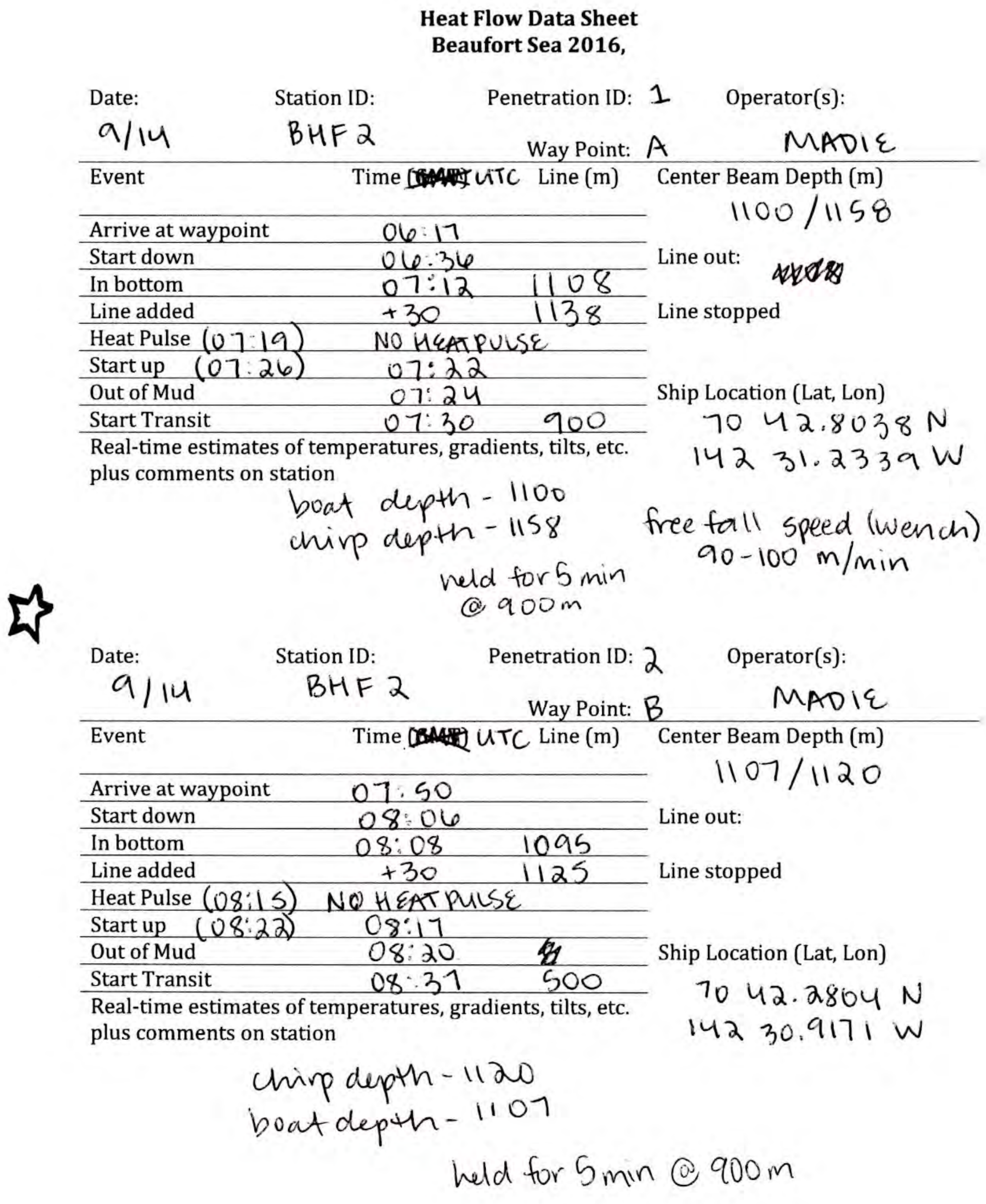
Chirp: 963.1m

Boat Dpt: 936m

Waited approx 10 min for probe to stabilize,

Probe being brought back on deck for checkup + data dump.

BHF 2 -September 14, 2017. 6 Penetrations.



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/14
Station ID: BHF2
Penetration ID: 1
Way Point: A
Operator(s): MADIE

Event	Time (~~[illegible]~~) UTC	Line (m)
Arrive at waypoint	06:17	
Start down	06:36	
In bottom	07:12	1108
Line added	+30	1138
Heat Pulse (07:19)	NO HEAT PULSE	
Start up (07:26)	07:22	
Out of Mud	07:24	
Start Transit	07:30	900

Center Beam Depth (m): 1100/1158
Line out: ~~[illegible]~~
Line stopped
Ship Location (Lat, Lon): 70 42.8038 N
142 31.2339 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

boat depth - 1100
chirp depth - 1158
held for 5 min @ 900m

free fall speed (wench)
90-100 m/min

☆

Date: 9/14
Station ID: BHF 2
Penetration ID: 2
Way Point: B
Operator(s): MADIE

Event	Time (~~[illegible]~~) UTC	Line (m)
Arrive at waypoint	07:50	
Start down	08:06	
In bottom	08:08	1095
Line added	+30	1125
Heat Pulse (08:15)	NO HEAT PULSE	
Start up (08:22)	08:17	
Out of Mud	08:20	~~[illegible]~~
Start Transit	08:31	500

Center Beam Depth (m): 1107/1120
Line out:
Line stopped
Ship Location (Lat, Lon): 70 42.2804 N
142 30.9171 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp depth - 1120
boat depth - 1107

held for 5 min @ 900m

Heat Flow Data Sheet
Beaufort Sea 2016,

Date:	Station ID:	Penetration ID: 3	Operator(s):
9/14	BHF2	Way Point: C	MADIE

Event	Time ([illegible]) UTC	Line (m)
Arrive at waypoint	09:12	
Start down	09:15	
In bottom	09:26	1020
Line added	+30	1050
Heat Pulse (09:33)	NO HEAT PULSE	
Start up (09:40)	09:34	
Out of Mud	09:37	
Start Transit	09:43	850

Center Beam Depth (m)
1031/1050

Line out:

Line stopped

Ship Location (Lat, Lon)
70 41.1843 N
142 30.8620 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp depth - 1050
boat depth - 1031 held for 5min @ 900m
appears entire probe went into mud w/ minimal tilt

Date:	Station ID:	Penetration ID: 4	Operator(s):
9/14	BHF2	Way Point: D	MADIE

Event	Time ([illegible]) UTC	Line (m)
Arrive at waypoint	09:58	
Start down	10:10	
In bottom	10:11	871
Line added	+30	901
Heat Pulse (10:18)	NO HEAT PULSE	
Start up (10:25)	10:19	
Out of Mud	10:21	
Start Transit	10:27	700

Center Beam Depth (m)
890/910

Line out:

Line stopped

Ship Location (Lat, Lon)
70 40.6582 N
142 30.8776 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp depth - 910
boat depth - 890

moved probe up to 800m
before waiting 5 min for drop

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/14
Station ID: BHF2
Penetration ID: 5
Way Point: 17
Operator(s): MADIE

Event	Time ([illegible])UTC	Line (m)
Arrive at waypoint	10:42	
Start down	10:48	
In bottom	10:50	824
Line added	+30	854
Heat Pulse	NO HEAT PULSE	
Start up	10:57	
Out of Mud	11:01	
Start Transit	11:08	600

pinger signal disappeared once it hit the bottom

Center Beam Depth (m) 810/820

Line out:

Line stopped

Ship Location (Lat, Lon)
70 40.3802 N
142 31.0442 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

+ possibly near the headwall of a submarine slide, based on chirp (PD to P17)

chirp depth - 820
boat depth - 810

waited 5 min @ 700m

Date: 9/14
Station ID: BHF2
Penetration ID: 6
Way Point: 18
Operator(s): MADIE

Event	Time ([illegible])UTC	Line (m)
Arrive at waypoint	11:27	
Start down		
In bottom		
Line added		
Heat Pulse		
Start up		
Out of Mud		
Start Transit		

Center Beam Depth (m) 736/750

Line out:

Line stopped

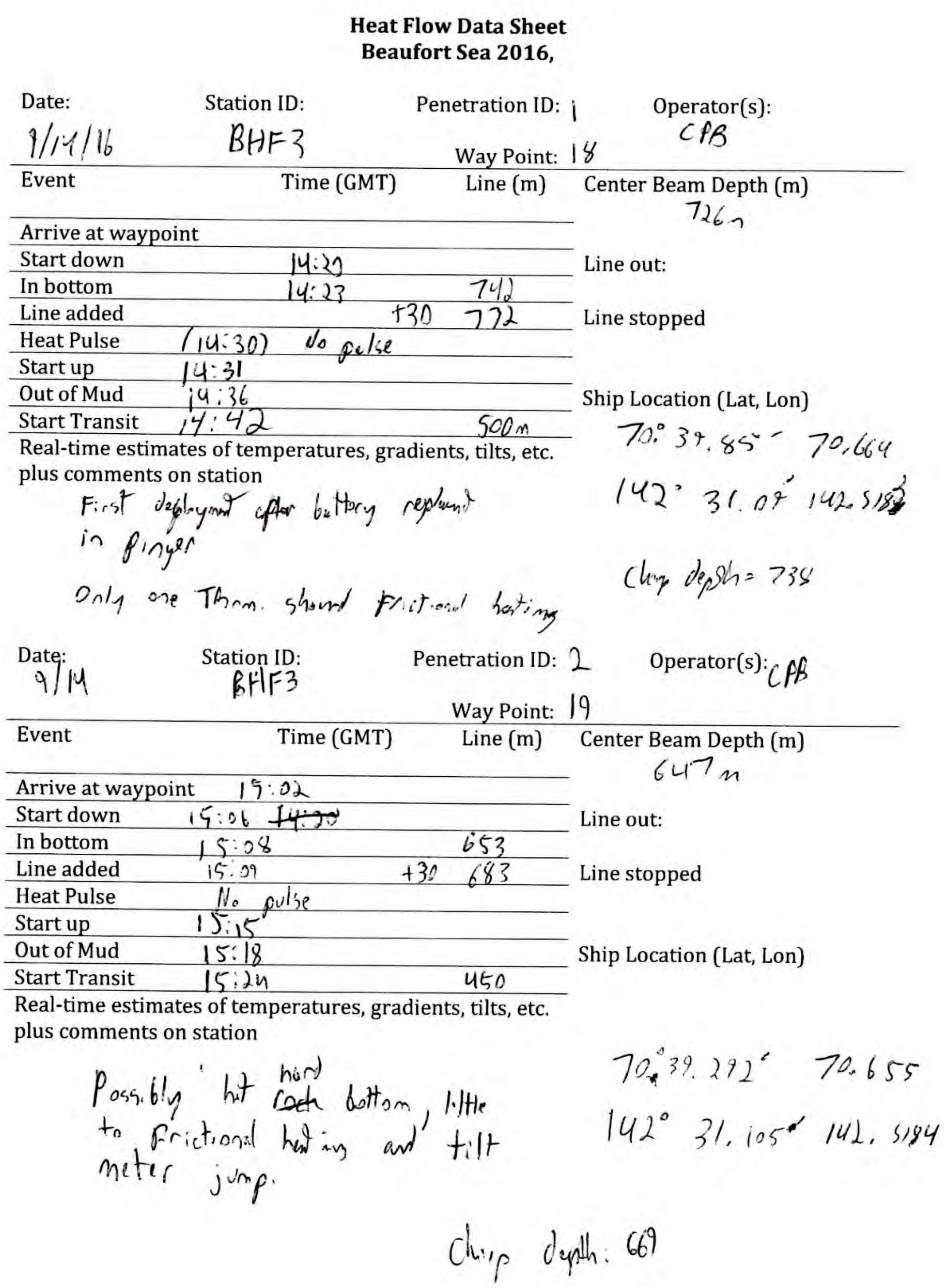
Ship Location (Lat, Lon)
70 39.8531 N
142 31.1115 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp depth - 750
boat depth - 736

HeatFlow Probe brought back up to surface @ 11:55 bc no signal from pinger.

BHF 3 -September 14-15, 2017. 14 Penetrations.



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/14/16
Station ID: BHF3
Penetration ID: 1
Way Point: 18
Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint		
Start down	14:20	
In bottom	14:23	742
Line added		+30 772
Heat Pulse	(14:30) No pulse	
Start up	14:31	
Out of Mud	14:36	
Start Transit	14:42	500m

Center Beam Depth (m) 726 m

Line out:

Line stopped

Ship Location (Lat, Lon)
70° 39.85' 70.664
142° 31.07' 142.518

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

First deployment after battery replacement in pinger

Only one Therm. showed Frictional heating

Chirp depth = 734

Date: 9/14
Station ID: BHF3
Penetration ID: 2
Way Point: 19
Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	15:02	
Start down	15:06 ~~14:30~~	
In bottom	15:08	653
Line added	15:09	+30 683
Heat Pulse	No pulse	
Start up	15:15	
Out of Mud	15:18	
Start Transit	15:24	450

Center Beam Depth (m) 647 m

Line out:

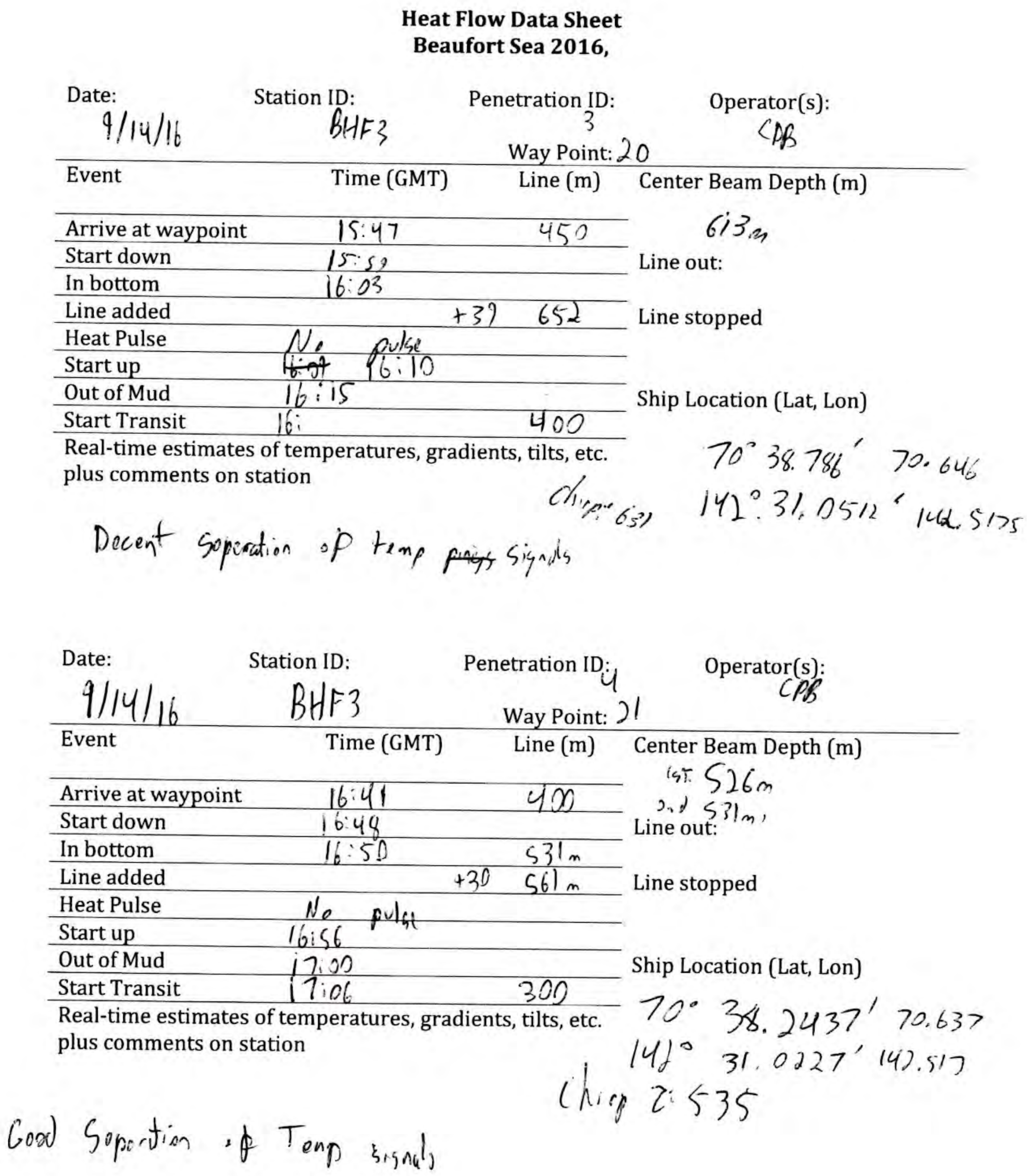
Line stopped

Ship Location (Lat, Lon)
70° 39.292' 70.655
142° 31.105' 142.5184

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Possibly hit hard ~~rock~~ bottom, little to frictional heating and tilt meter jump.

Chirp depth: 669



Heat Flow Data Sheet
Beaufort Sea 2016,

Date:	Station ID:	Penetration ID:	Operator(s):
9/14/16	BHF3	3 Way Point: 20	CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	15:47	450
Start down	15:59	
In bottom	16:03	
Line added	+39	652
Heat Pulse	No pulse	
Start up	~~16:07~~ 16:10	
Out of Mud	16:15	
Start Transit	16:	400

Center Beam Depth (m) 613m

Line out:

Line stopped

Ship Location (Lat, Lon)

70° 38.786' 70.646
141° 31.0512' 141.5175

Chirp: 631

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Decent soperation of temp ~~pings~~ signals

Date:	Station ID:	Penetration ID:	Operator(s):
9/14/16	BHF3	4 Way Point: 21	CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	16:41	400
Start down	16:48	
In bottom	16:50	531m
Line added	+30	561 m
Heat Pulse	No pulse	
Start up	16:56	
Out of Mud	17:00	
Start Transit	17:06	300

Center Beam Depth (m)
1st 526m
2nd 531m,

Line out:

Line stopped

Ship Location (Lat, Lon)

70° 38.2437' 70.637
141° 31.0227' 141.517

Chirp 2: 535

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Good Soperation of Temp signals

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/14/16
Station ID: BHF3
Penetration ID: 5
Operator(s): CPB
Way Point: ~~21~~ 22

Event	Time (GMT)	Line (m)
Arrive at waypoint	~~16:24~~ 17:24	300 m
Start down	17:33	
In bottom	17:35	477m
Line added	+30	507
Heat Pulse	No pulse	
Start up	17:41	
Out of Mud	17:45	
Start Transit	17:52	250

Center Beam Depth (m)
at arrival (477m) 477m bottom

Line out:

Line stopped

Ship Location (Lat, Lon)
70° 37.6808' 70.628
142° 31.0823' 142.518

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Chirp: 500m

Date: 9/14/16
Station ID: BHF3
Penetration ID: 6
Operator(s): CPB
Way Point: 23

Event	Time (GMT)	Line (m)
Arrive at waypoint	18:09	250
Start down	18:19	
In bottom	18:21	443
Line added	+30	473
Heat Pulse	No pulse	
Start up	18:26	
Out of Mud	18:31	
Start Transit	18:36	250

Center Beam Depth (m)
449m
443m

Line out:

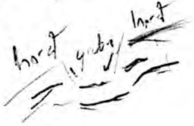
Line stopped

Ship Location (Lat, Lon)
70° 37.1353, 70.619
142°. 31.0880 142.518

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp: 460m

Site Right by Faulted ridge



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/14/16
Station ID: BHF3
Penetration ID: 7
Operator(s): CPB
Way Point: ~~23~~ 24

Event	Time (GMT)	Line (m)
Arrive at waypoint	18:52	250
Start down	19:01	
In bottom	19:03	416
Line added		+30 446
Heat Pulse	No pulse	
Start up	19:09	
Out of Mud	19:13	
Start Transit	19:17	250

Center Beam Depth (m): 424m

Line out:

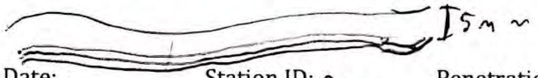
Line stopped

Ship Location (Lat, Lon)
70° 36.5836' 70.61
142° 31.0495 142.5175

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Good stratification approx 5m ~~below~~ below sea floor.
Faulting/Folding in strata is apparent

Chirp dpt = 435m



Date: 9/14/16
Station ID: BHF3
Penetration ID: 8
Operator(s): CPB
Way Point: 25

Event	Time (GMT)	Line (m)
Arrive at waypoint	19:34	250
Start down	19:43	
In bottom	19:45	390
Line added		+30 420
Heat Pulse	No Pulse	
Start up	19:51	
Out of Mud	19:55	
Start Transit	20:00	200

Center Beam Depth (m): 400

Line out:

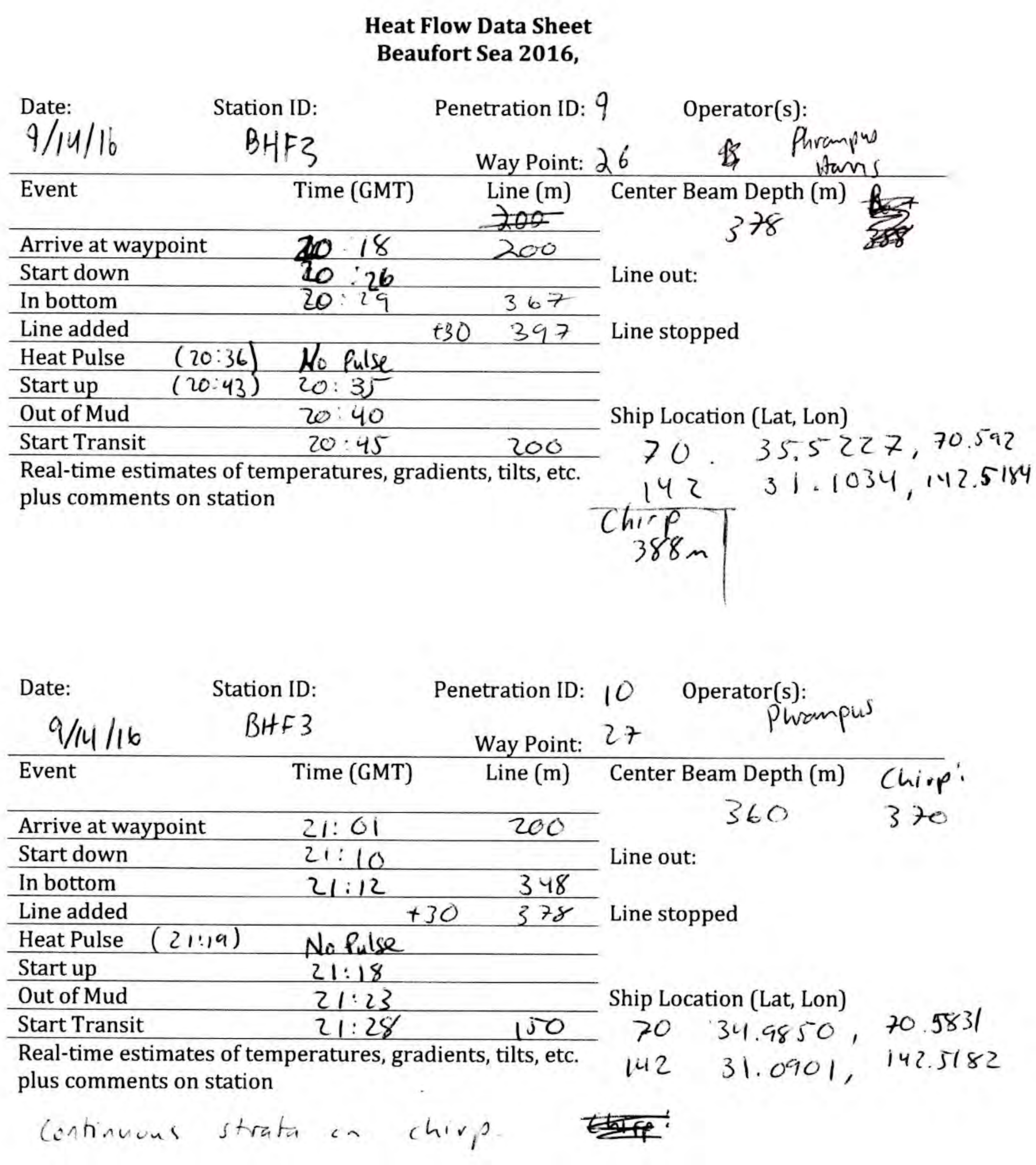
Line stopped

Ship Location (Lat, Lon)
70° 36.0603' 70.601
142° 31.1282' 142.519

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Chirp: 410m

On slope, strata still well represented in profile



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/14/16
Station ID: BHF3
Penetration ID: 9
Way Point: 26
Operator(s): ~~B~~ Phrampus Harris

Event	Time (GMT)	Line (m)
		~~200~~
Arrive at waypoint	20:18	200
Start down	20:26	
In bottom	20:29	367
Line added	+30	397
Heat Pulse (20:36)	No Pulse	
Start up (20:43)	20:35	
Out of Mud	20:40	
Start Transit	20:45	200

Center Beam Depth (m) 378 ~~388~~

Line out:

Line stopped

Ship Location (Lat, Lon)
70. 35.5227, 70.592
142 31.1034, 142.5184

Chirp 388m

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9/14/16
Station ID: BHF3
Penetration ID: 10
Way Point: 27
Operator(s): Phrampus

Event	Time (GMT)	Line (m)
Arrive at waypoint	21:01	200
Start down	21:10	
In bottom	21:12	348
Line added	+30	378
Heat Pulse (21:19)	No Pulse	
Start up	21:18	
Out of Mud	21:23	
Start Transit	21:28	150

Center Beam Depth (m) 360 Chirp: 370

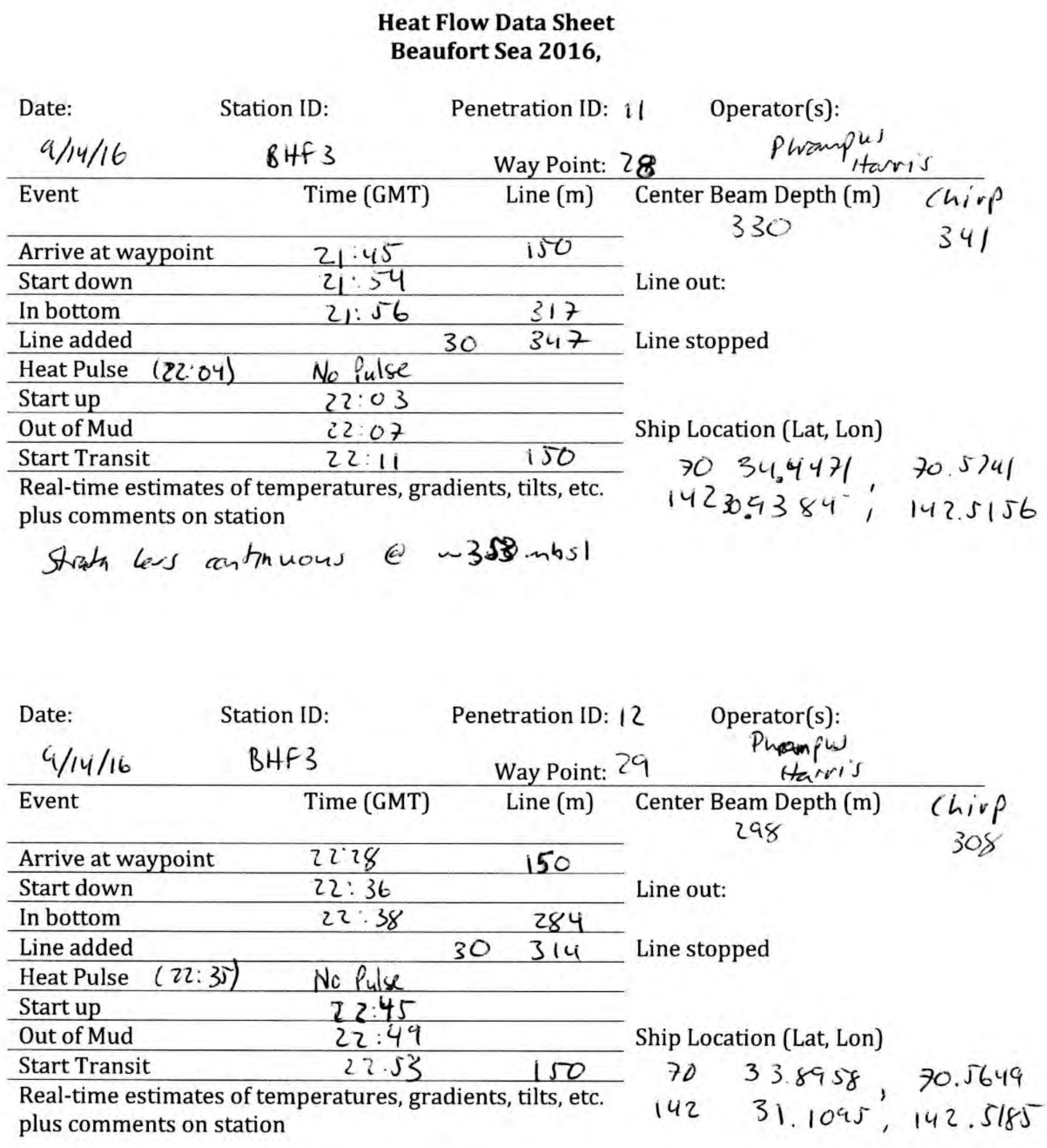
Line out:

Line stopped

Ship Location (Lat, Lon)
70 34.9850, 70.5831
142 31.0901, 142.5182

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Continuous strata on chirp. ~~Chirp~~:



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/14/16
Station ID: BHF3
Penetration ID: 11
Way Point: 28
Operator(s): Phrampus, Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	21:45	150
Start down	21:54	
In bottom	21:56	317
Line added		30 347
Heat Pulse (22:04)	No Pulse	
Start up	22:03	
Out of Mud	22:07	
Start Transit	22:11	150

Center Beam Depth (m): 330
Chirp: 341
Line out:
Line stopped
Ship Location (Lat, Lon):
70 34.4471, 70.5741
142 30.9384, 142.5156

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

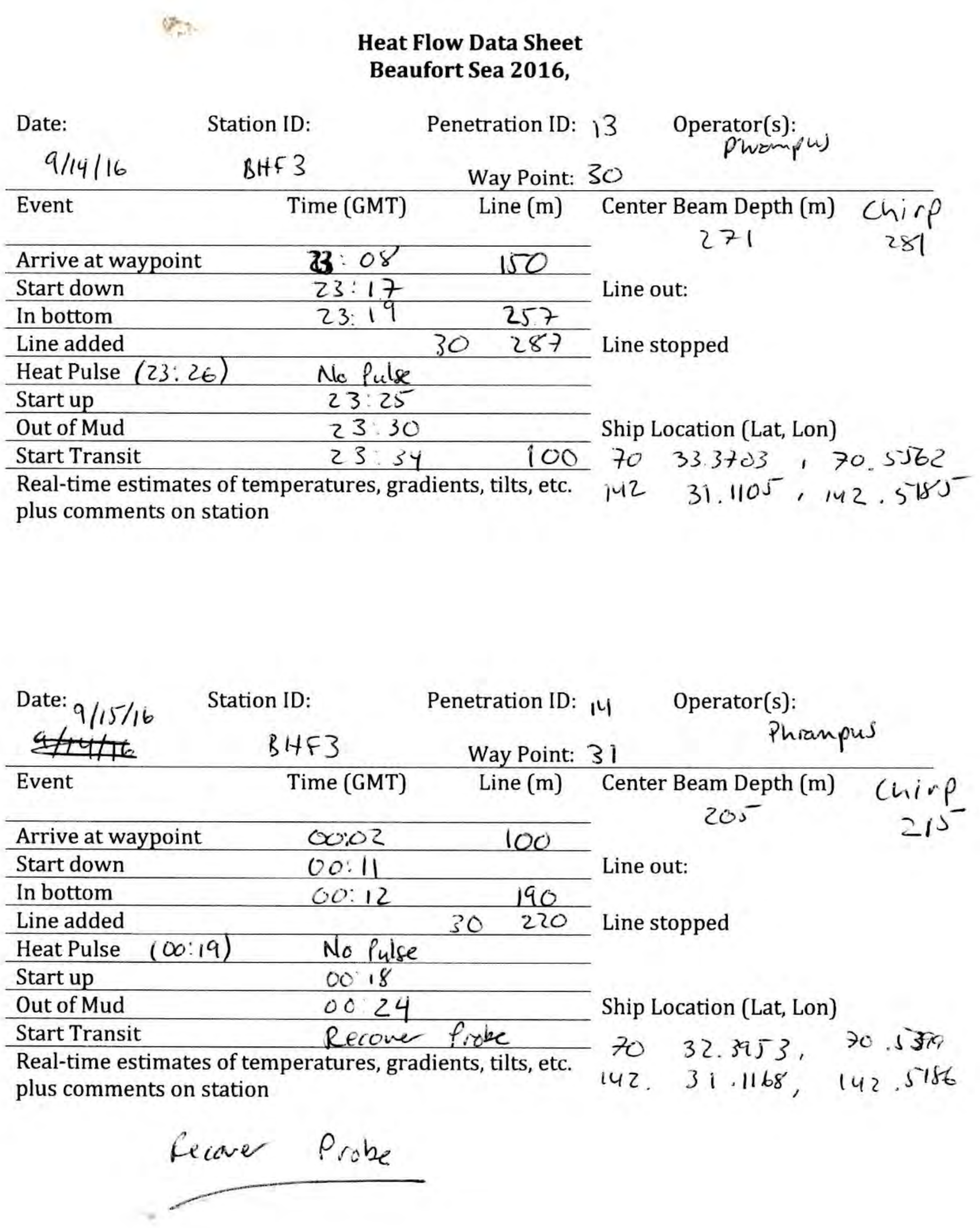
Strata less continuous @ ~358 mbsl

Date: 9/14/16
Station ID: BHF3
Penetration ID: 12
Way Point: 29
Operator(s): Phrampus, Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	22:28	150
Start down	22:36	
In bottom	22:38	284
Line added		30 314
Heat Pulse (22:35)	No Pulse	
Start up	22:45	
Out of Mud	22:49	
Start Transit	22:53	150

Center Beam Depth (m): 298
Chirp: 308
Line out:
Line stopped
Ship Location (Lat, Lon):
70 33.8958, 70.5649
142 31.1095, 142.5185

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/14/16
Station ID: BHF3
Penetration ID: 13
Operator(s): Phrampus
Way Point: 30

Event	Time (GMT)	Line (m)	Center Beam Depth (m)	Chirp
			271	281
Arrive at waypoint	23:08	150		
Start down	23:17		Line out:	
In bottom	23:19	257		
Line added		30 287	Line stopped	
Heat Pulse (23:26)	No Pulse			
Start up	23:25			
Out of Mud	23:30		Ship Location (Lat, Lon)	
Start Transit	23:34	100	70 33.3703 , 70.5562	
Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station			142 31.1105 , 142.5185	

Date: 9/15/16 ~~9/14/16~~
Station ID: BHF3
Penetration ID: 14
Operator(s): Phrampus
Way Point: 31

Event	Time (GMT)	Line (m)	Center Beam Depth (m)	Chirp
			205	215
Arrive at waypoint	00:02	100		
Start down	00:11		Line out:	
In bottom	00:12	190		
Line added		30 220	Line stopped	
Heat Pulse (00:19)	No Pulse			
Start up	00:18			
Out of Mud	00:24		Ship Location (Lat, Lon)	
Start Transit	Recover Probe		70 32.3953, 70.5399	
Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station			142. 31.1168, 142.5186	

Recover Probe

BHF 4 -September 15-16, 2017. 11 Penetrations.

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 15-SEP-16
Station ID: BHF4
Penetration ID: 1
Operator(s): CPB
Way Point: 2

Event	Time (GMT)	Line (m)
Arrive at waypoint	18:12	25 going to 100m
Start down	18:21	100m
In bottom	18:23	208m
Line added	18:23	+30 238m
Heat Pulse	No pulse	
Start up	18:30	238m
Out of Mud	18:34	~~18~~
Start Transit	18:36	125m

Center Beam Depth (m)
203

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 12.136′ 71.202
~~[illegible]~~ 148° 41.44′ 148.6907
Chirp Z = 209m

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

1st deployment on BHF4

Waypoint 1 was too shallow <100m so we moved on to this one Waypoint 2

Date: 15-Sep-16
Station ID: BHF4
Penetration ID: 2
Operator(s): CPB
Way Point: 3

Event	Time (GMT)	Line (m)
	1	125m
Arrive at waypoint	18:53	125m
Start down	19:03	
In bottom	19:05	294m
Line added		+30 ~~325~~ 324m
Heat Pulse	No pulse	
Start up	19:11	324m
Out of Mud	19:16	294, ~~[illegible]~~
Start Transit	19:18	200m

Center Beam Depth (m)
290m

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 12.6049′ 71.210
148° 40.6651′ 148.6778
Chirp Z: 300m

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9-15-16
Station ID: BHF4
Penetration ID: 3
Way Point: 4
Operator(s): CPB

Event	Time (GMT)		Line (m)
			~~200~~
Arrive at waypoint	19:34		200
Start down	19:44		
In bottom	19:47		421
Line added		+30	451
Heat Pulse	No pulse		
Start up	19:53		
Out of Mud	19:57		
Start Transit	20:00		300

Center Beam Depth (m): 400m

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 13.0840′ ~~71.218~~ 71.218
148° 39.935· 148.6565

Chirp z = 412m

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Tilt meter showing lots of movement, though it — is more likely a fault in the meter rather than probe oscillation. ~~of the probe~~

Date: 9.15.16
Station ID: BHF4
Penetration ID: 4
Way Point: 5
Operator(s): ~~BP~~ Phrampus Harris

Event	Time (GMT)		Line (m)
Arrive at waypoint	20:29		300
Start down	20:39		
In bottom	20:43		~~537~~ 551
Line added		30	581
Heat Pulse (20:49)	No Pulse		
Start up	20:49		
Out of Mud	20:53		
Start Transit	20:55		450

Center Beam Depth (m): 540
Chirp: 550

Line out:

Line stopped

Ship Location (Lat, Lon)
71 13.5634, 71.2261
148 39.1543, 142.6526

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Went into bottom @ ~60 m/min

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/15/16
Station ID: BHF4
Penetration ID: 5
Way Point: 6
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	21:13	450
Start down	21:23	
In bottom	21:26	682
Line added		30 717
Heat Pulse (21:33)	No Pulse	
Start up	21:32	
Out of Mud	21:37	
Start Transit	21:41	550

Center Beam Depth (m) 648 Chirp 662

Line out:

Line stopped

Ship Location (Lat, Lon)
71 14.0341, 71.2339
148 38.4820, 148.6424

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9/15/16
Station ID: BHF4
Penetration ID: 6
Way Point: 7
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	22:04	550 ↓ 600
Start down	22:13	
In bottom	22:17	798
Line added		40 838
Heat Pulse (22:24)	No Pulse	
Start up	22:23	
Out of Mud	22:29	
Start Transit	22:32	700

Center Beam Depth (m) 783 Chirp 761

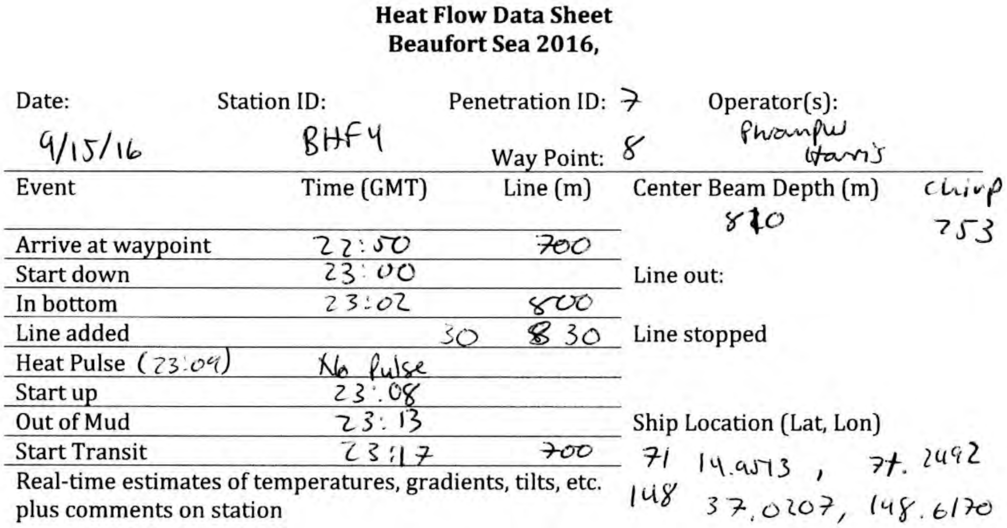
Line out:

Line stopped

Ship Location (Lat, Lon)
71 14.4987, 71.2416
148 37.7090, 148.6285

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

lowered probe from 550 to 600 m
before drop



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/15/16
Station ID: BHF4
Penetration ID: 7
Way Point: 8
Operator(s): Phampu Harris

Event	Time (GMT)		Line (m)
Arrive at waypoint	22:50		700
Start down	23:00		
In bottom	23:02		800
Line added		30	830
Heat Pulse (23:09)	No Pulse		
Start up	23:08		
Out of Mud	23:13		
Start Transit	23:17		700

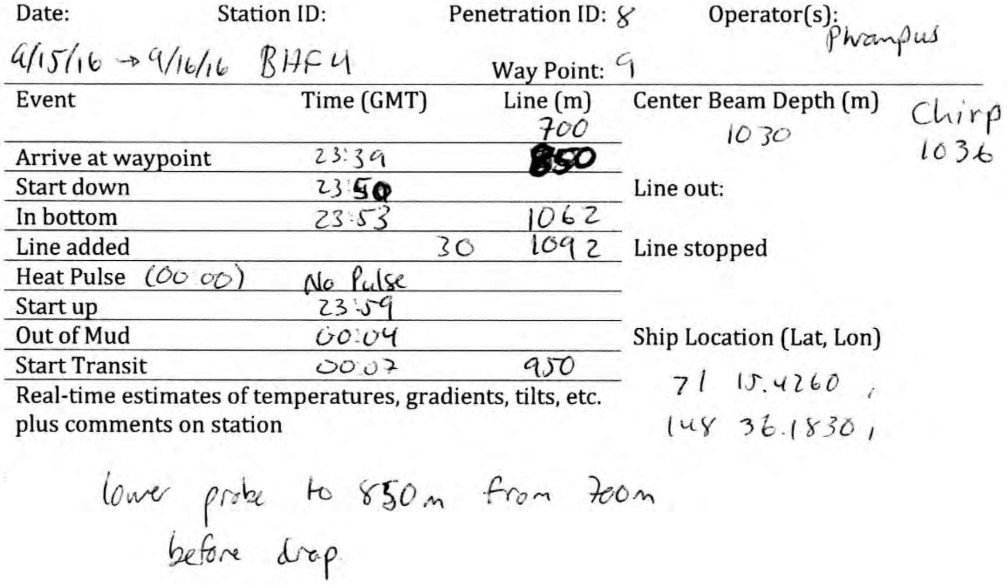
Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Center Beam Depth (m) 810 chirp 753

Line out:

Line stopped

Ship Location (Lat, Lon)
71 14.9573 , 71.2492
148 37.0207, 148.6170



Date: 9/15/16 → 9/16/16
Station ID: BHF4
Penetration ID: 8
Way Point: 9
Operator(s): Phampus

Event	Time (GMT)		Line (m)
			700
Arrive at waypoint	23:39		850
Start down	23:50		
In bottom	23:53		1062
Line added		30	1092
Heat Pulse (00 00)	No Pulse		
Start up	23:59		
Out of Mud	00:04		
Start Transit	00:07		950

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Center Beam Depth (m) 1030 Chirp 1036

Line out:

Line stopped

Ship Location (Lat, Lon)
71 15.4260 ,
148 36.1830 ,

lower probe to 850m from 700m
before drop

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/16/16
Station ID: BHF4
Penetration ID: 9
Way Point: 10
Operator(s): Phrampus
Harris

Event	Time (GMT)	Line (m)	Center Beam Depth (m)	Chirp
			1248	1200
Arrive at waypoint	00:47	~~[illegible]~~ 1000		
Start down	00:55		Line out:	
In bottom	00:58	1256		
Line added		30 1286	Line stopped	
Heat Pulse (01-05)	No Pulse			
Start up	01:04			
Out of Mud	01:10		Ship Location (Lat, Lon)	
Start Transit	01:15	1100	71 15.9972 , 71.2666	
Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station			148 35.4268 ; 148.5904	

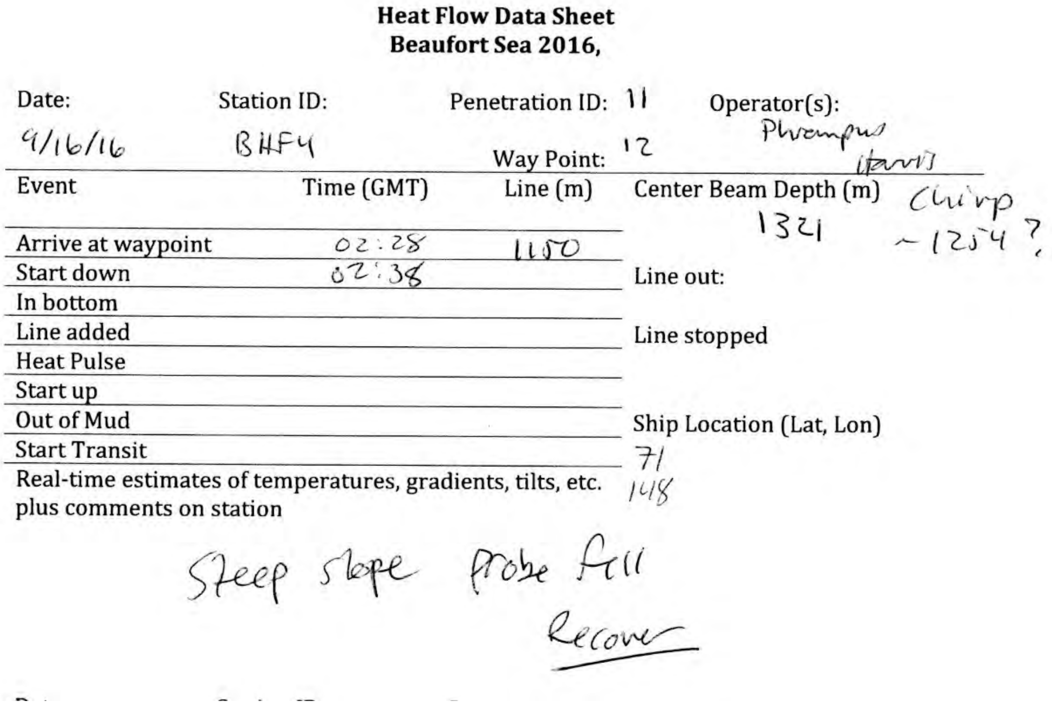
~~pings reset, is now between~~

very steep slope potentially

Date: 9/16/16
Station ID: BHF4
Penetration ID: 10
Way Point: 11
Operator(s): Phrampus
Harris

Event	Time (GMT)	Line (m)	Center Beam Depth (m)	Chirp
			1247	~1225
Arrive at waypoint	01:37	1100		
Start down	01:47		Line out:	
In bottom	01:50	1295		
Line added			Line stopped	
Heat Pulse (	No Pulse			
Start up				
Out of Mud			Ship Location (Lat, Lon)	
Start Transit	01:58	1150	71	
Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station			148	

steep slope / tipped over probe
move on to next
station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/16/16
Station ID: BHF4
Penetration ID: 11
Way Point: 12
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	02:28	1150
Start down	02:38	
In bottom		
Line added		
Heat Pulse		
Start up		
Out of Mud		
Start Transit		

Center Beam Depth (m) 1321 Chirp ~1254 ?

Line out:

Line stopped

Ship Location (Lat, Lon)
71
148

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

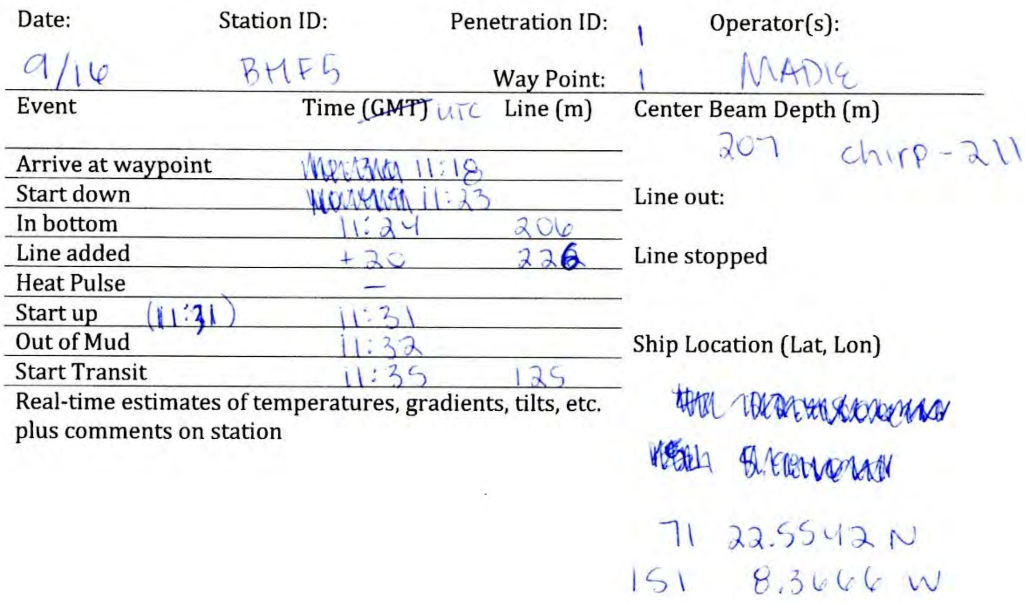
Steep slope probe fell

Recover

(Image above was cropped – bottom of page pertains to BHF 5, appearing in next section.)

BHF 5 -September 16, 2017. 12 Penetrations.

(Image below was cropped – top of page pertains to BHF 4, appearing in previous section.)



Date: 9/16

Station ID: BHF5

Penetration ID: 1

Way Point: 1

Operator(s): MADIE

Event	Time ~~(GMT)~~ UTC	Line (m)
Arrive at waypoint	11:18	
Start down	11:23	
In bottom	11:24	206
Line added	+20	226
Heat Pulse	—	
Start up (11:31)	11:31	
Out of Mud	11:32	
Start Transit	11:35	125

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

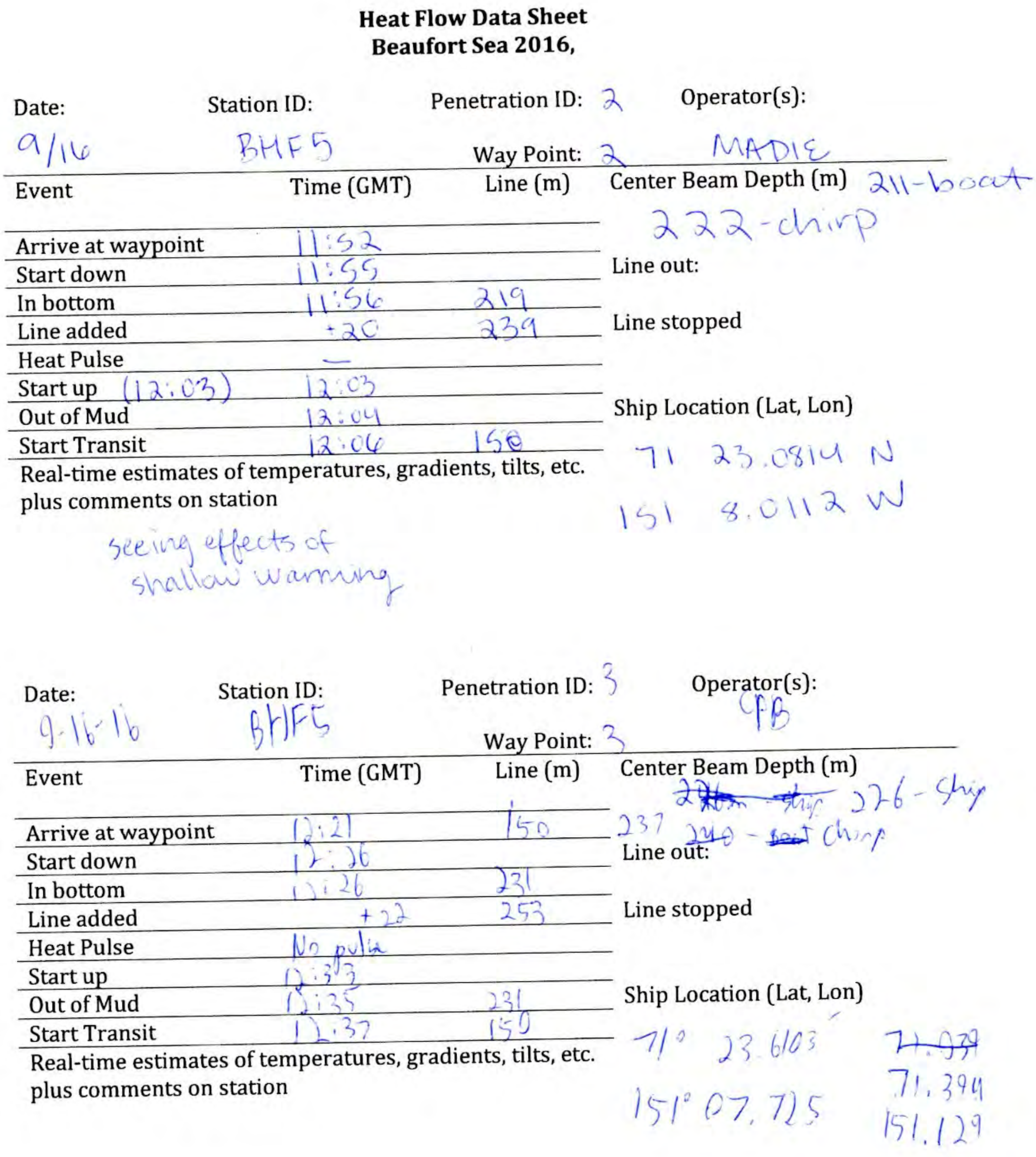
Center Beam Depth (m) 207 chirp - 211

Line out:

Line stopped

Ship Location (Lat, Lon)

71 22.5542 N
151 8.3666 W



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/16
Station ID: BHF5
Penetration ID: 2
Way Point: 2
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	11:52	
Start down	11:55	
In bottom	11:56	219
Line added	+20	239
Heat Pulse	—	
Start up (12:03)	12:03	
Out of Mud	12:04	
Start Transit	12:06	150

Center Beam Depth (m) 211-boat
222-chirp

Line out:

Line stopped

Ship Location (Lat, Lon)
71 23.0814 N
151 8.0112 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

seeing effects of
shallow warming

Date: 9-16-16
Station ID: BHF5
Penetration ID: 3
Way Point: 3
Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	12:21	150
Start down	12:26	
In bottom	12:26	231
Line added	+22	253
Heat Pulse	No pulse	
Start up	12:33	
Out of Mud	12:35	231
Start Transit	12:37	150

Center Beam Depth (m) ~~22[illegible] - ship~~ 226 - ship
237 ~~240~~ - ~~boat~~ chirp

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 23.6103 ~~71.939~~
151° 07.725 71.394
151.129

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9-16-16
Station ID: BHF5
Penetration ID: 4
Way Point: 4
Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	12:57	150
Start down	13:02	
In bottom	13:03	251
Line added		+20 271
Heat Pulse	No pulse	
Start up	13:09	271
Out of Mud	13:11	251
Start Transit	13:13	175

Center Beam Depth (m)
250 - ship
258 - chirp

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 24.13' 71.402
151° 07.361' 151.123

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Decay in Temp profile
Seasonal effects dominated

Date: 9·16·16
Station ID: BHF5
Penetration ID: 5
Way Point: 5
Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	~~12:56~~ 13:31	175
Start down	13:37	
In bottom	13:38	297
Line added	0	318
Heat Pulse	No pulse	
Start up	13:44	319
Out of Mud	13:47	
Start Transit	13:48	225

Center Beam Depth (m)
294 - ship 305 - chirp

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 24.659' 71.411
151° 06.996 151.117

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9-16-16

Station ID: BHF5

Penetration ID: 6

Way Point: 6

Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	14:10	225
Start down	14:18	
In bottom	14:17	377
Line added		+23 400
Heat Pulse	No pulse	
Start up	14:24	400
Out of Mud	14:25	
Start Transit	14:27	200

Center Beam Depth (m)
381 - Ship 390 - Chirp

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 25.188´ 71.4198 71.42
151° 06.704´ 151.112

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9·16·16

Station ID: BHF5

Penetration ID: 7

Way Point: 7

Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	14:48	300
Start down	14:53	
In bottom	14:55	508
Line added		+22 530
Heat Pulse	No pulse	
Start up	15:02	
Out of Mud	15:03	
Start Transit	15:05	450

Center Beam Depth (m)
511 - Ship 524 - Chirp

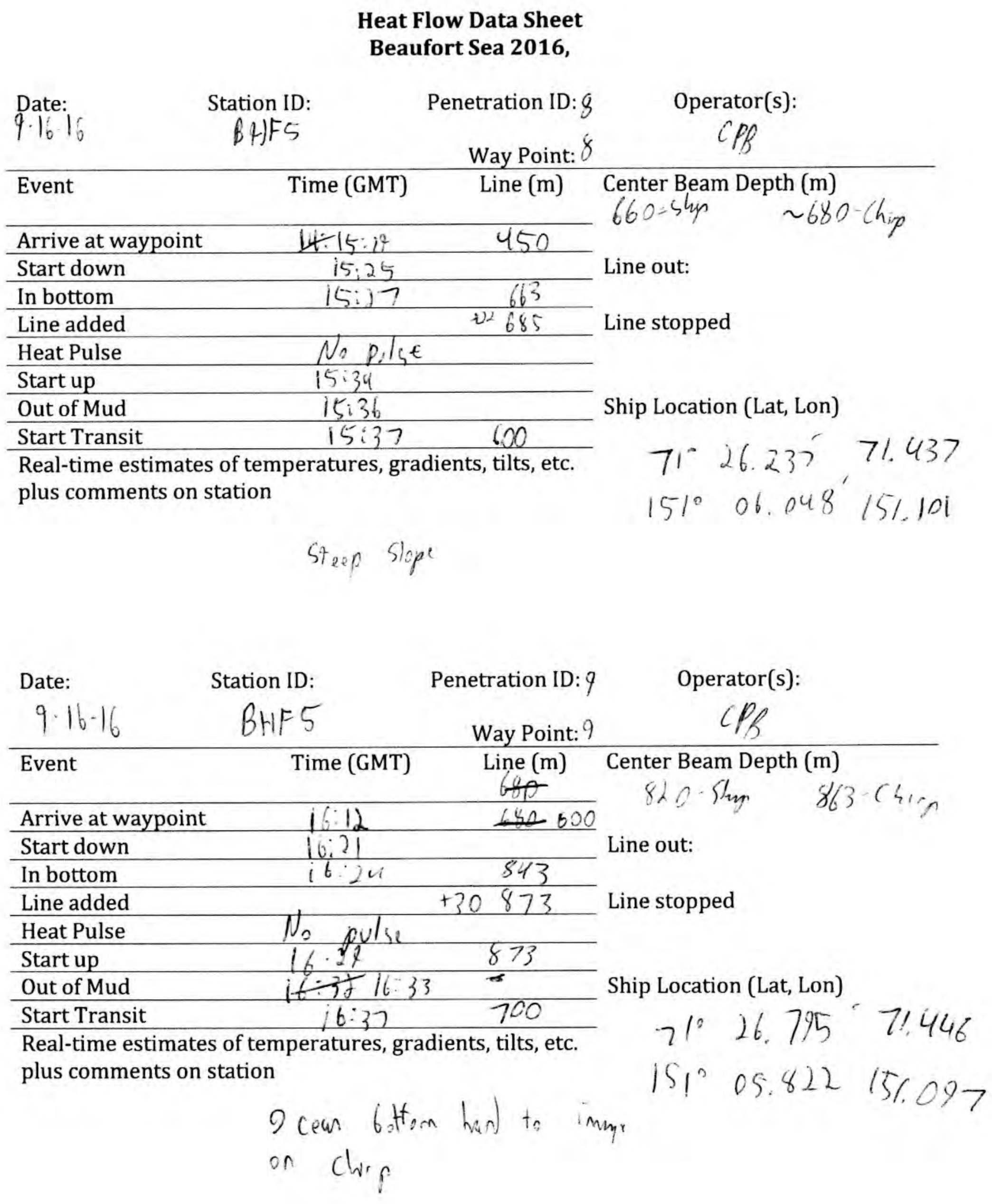
Line out:

Line stopped

Ship Location (Lat, Lon)
71° 25.722´ 71.429
151° 06.358´ 151.106

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Small seperation of Temp signals, little frictional heating



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9.16.16
Station ID: BHF5
Penetration ID: 8
Way Point: 8
Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	~~14:~~ 15:19	450
Start down	15:25	
In bottom	15:27	663
Line added		+22 685
Heat Pulse	No pulse	
Start up	15:34	
Out of Mud	15:36	
Start Transit	15:37	600

Center Beam Depth (m)
660-Ship ~680-Chirp

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 26.237' 71.437
151° 06.048' 151.101

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Steep Slope

Date: 9.16.16
Station ID: BHF5
Penetration ID: 9
Way Point: 9
Operator(s): CPB

Event	Time (GMT)	Line (m)
		~~680~~
Arrive at waypoint	16:12	~~680~~ 600
Start down	16:21	
In bottom	16:24	843
Line added		+30 873
Heat Pulse	No pulse	
Start up	16:28	873
Out of Mud	~~16:33~~ 16:33	
Start Transit	16:37	700

Center Beam Depth (m)
820-Ship 863-Chirp

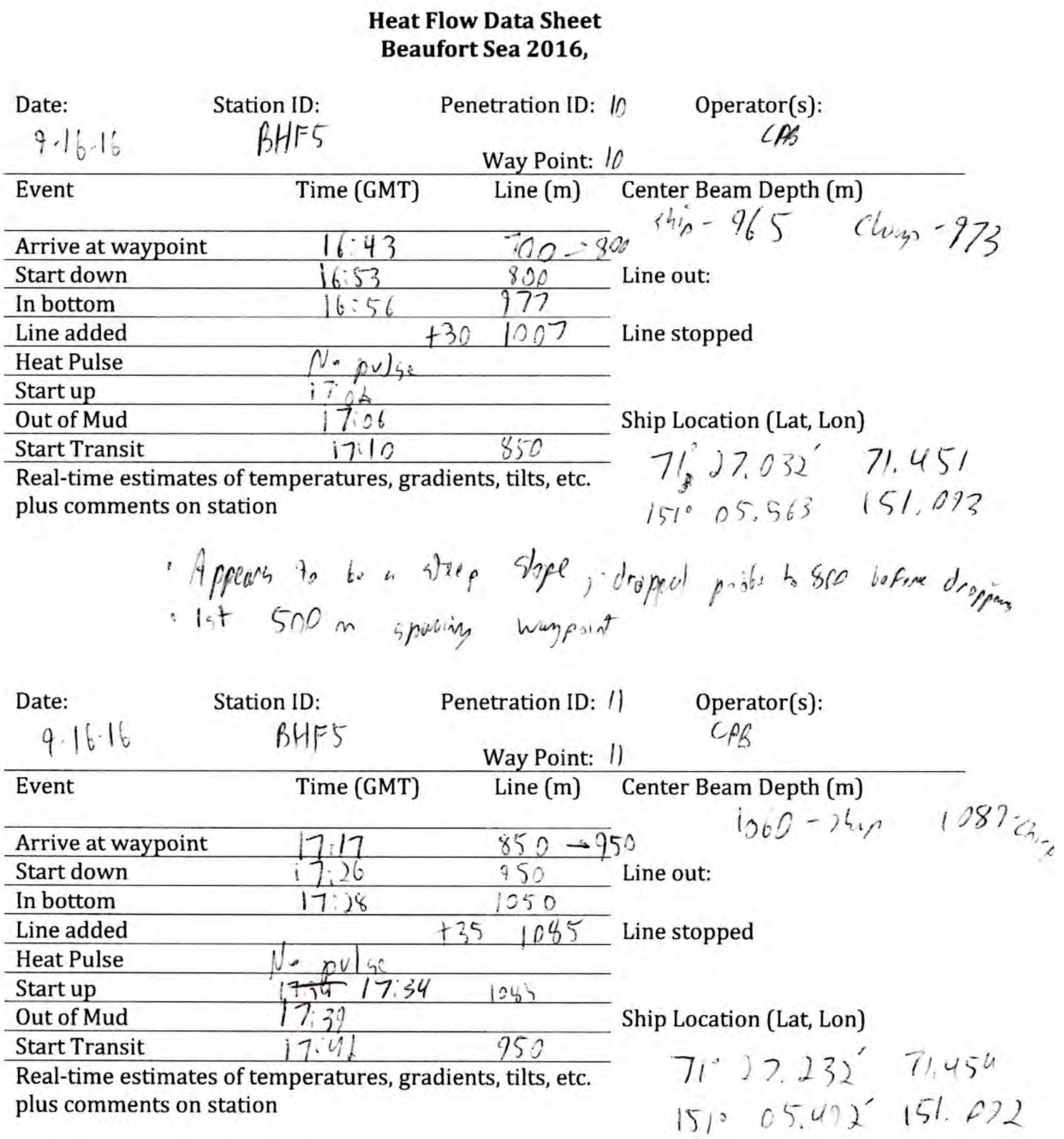
Line out:

Line stopped

Ship Location (Lat, Lon)
71° 26.795' 71.446
151° 05.822 151.097

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Ocean bottom hard to image on Chirp



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9.16.16
Station ID: BHF5
Penetration ID: 10
Operator(s): CPB
Way Point: 10

Event	Time (GMT)	Line (m)
Arrive at waypoint	16:43	700 → 800
Start down	16:53	800
In bottom	16:56	977
Line added		+30 1007
Heat Pulse	No pulse	
Start up	17:06	
Out of Mud	17:06	
Start Transit	17:10	850

Center Beam Depth (m): ship - 965 Chirp - 973

Line out:

Line stopped

Ship Location (Lat, Lon)

71° 27.032′ 71.451
151° 05.563 151.093

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

- Appears to be a steep slope; dropped probe to 800 before dropping
- 1st 500 m spacing waypoint

Date: 9.16.16
Station ID: BHF5
Penetration ID: 11
Operator(s): CPB
Way Point: 11

Event	Time (GMT)	Line (m)
Arrive at waypoint	17:17	850 → 950
Start down	17:26	950
In bottom	17:28	1050
Line added		+35 1085
Heat Pulse	No pulse	
Start up	~~17:34~~ 17:34	1043
Out of Mud	17:39	
Start Transit	17:41	950

Center Beam Depth (m): 1060 - ship 1087 Chirp

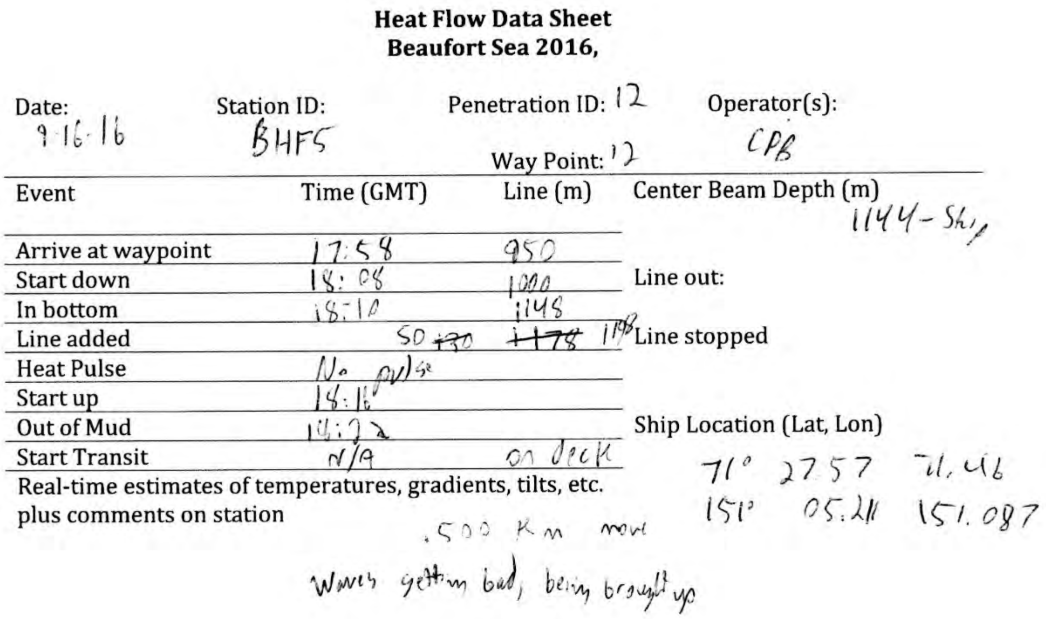
Line out:

Line stopped

Ship Location (Lat, Lon)

71° 27.232′ 71.454
151° 05.492′ 151.092

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9.16.16

Station ID: BHF5

Penetration ID: 12

Way Point: 12

Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	17:58	950
Start down	18:08	1000
In bottom	18:10	1148
Line added	50 ~~130~~	~~1178~~ 1198
Heat Pulse	No pulse	
Start up	18:16	
Out of Mud	18:22	
Start Transit	N/A	on deck

Center Beam Depth (m) 1144 - Ship

Line out:

Line stopped

Ship Location (Lat, Lon)

71°	27.57	71.46
151°	05.211	151.087

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

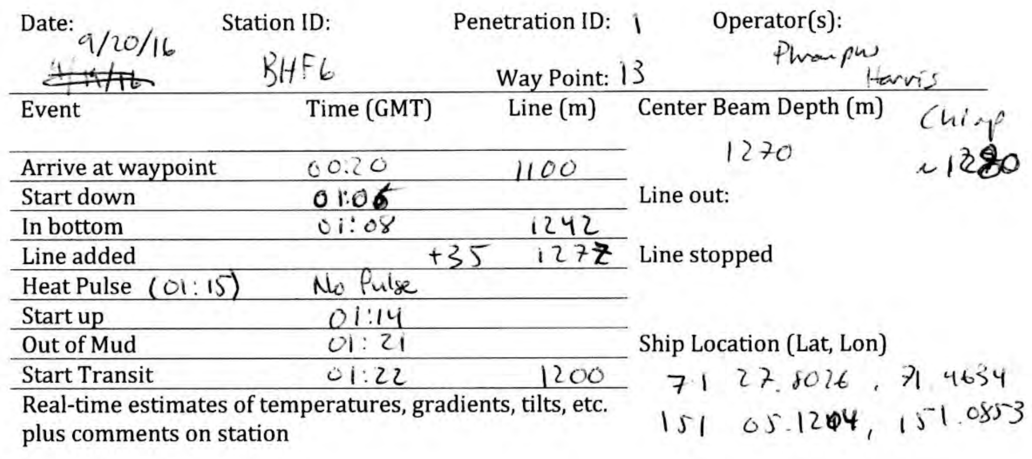
.500 Km move

Waves getting bad, being brought up

(Image above was cropped – bottom of page pertains to BHF 6, appearing in next section.)

BHF 6 – September 20, 2017. 22 Penetrations

(Image below was cropped – top of page pertains to BHF 5, appearing in previous section.)



Date: 9/20/16

Station ID: BHF6

Penetration ID: 1

Way Point: 13

Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	00:20	1100
Start down	01:06	
In bottom	01:08	1242
Line added	+35	1277
Heat Pulse (01:15)	No Pulse	
Start up	01:14	
Out of Mud	01:21	
Start Transit	01:22	1200

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Center Beam Depth (m) 1270

Chirp ~1280

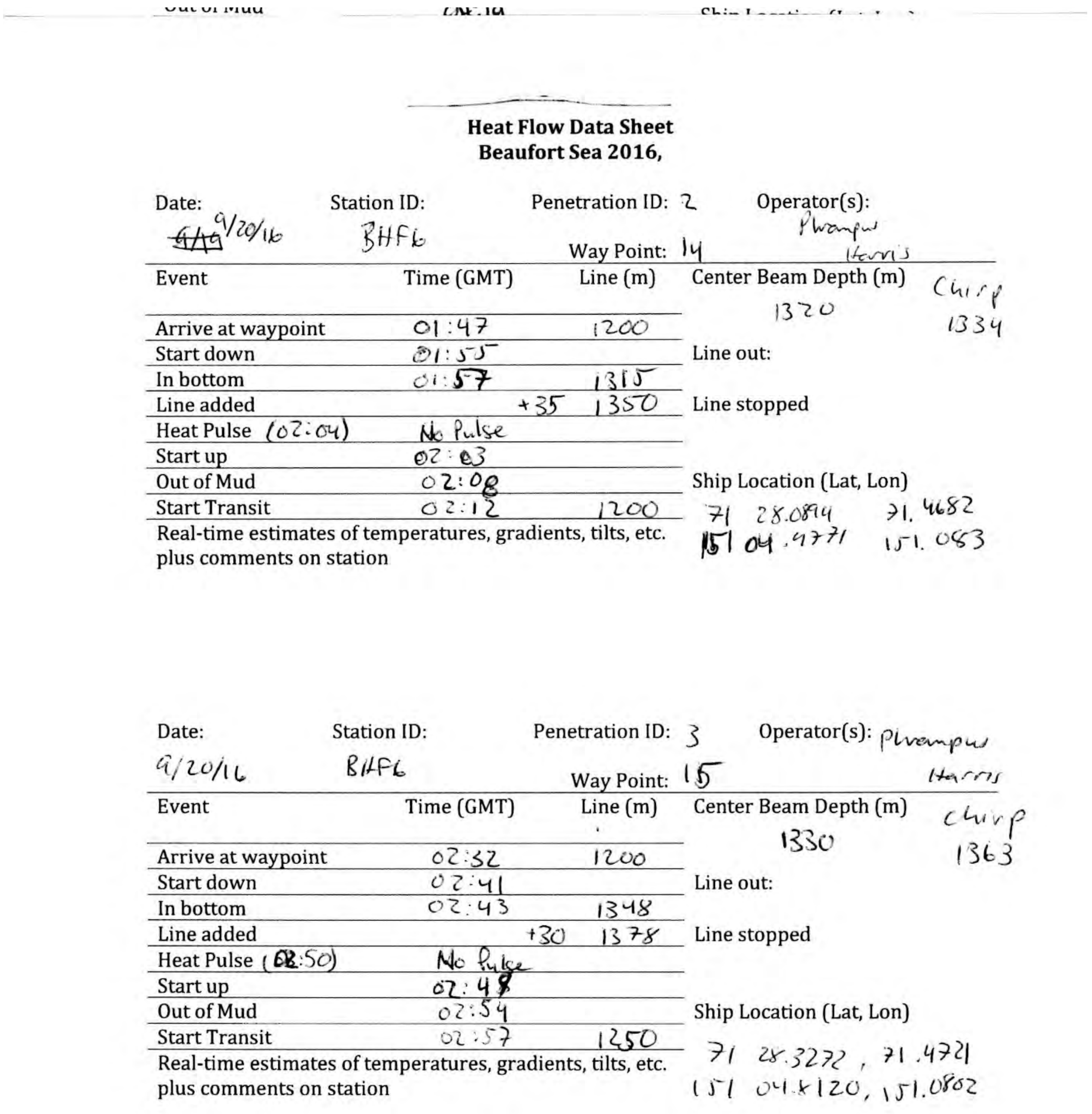
Line out:

Line stopped

Ship Location (Lat, Lon)

71 27.8026, 71.4634

151 05.1204, 151.0853



Out of Mud

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: ~~6/19~~ 9/20/16
Station ID: BHF6
Penetration ID: 2
Way Point: 14
Operator(s): Phrampus, Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	01:47	1200
Start down	01:55	
In bottom	01:57	1315
Line added		+35 1350
Heat Pulse (02:04)	No Pulse	
Start up	02:03	
Out of Mud	02:08	
Start Transit	02:12	1200

Center Beam Depth (m) 1320 Chirp 1334

Line out:

Line stopped

Ship Location (Lat, Lon)
71 28.0894 71.4682
151 04.4771 151.083

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Date: 9/20/16
Station ID: BHF6
Penetration ID: 3
Way Point: 15
Operator(s): Phrampus, Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	02:32	1200
Start down	02:41	
In bottom	02:43	1348
Line added		+30 1378
Heat Pulse (02:50)	No Pulse	
Start up	02:48	
Out of Mud	02:54	
Start Transit	02:57	1250

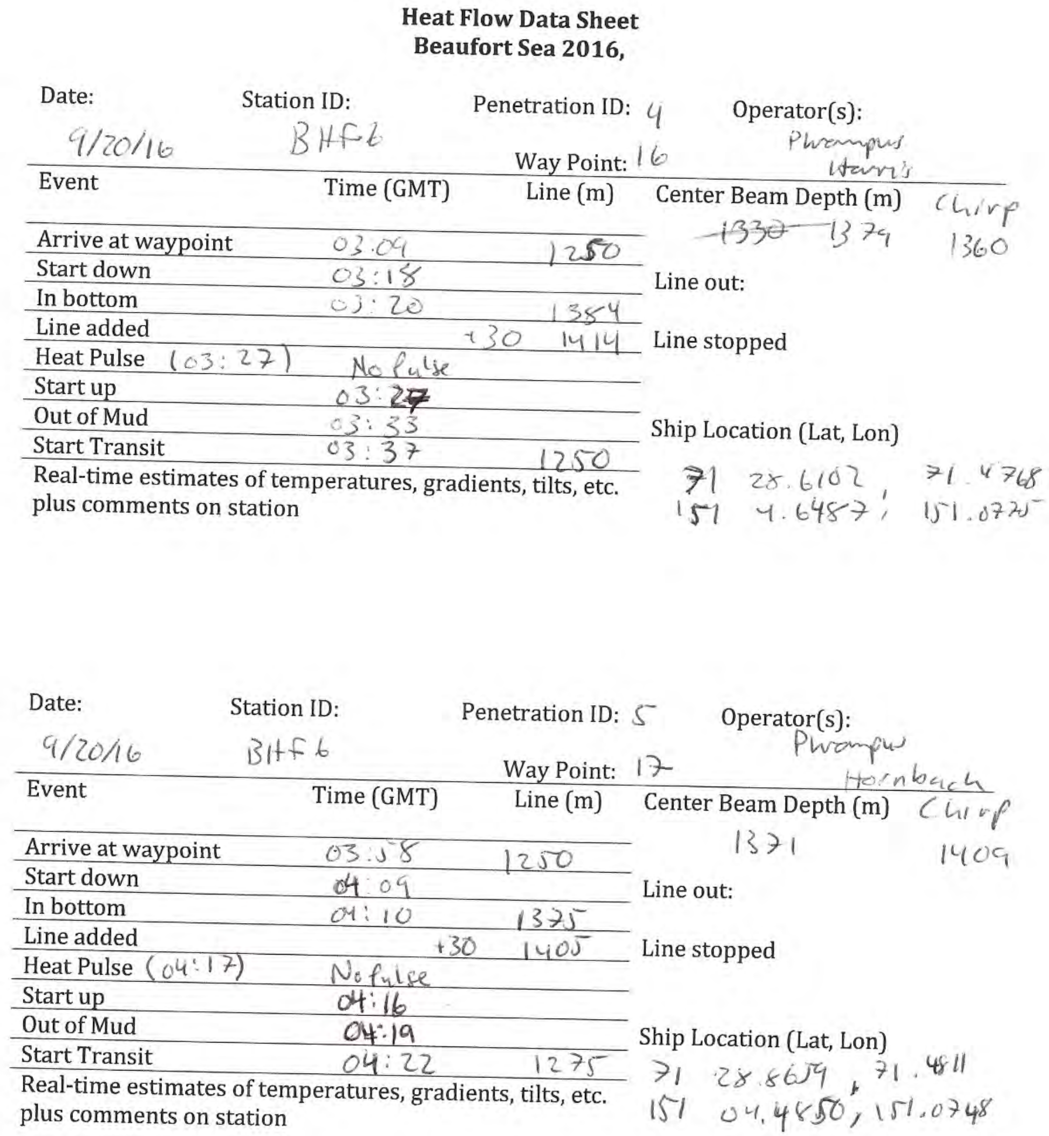
Center Beam Depth (m) 1330 Chirp 1363

Line out:

Line stopped

Ship Location (Lat, Lon)
71 28.3272, 71.4721
151 04.8120, 151.0802

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20/16
Station ID: BHF6
Penetration ID: 4
Way Point: 16
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	03:09	1250
Start down	03:18	
In bottom	03:20	1384
Line added		+30 1414
Heat Pulse (03:27)	No Pulse	
Start up	03:27	
Out of Mud	03:33	
Start Transit	03:37	1250

Center Beam Depth (m) ~~1330~~ 1379 Chirp 1360

Line out:

Line stopped

Ship Location (Lat, Lon)
71 28.6102, 71.4768
151 4.6487, 151.0775

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Date: 9/20/16
Station ID: BHF6
Penetration ID: 5
Way Point: 17
Operator(s): Phrampus Hornbach

Event	Time (GMT)	Line (m)
Arrive at waypoint	03:58	1250
Start down	04:09	
In bottom	04:10	1375
Line added		+30 1405
Heat Pulse (04:17)	No Pulse	
Start up	04:16	
Out of Mud	04:19	
Start Transit	04:22	1275

Center Beam Depth (m) 1371 Chirp 1409

Line out:

Line stopped

Ship Location (Lat, Lon)
71 28.8659, 71.4811
151 04.4850, 151.0748

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20
Station ID: BHF6
Penetration ID: 6
Way Point: 18
Operator(s): MADIE

Event	Time (~~GMT~~)	Line (m)
Arrive at waypoint	4:41	~~1275~~→1250
Start down	4:50	
In bottom	4:52	1395
Line added	+30	1425
Heat Pulse	—	
Start up	4:59	
Out of Mud	5:01	
Start Transit	5:05	1275

Center Beam Depth (m) 1405
Line out:
Line stopped
Ship Location (Lat, Lon)
71° 29.1356 N
151 4.3491 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

boat depth - 1405
chirp depth - 1421

just passed over ridge before reaching the site - May cause high HF?
brought line up to 1250

Date: 9/20
Station ID: BHF6
Penetration ID: 7
Way Point: 19
Operator(s): MADIE

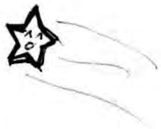
Event	Time (~~GMT~~)	Line (m)
Arrive at waypoint	5:22	1250
Start down	5:30	
In bottom	5:32	1410
Line added	+30	1440
Heat Pulse	—	
Start up (5:39)	5:39	
Out of Mud	5:41	
Start Transit	5:44	1300

Center Beam Depth (m) 1420
Line out:
Line stopped
Ship Location (Lat, Lon)
71° 29.3897 N
151 4.0910 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

boat depth - 1420
chirp depth - 1435

also near a small ridge/seamount



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20
Station ID: BHF6
Penetration ID: 8
Way Point: 20
Operator(s): MADIE

Event	Time (~~GMT~~)	Line (m)
Arrive at waypoint	6:03	
Start down (6:13)	6:12	
In bottom	6:13	1420
Line added	+30	1450
Heat Pulse	—	
Start up (6:20)	6:20	
Out of Mud	6:23	
Start Transit	6:25	1350

Center Beam Depth (m) 1431

Line out:

Line stopped

Ship Location (Lat, Lon)
71 29.6459 N
151 3.9084 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

boat depth - 1431
chirp depth - 1453

Date: 9/20
Station ID: BHF6
Penetration ID: 9
Way Point: 21
Operator(s): MADIE

Event	Time (~~GMT~~)	Line (m)
Arrive at waypoint	6:42	
Start down (6:52)	6:50	
In bottom	6:51	1435
Line added	+30	1465
Heat Pulse	—	
Start up (6:58)	6:59	
Out of Mud	7:01	
Start Transit	7:03	1350

Center Beam Depth (m) 1454

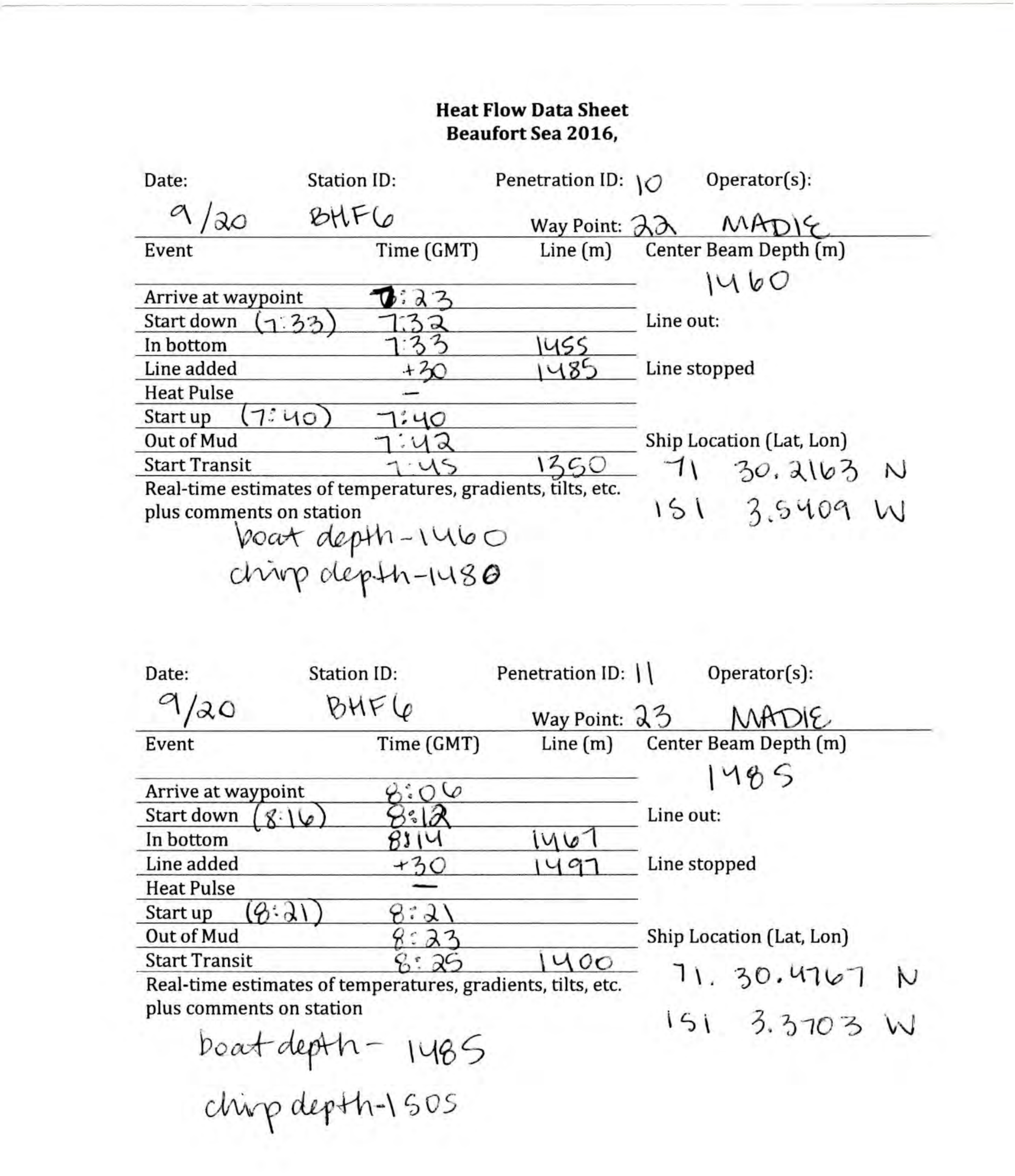
Line out:

Line stopped

Ship Location (Lat, Lon)
71 29.8680 N
151 3.7265 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

boat depth - 1454
chirp depth - 1470



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20
Station ID: BHF6
Penetration ID: 10
Operator(s): MADIE
Way Point: 22

Event		Time (GMT)	Line (m)
Arrive at waypoint		7:23	
Start down	(7:33)	7:32	
In bottom		7:33	1455
Line added		+30	1485
Heat Pulse		—	
Start up	(7:40)	7:40	
Out of Mud		7:42	
Start Transit		7:45	1350

Center Beam Depth (m): 1460

Line out:

Line stopped

Ship Location (Lat, Lon)
71 30.2163 N
151 3.5409 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

boat depth-1460
chirp depth-1480

Date: 9/20
Station ID: BHF6
Penetration ID: 11
Operator(s): MADIE
Way Point: 23

Event		Time (GMT)	Line (m)
Arrive at waypoint		8:06	
Start down	(8:16)	8:12	
In bottom		8:14	1467
Line added		+30	1497
Heat Pulse		—	
Start up	(8:21)	8:21	
Out of Mud		8:23	
Start Transit		8:25	1400

Center Beam Depth (m): 1485

Line out:

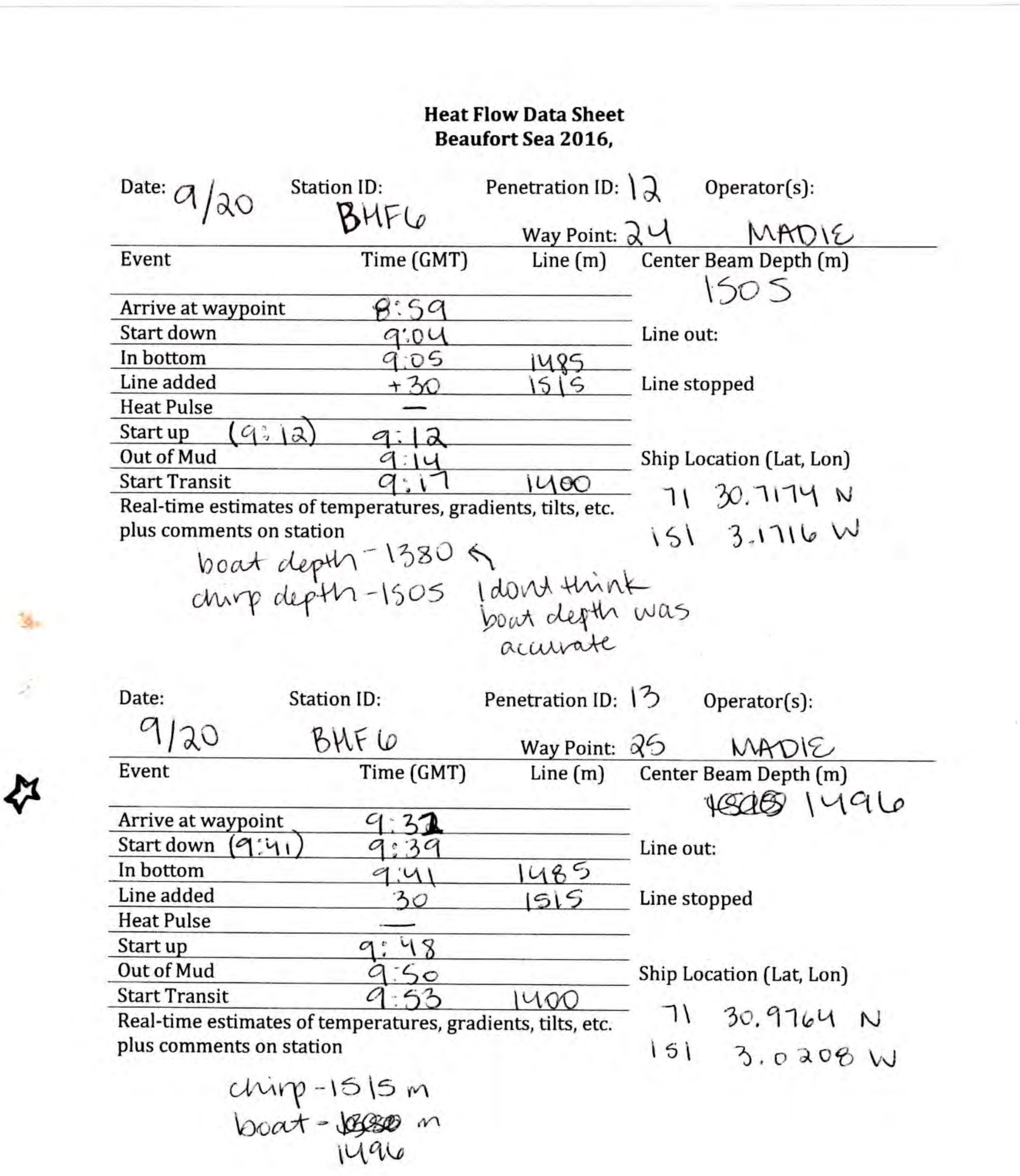
Line stopped

Ship Location (Lat, Lon)
71. 30.4767 N
151 3.3703 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

boat depth- 1485

chirp depth-1505



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20
Station ID: BHF6
Penetration ID: 12
Operator(s): MADIE
Way Point: 24

Event	Time (GMT)	Line (m)
Arrive at waypoint	8:59	
Start down	9:04	
In bottom	9:05	1485
Line added	+30	1515
Heat Pulse	—	
Start up (9:12)	9:12	
Out of Mud	9:14	
Start Transit	9:17	1400

Center Beam Depth (m): 1505
Line out:
Line stopped
Ship Location (Lat, Lon)
71 30.7174 N
151 3.1716 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

boat depth - 1380 ↖
chirp depth - 1505
I dont think boat depth was accurate

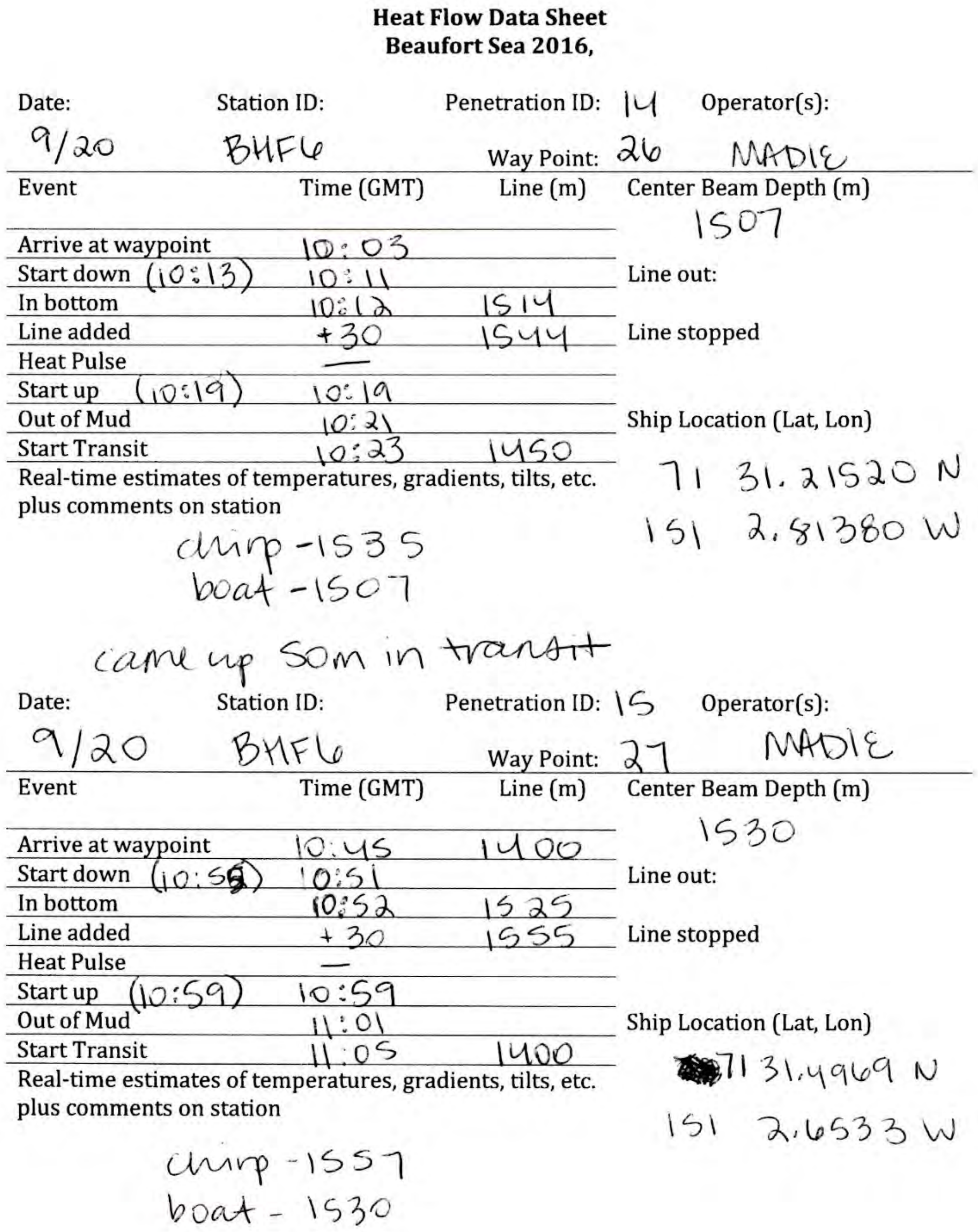
Date: 9/20
Station ID: BHF6
Penetration ID: 13
Operator(s): MADIE
Way Point: 25

Event	Time (GMT)	Line (m)
Arrive at waypoint	9:32	
Start down (9:41)	9:39	
In bottom	9:41	1485
Line added	30	1515
Heat Pulse	—	
Start up	9:48	
Out of Mud	9:50	
Start Transit	9:53	1400

Center Beam Depth (m): [illegible] 1496
Line out:
Line stopped
Ship Location (Lat, Lon)
71 30.9764 N
151 3.0208 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp - 1515 m
boat - [illegible] m
1496



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20
Station ID: BHF6
Penetration ID: 14
Way Point: 26
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	10:03	
Start down (10:13)	10:11	
In bottom	10:12	1514
Line added	+30	1544
Heat Pulse	—	
Start up (10:19)	10:19	
Out of Mud	10:21	
Start Transit	10:23	1450

Center Beam Depth (m): 1507

Line out:

Line stopped

Ship Location (Lat, Lon)
71 31.21520 N
151 2.81380 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp -1535
boat -1507

came up 50m in transit

Date: 9/20
Station ID: BHF6
Penetration ID: 15
Way Point: 27
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	10:45	1400
Start down (10:52)	10:51	
In bottom	10:52	1525
Line added	+ 30	1555
Heat Pulse	—	
Start up (10:59)	10:59	
Out of Mud	11:01	
Start Transit	11:05	1400

Center Beam Depth (m): 1530

Line out:

Line stopped

Ship Location (Lat, Lon)
71 31.4969 N
151 2.6533 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

chirp -1557
boat - 1530

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20
Station ID: BHF6
Penetration ID: 16
Way Point: 28
Operator(s): MADIE

Event		Time (GMT)	Line (m)
Arrive at waypoint		11:18	
Start down	(11:28)	11:24	
In bottom		11:26	1563
Line added		+30	1593
Heat Pulse		—	
Start up	(11:33)	11:33	
Out of Mud		11:36	
Start Transit		11:39	1450

Center Beam Depth (m) 1550

Line out:

Line stopped

Ship Location (Lat, Lon)

71 31.7797 N
151 2.5177 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

★ chirp-1575
boat-1550

Date: 9/20
Station ID: BHF6
Penetration ID: 17
Way Point: 29
Operator(s): MADIE

Event		Time (GMT)	Line (m)
Arrive at waypoint		11:48	
Start down	(11:58)	11:54	
In bottom		11:56	1593
Line added		+30	1623
Heat Pulse		—	
Start up	(12:03)	12:03	
Out of Mud		12:06	
Start Transit			1475

Center Beam Depth (m) 1580

Line out:

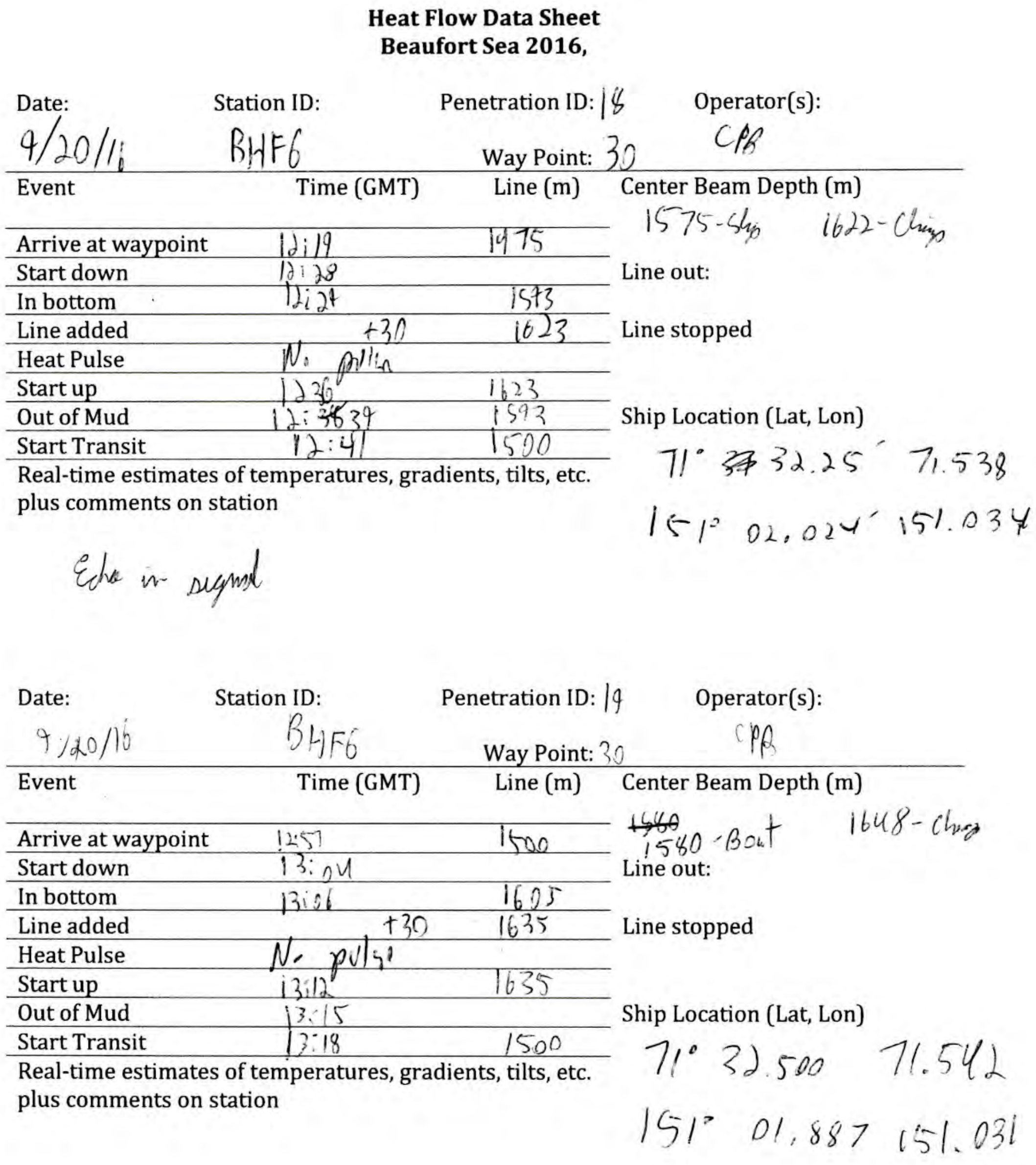
Line stopped

Ship Location (Lat, Lon)

71 32.0252 N
151 2.3232 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

boat - 1580
chirp - 1600



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20/16
Station ID: BHF6
Penetration ID: 18
Operator(s): CPB
Way Point: 30

Event	Time (GMT)	Line (m)
Arrive at waypoint	12:19	1475
Start down	12:28	
In bottom	12:24	1573
Line added	+30	1623
Heat Pulse	No pulse	
Start up	12:36	1623
Out of Mud	12:~~38~~39	1593
Start Transit	12:41	1500

Center Beam Depth (m)
1575-Ship 1622-Chirp

Line out:

Line stopped

Ship Location (Lat, Lon)
71° ~~33~~ 32.25´ 71.538
151° 02.024´ 151.034

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Echo in signal

Date: 9/20/16
Station ID: BHF6
Penetration ID: 19
Operator(s): CPB
Way Point: 30

Event	Time (GMT)	Line (m)
Arrive at waypoint	12:57	1500
Start down	13:04	
In bottom	13:06	1605
Line added	+30	1635
Heat Pulse	No pulse	
Start up	13:12	1635
Out of Mud	13:15	
Start Transit	13:18	1500

Center Beam Depth (m)
~~1560~~ 1580-Boat 1648-Chirp

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 32.500 71.542
151° 01.887 151.031

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20/16
Station ID: BHF6
Penetration ID: 20
Way Point: 32
Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	13:36	1500
Start down	13:44	
In bottom	13:46	1640
Line added	+30	1670
Heat Pulse	No Pulse	
Start up	13:52	1670
Out of Mud	13:55	1640
Start Transit	13:58	1550

Center Beam Depth (m) ~~1539~~-Sys 1640 1692-Chirp

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 32.762′ 71.546
151° 01.603′ 151,027

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Echos in temp signal

Date: 9/20/16
Station ID: BHF6
Penetration ID: 21
Way Point: 33
Operator(s): CPB

Event	Time (GMT)	Line (m)
Arrive at waypoint	14:14	1550
Start down	14:22	
In bottom	14:23	1660
Line added	+30	1690
Heat Pulse	14:30	1690
Start up	14:30 ~~14:33~~	
Out of Mud	14:33	
Start Transit		1550

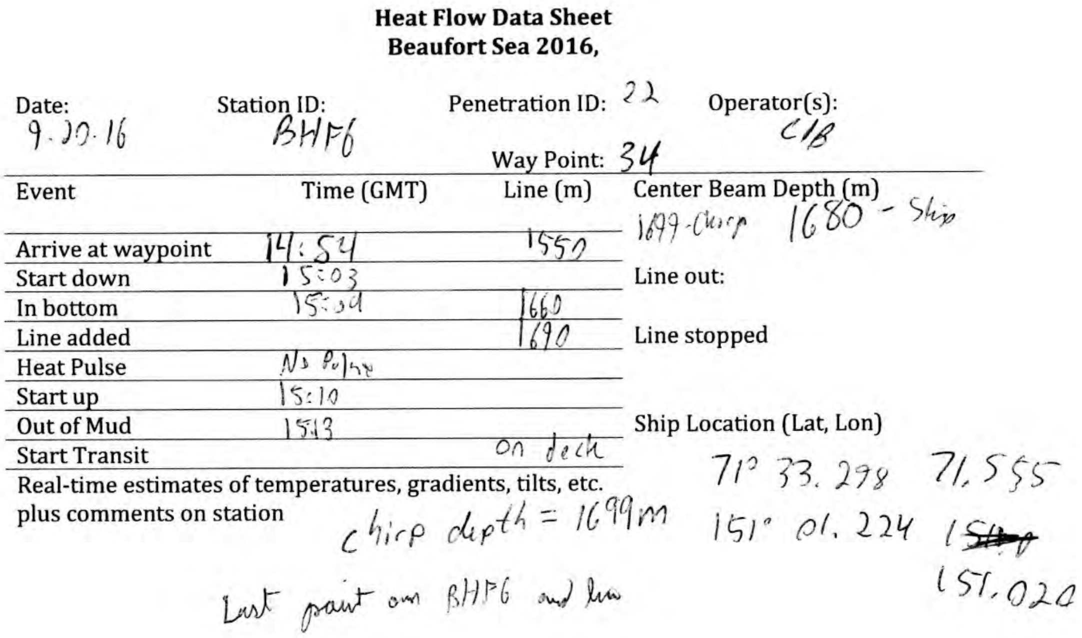
Center Beam Depth (m) 1670-Sys 1695-Chirp

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 33.032′ 71.551
151° 01.416′ 151.024

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9.20.16
Station ID: BHF6
Penetration ID: 22
Operator(s): C/B
Way Point: 34

Event	Time (GMT)	Line (m)
Arrive at waypoint	14:54	1550
Start down	15:03	
In bottom	15:09	1660
Line added		1690
Heat Pulse	No Pulse	
Start up	15:10	
Out of Mud	1513	
Start Transit		on deck

Center Beam Depth (m) 1699-Chirp 1680 - Ship

Line out:

Line stopped

Ship Location (Lat, Lon)
71° 33.298 71.555
151° 01.224 1~~5~~
151.020

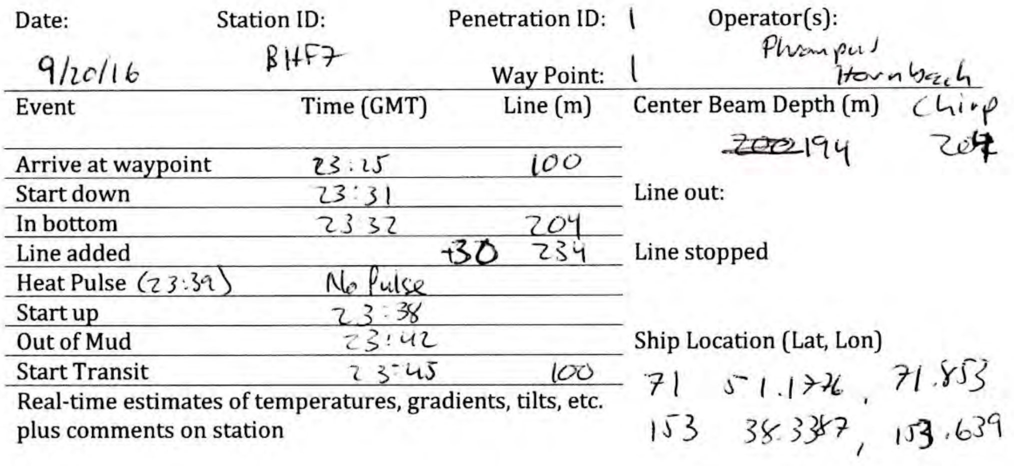
Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station
chirp depth = 1699m

Last point on BHF6 and line

(Image above was cropped – bottom of page pertains to BHF 7, appearing in next section.)

BHF 7 – September 20-21, 2017. 21 Penetrations

(Image below was cropped – top of page pertains to BHF 6, appearing in previous section.)



Date: 9/20/16

Station ID: BHF7

Penetration ID: 1

Way Point: 1

Operator(s): Phrampus Hornbach

Event	Time (GMT)	Line (m)
Arrive at waypoint	23:25	100
Start down	23:31	
In bottom	23 32	204
Line added		+30 234
Heat Pulse (23:39)	No Pulse	
Start up	23:38	
Out of Mud	23:42	
Start Transit	23:45	100

Center Beam Depth (m) ~~200~~ 194

Chirp 207

Line out:

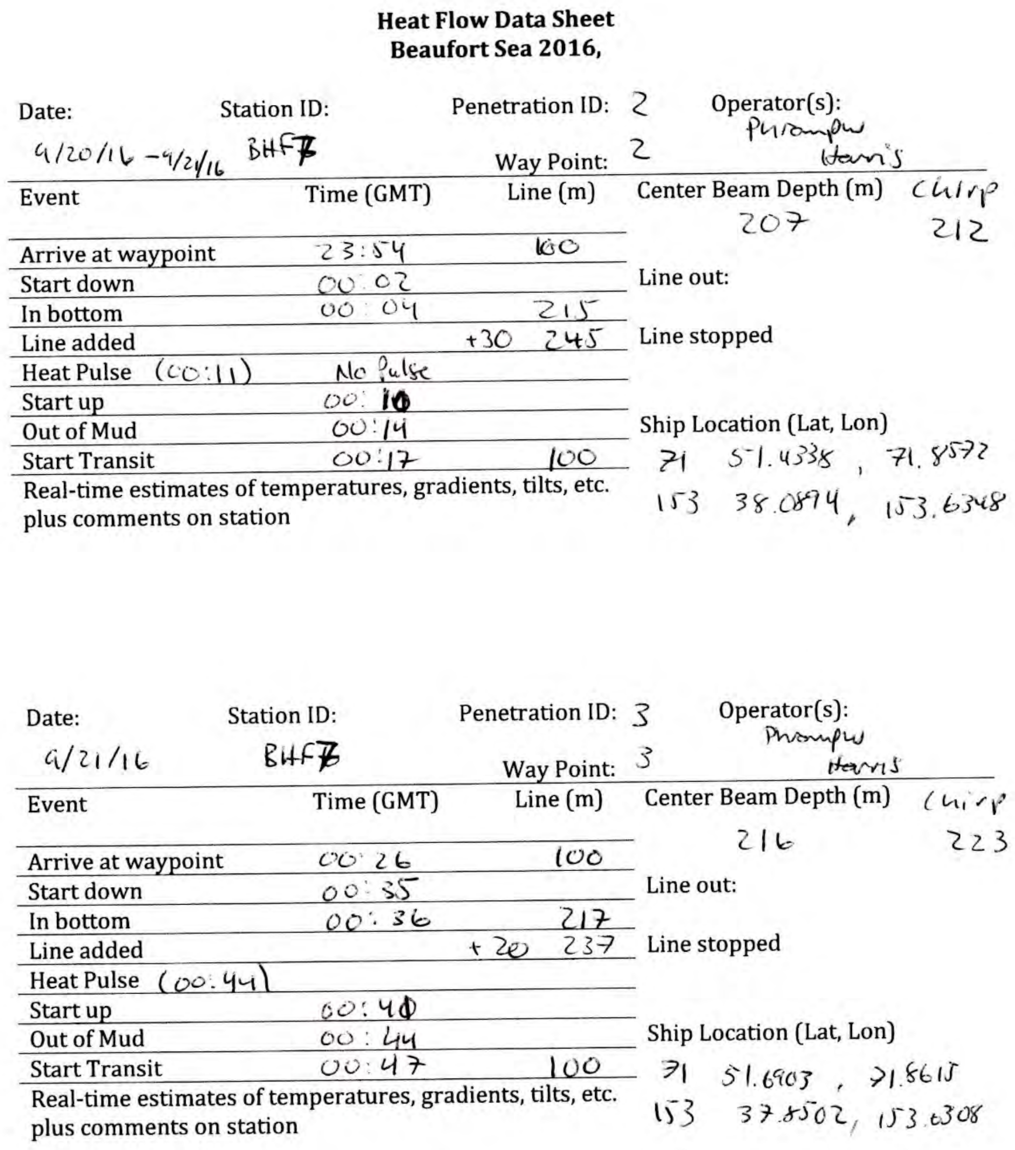
Line stopped

Ship Location (Lat, Lon)

71 51.1776, 71.853

153 38.3387, 153.639

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20/16 – 9/21/16
Station ID: BHF7
Penetration ID: 2
Way Point: 2
Operator(s): Phrampus, Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	23:54	100
Start down	00:02	
In bottom	00:04	215
Line added		+30 245
Heat Pulse (00:11)	No Pulse	
Start up	00:10	
Out of Mud	00:14	
Start Transit	00:17	100

Center Beam Depth (m) 207 Chirp 212
Line out:
Line stopped
Ship Location (Lat, Lon)
71 51.4338, 71.8572
153 38.0894, 153.6348

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Date: 9/21/16
Station ID: BHF7
Penetration ID: 3
Way Point: 3
Operator(s): Phrampus, Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	00:26	100
Start down	00:35	
In bottom	00:36	217
Line added		+20 237
Heat Pulse (00:44)		
Start up	00:40	
Out of Mud	00:44	
Start Transit	00:47	100

Center Beam Depth (m) 216 Chirp 223
Line out:
Line stopped
Ship Location (Lat, Lon)
71 51.6903, 71.8615
153 37.8502, 153.6308

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/20/16
Station ID: BHF7
Penetration ID: 4
Way Point: 4
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	00:56	100
Start down	01:05	
In bottom	01:07	228
Line added		+20 248
Heat Pulse (01:14)	No Pulse	
Start up	01:13	
Out of Mud	01:18	
Start Transit	01:21	100

Center Beam Depth (m) 226 Chirp 237

Line out:

Line stopped

Ship Location (Lat, Lon)
71 51.9497, 71.8655
153 37.5417, 153.6257

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9/21/16
Station ID: BHF7
Penetration ID: 5
Way Point: 5
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	01:30	100
Start down	01:39	
In bottom	01:41	253
Line added		+20 273
Heat Pulse (01:48)	No Pulse	
Start up	01:47	
Out of Mud	01:50	
Start Transit	01:53	150

Center Beam Depth (m) 248 Chirp 260

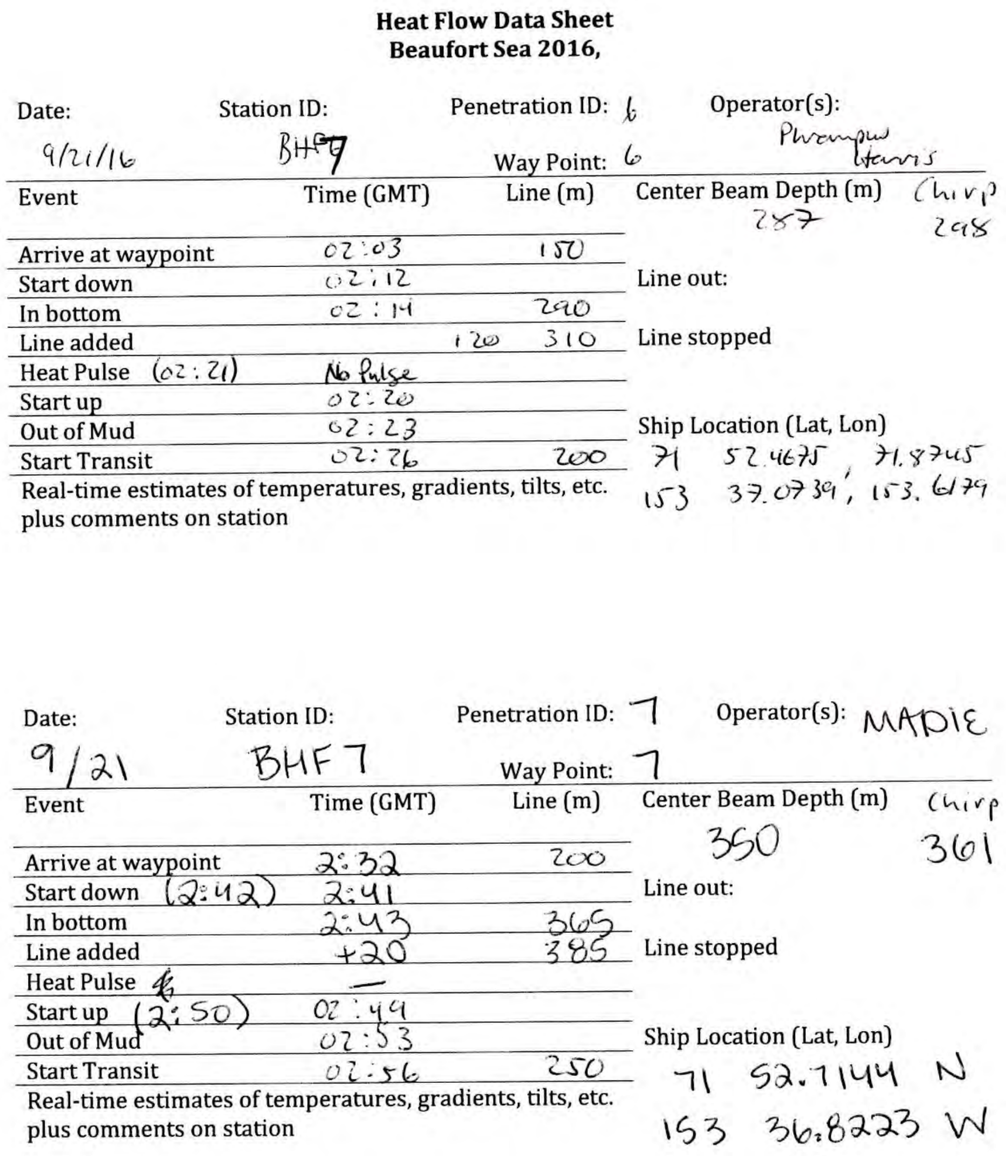
Line out:

Line stopped

Ship Location (Lat, Lon)
71 52.2067, 71.8701
153 37.3121, 153.6219

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Start of warm waters
~250m
Cooler TG



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/21/16
Station ID: BHF7
Penetration ID: 6
Way Point: 6
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	02:03	150
Start down	02:12	
In bottom	02 : 14	290
Line added		+20 310
Heat Pulse (02 : 21)	No Pulse	
Start up	02:20	
Out of Mud	02 : 23	
Start Transit	02:26	200

Center Beam Depth (m) 287 Chirp 298

Line out:

Line stopped

Ship Location (Lat, Lon)
71 52.4675, 71.8745
153 37.0739', 153.6179

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9/21
Station ID: BHF7
Penetration ID: 7
Way Point: 7
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	2:32	200
Start down (2:42)	2:41	
In bottom	2:43	365
Line added	+20	385
Heat Pulse	—	
Start up (2:50)	02 : 49	
Out of Mud	02 : 53	
Start Transit	02:56	250

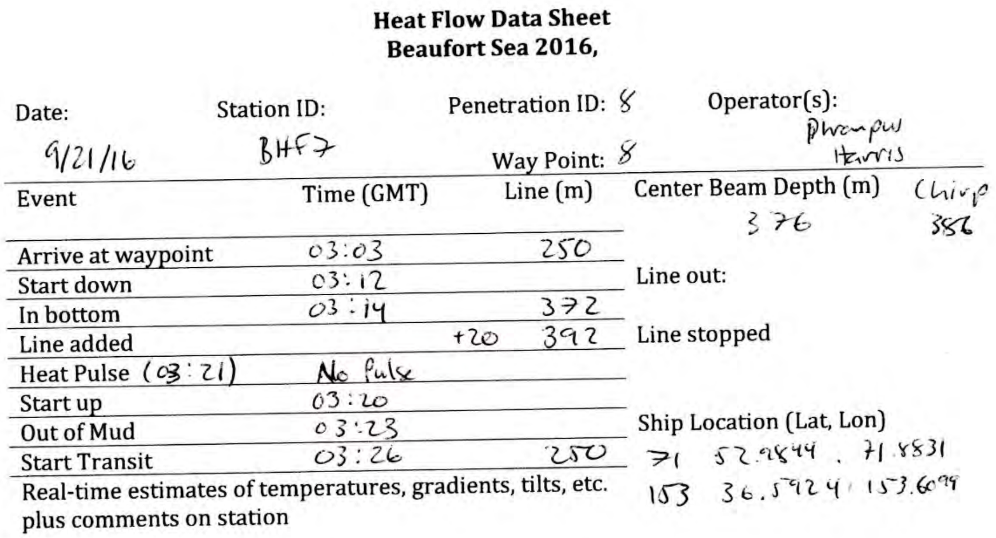
Center Beam Depth (m) 350 Chirp 361

Line out:

Line stopped

Ship Location (Lat, Lon)
71 52.7144 N
153 36.8223 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/21/16
Station ID: BHF7
Penetration ID: 8
Way Point: 8
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	03:03	250
Start down	03:12	
In bottom	03:14	372
Line added		+20 392
Heat Pulse (03:21)	No Pulse	
Start up	03:20	
Out of Mud	03:23	
Start Transit	03:26	250

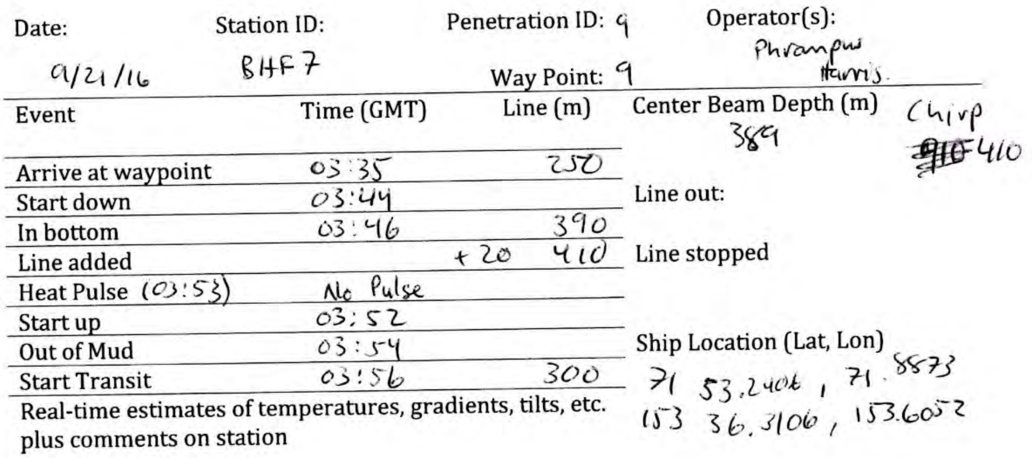
Center Beam Depth (m) 376 Chirp 386

Line out:

Line stopped

Ship Location (Lat, Lon)
71 52.9844 , 71.8831
153 36.5924 , 153.6099

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Date: 9/21/16
Station ID: BHF7
Penetration ID: 9
Way Point: 9
Operator(s): Phrampus Harris.

Event	Time (GMT)	Line (m)
Arrive at waypoint	03:35	250
Start down	03:44	
In bottom	03:46	390
Line added		+ 20 410
Heat Pulse (03:53)	No Pulse	
Start up	03:52	
Out of Mud	03:54	
Start Transit	03:56	300

Center Beam Depth (m) 389 Chirp ~~410~~ 410

Line out:

Line stopped

Ship Location (Lat, Lon)
71 53.2406 , 71.8873
153 36.3106 , 153.6052

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/21
Station ID: BHF 7
Penetration ID: 10
Way Point: 10
Operator(s): MADIE

Center Beam Depth (m): 491
chirp 510

Event	Time (GMT)	Line (m)
Arrive at waypoint	4.15	
Start down	4:21	
In bottom	4:23	505
Line added	+30	535
Heat Pulse	—	
Start up	4:29	
Out of Mud	4:31	
Start Transit	4:37	300

Line out:

Line stopped

Ship Location (Lat, Lon)
71 53.7609 N
153 35.8196 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

went over a fault feature en route to this way pt, going back over it for 1 deployment then back to list of waypoints (P9 to P10)

Date: 9/21
Station ID: BHF 7
Penetration ID: 11
Way Point: A
Operator(s): MADIE

Center Beam Depth (m): 370
chirp 380

Event	Time (GMT)	Line (m)
Arrive at waypoint	4:55	
Start down	4:56	
In bottom	4:57	374
Line added	+30	404
Heat Pulse	—	
Start up (5:04)	5:04	
Out of Mud	5:06	
Start Transit	5:07	325

Line out:

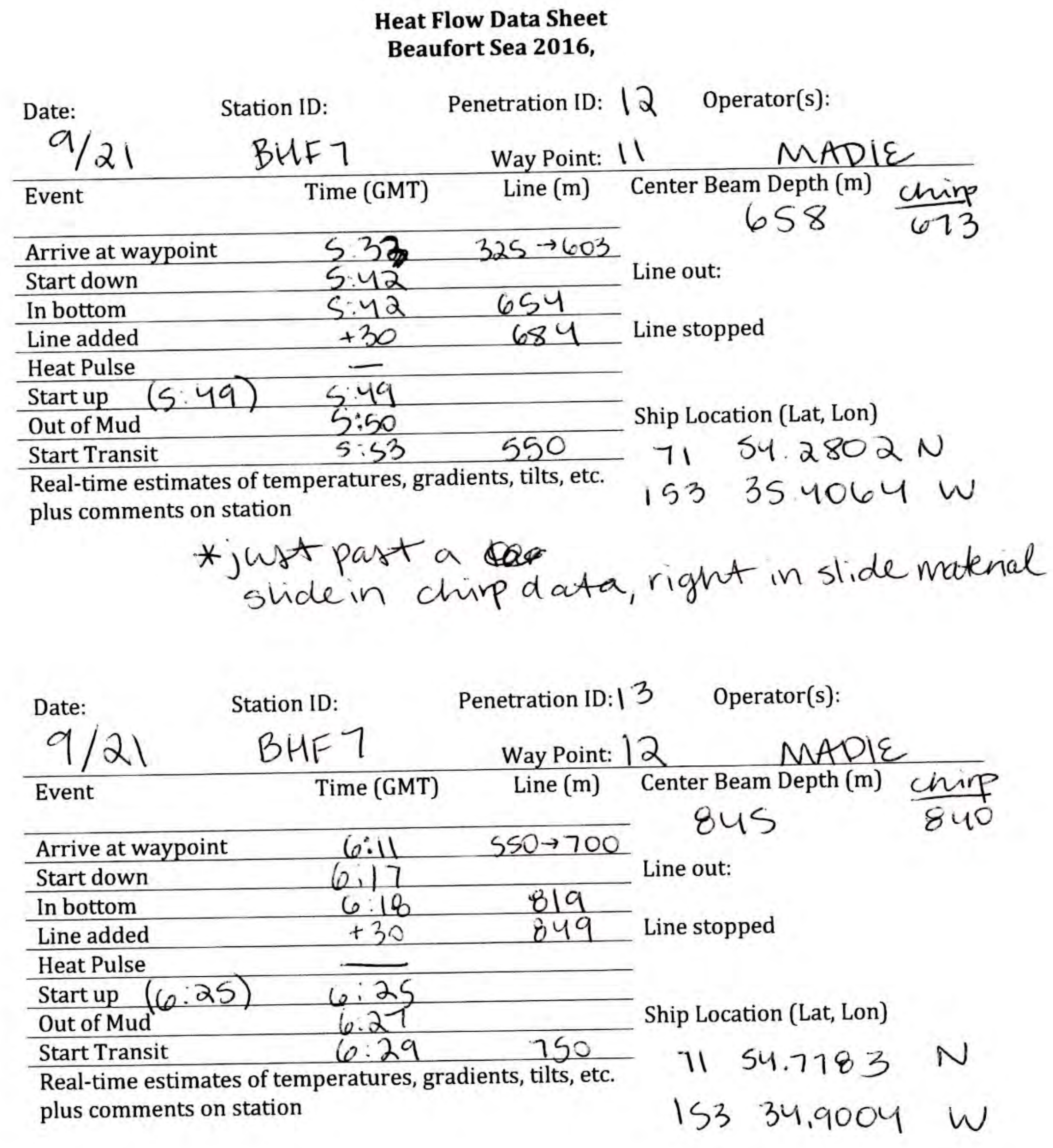
Line stopped

Ship Location (Lat, Lon)
71 53.4038 N
153 35.9297 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

over fault/feature of interest seen in chirp profile

HF seemed cold in pinger data



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/21
Station ID: BHF7
Penetration ID: 12
Way Point: 11
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	5:33	325 → 603
Start down	5:42	
In bottom	5:42	654
Line added	+30	684
Heat Pulse	—	
Start up (5:49)	5:49	
Out of Mud	5:50	
Start Transit	5:53	550

Center Beam Depth (m) 658 chirp 673
Line out:
Line stopped
Ship Location (Lat, Lon)
71 54.2802 N
153 35.4064 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

*just past a slide in chirp data, right in slide material

Date: 9/21
Station ID: BHF7
Penetration ID: 13
Way Point: 12
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	6:11	550 → 700
Start down	6:17	
In bottom	6:18	819
Line added	+30	849
Heat Pulse	—	
Start up (6:25)	6:25	
Out of Mud	6:27	
Start Transit	6:29	750

Center Beam Depth (m) 845 chirp 840
Line out:
Line stopped
Ship Location (Lat, Lon)
71 54.7783 N
153 34.9004 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/21 Station ID: BHF 7 Penetration ID: 14 Operator(s): MADIE

Way Point: 13

Event	Time (GMT)	Line (m)
Arrive at waypoint	6:50	
Start down	6:56	
In bottom	6:58	942
Line added	+30	972
Heat Pulse	—	
Start up (7:05)	7:05	
Out of Mud	7:07	
Start Transit	7:09	890

Center Beam Depth (m) 965 chirp 913

Line out:

Line stopped

Ship Location (Lat, Lon)
71 55.3035 N
153 34.4571 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: Station ID: Penetration ID: Operator(s):

Way Point:

Event	Time (GMT)	Line (m)
Arrive at waypoint		
Start down		
In bottom		
Line added		
Heat Pulse		
Start up		
Out of Mud		
Start Transit		

Center Beam Depth (m) [illegible]

Line out:

Line stopped

Ship Location (Lat, Lon)

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

AURORAH

BALTO

U.S.

USBS
GHHF

M
BA[illegible]HFS

BARHFS

AG[illegible]
[illegible]

Oceanic Margin

North Slope Alaska

Arctic
Beaufort Sea
Heat Gas
Flow Methane
Temp Hydrate
Study Margin
Continental
Shelf

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/21
Station ID: BHF7
Penetration ID: 15
Way Point: 14
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	7:26	
Start down	7:32	
In bottom	7:35	1053
Line added	+30	1083
Heat Pulse	—	
Start up (7:43)	7:42	
Out of Mud	7:45	
Start Transit	7:48	900

Center Beam Depth (m): 1079 chirp 1086
Line out:
Line stopped
Ship Location (Lat, Lon)
71 55.8170 N
153 339958 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9/21
Station ID: BHF7
Penetration ID: 16
Way Point: 15
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	8:06	
Start down	8:13	
In bottom	8:16	1160
Line added	+30	1190
Heat Pulse	—	
Start up (8:23)	8:23	
Out of Mud	8:25	
Start Transit	8:33	900

Center Beam Depth (m): 1180 chirp 1191
Line out:
Line stopped
Ship Location (Lat, Lon)
71 56.3332 N
153 33.4494 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/21
Station ID: BHF 7
Penetration ID: 17
Way Point: 16
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	8:47	
Start down	8:54	
In bottom	8:57	1180
Line added	+30	1210
Heat Pulse	—	
Start up (9:04)	9:04	
Out of Mud	9:06	
Start Transit	9:13	950

Center Beam Depth (m) 1206
chirp 1218

Line out:

Line stopped

Ship Location (Lat, Lon)
71 56.5905 N
153 33.1658 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

★

Date: 9/21
Station ID: BHF 7
Penetration ID: 18
Way Point: 17
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	9:21	
Start down	9:28	
In bottom	9:31	1187
Line added	+30	1217
Heat Pulse	—	
Start up (9:38)	9:38	
Out of Mud	9:39	
Start Transit	9:44	1050

Center Beam Depth (m) 1207
chirp 1219

Line out:

Line stopped

Ship Location (Lat, Lon)
71 56.841 N
153 32.96 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

★

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/21
Station ID: BHF7
Penetration ID: 19
Way Point: 18
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	9:52	
Start down	10:00	
In bottom	10:01	1195
Line added	+30	1225
Heat Pulse	—	
Start up (10:08)	10:08	
Out of Mud	10:09	
Start Transit	10:17	950

Center Beam Depth (m): 1220
chirp: 1231
Line out:
Line stopped
Ship Location (Lat, Lon)
71 57.1078 N
153 32.6801 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

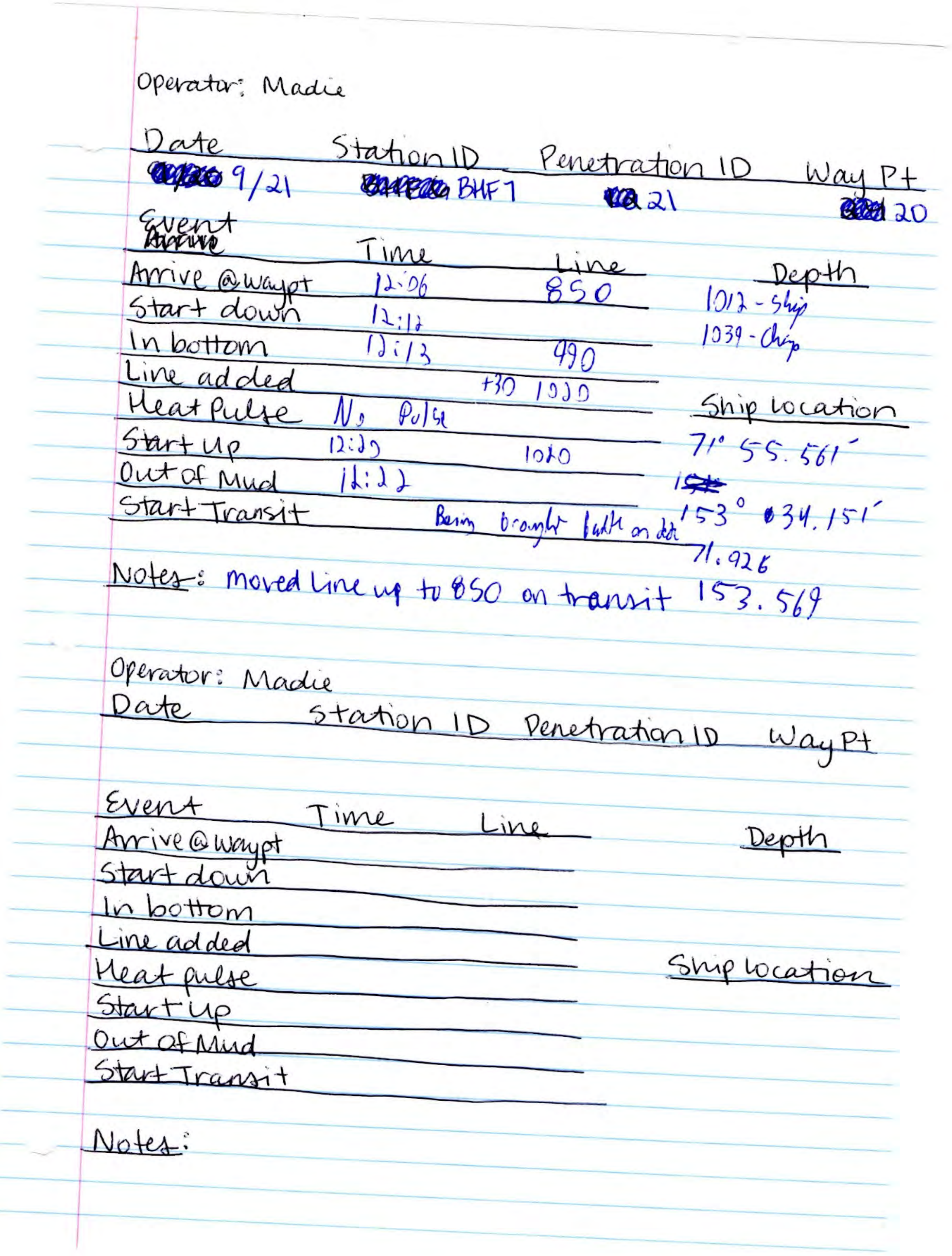
---

Date: 9/21
Station ID: BHF 7
Penetration ID: 20
Way Point: 19
Operator(s): MADIE

Event	Time (GMT)	Line (m)
Arrive at waypoint	11:02	
Start down	11:06	
In bottom	11:08	1118
Line added	+30	1148
Heat Pulse	—	
Start up (11:15)	11:15	
Out of Mud	11:17	
Start Transit	11:24	~~900~~ 850

Center Beam Depth (m): 1115
chirp: 1162
Line out:
Line stopped
Ship Location (Lat, Lon)
71 56.1206 N
153 33.5107 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Operator: Madie

Date	Station ID	Penetration ID	Way Pt
9/21	BHF7	21	20

Event	Time	Line	Depth
Arrive @waypt	12:06	850	1012 - Ship
Start down	12:12		1039 - Chirp
In bottom	12:13	990	
Line added		+30 1020	
Heat Pulse	No Pulse		Ship location
Start up	12:20	1020	71° 55.561′
Out of Mud	12:22		~~15~~
Start Transit	Being brought back on deck		153° 34.151′
			71.926

Notes: moved Line up to 850 on transit 153.569

Operator: Madie

Date	Station ID	Penetration ID	Way Pt

Event	Time	Line	Depth
Arrive @waypt			
Start down			
In bottom			
Line added			
Heat pulse			Ship location
Start up			
Out of Mud			
Start Transit			

Notes:

BHF 8 – September 21-22, 2017. 15 Penetrations.

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/21/16
Station ID: BHF8
Penetration ID: 1
Way Point: 2
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	22:50	300
Start down	22:54	
In bottom	22:56	411
Line added		+20 431
Heat Pulse (23:03)	No Pulse	
Start up	23:02	
Out of Mud	23:05	
Start Transit	23:08	300

Center Beam Depth (m) 405 Chirp 412

Line out:

Line stopped

Ship Location (Lat, Lon)
71 53.4976, 71.8916
153 36.1148, 153.6019

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Skip 1st waypt ~~due~~ to get away from polar bears

Date: 9/21/16
Station ID: BHF8
Penetration ID: 2
Way Point: 3
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	23:12	300
Start down	23:17	
In bottom	23:19	430
Line added		+20 450
Heat Pulse (23:26)	No Pulse	
Start up	23:25	
Out of Mud	23:28	
Start Transit	23:32	300

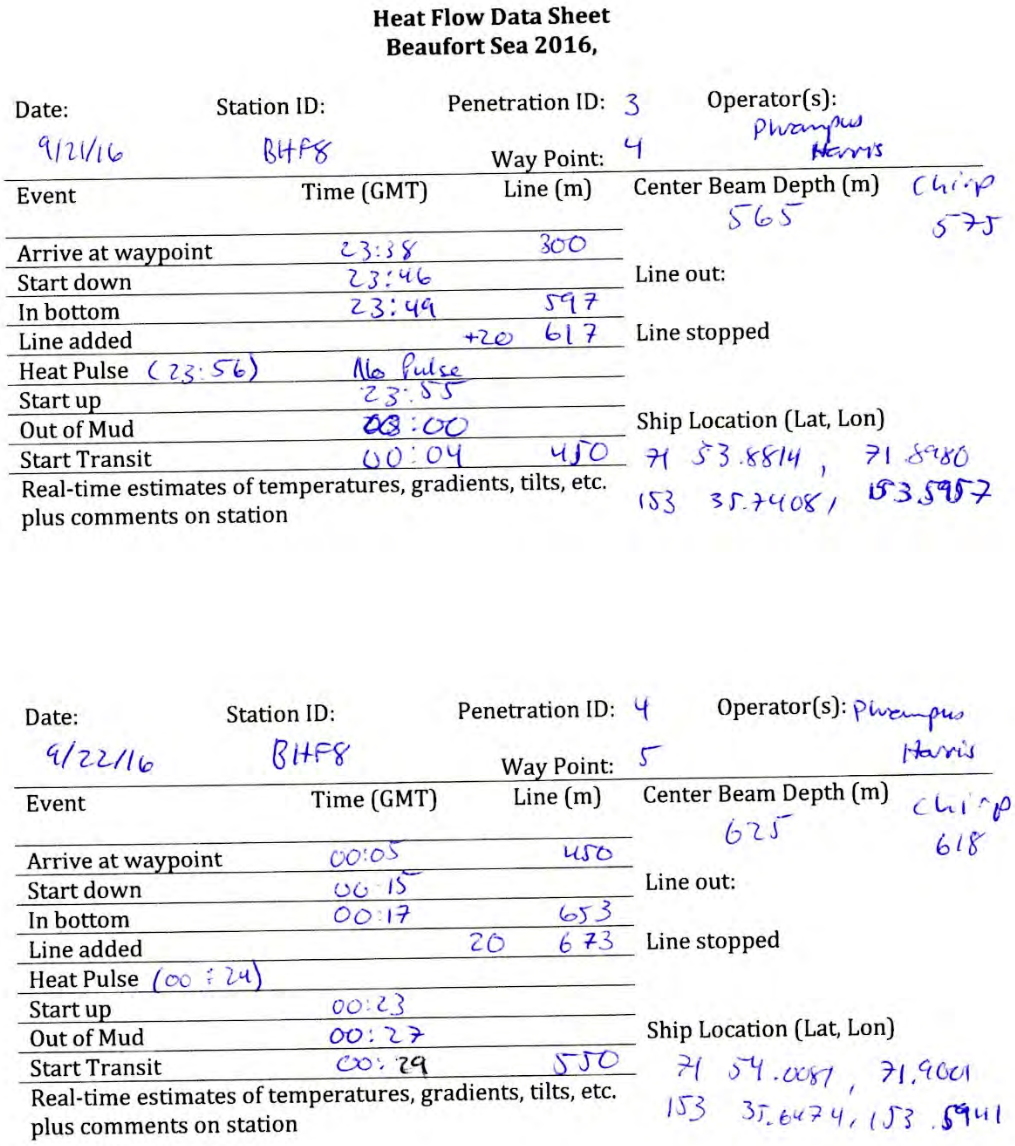
Center Beam Depth (m) 419 Chirp 430

Line out:

Line stopped

Ship Location (Lat, Lon)
71 53.6183, 71.8926
153 36.0096, 183.6002

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/21/16
Station ID: BHF8
Penetration ID: 3
Way Point: 4
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	23:38	300
Start down	23:46	
In bottom	23:49	597
Line added		+20 617
Heat Pulse (23:56)	No Pulse	
Start up	23:55	
Out of Mud	00:00	
Start Transit	00:04	450

Center Beam Depth (m) 565 Chirp 575

Line out:

Line stopped

Ship Location (Lat, Lon)
71 53.8814, 71.8980
153 35.7408, 153.5957

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9/22/16
Station ID: BHF8
Penetration ID: 4
Way Point: 5
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	00:05	450
Start down	00:15	
In bottom	00:17	653
Line added		20 673
Heat Pulse (00:24)		
Start up	00:23	
Out of Mud	00:27	
Start Transit	00:29	550

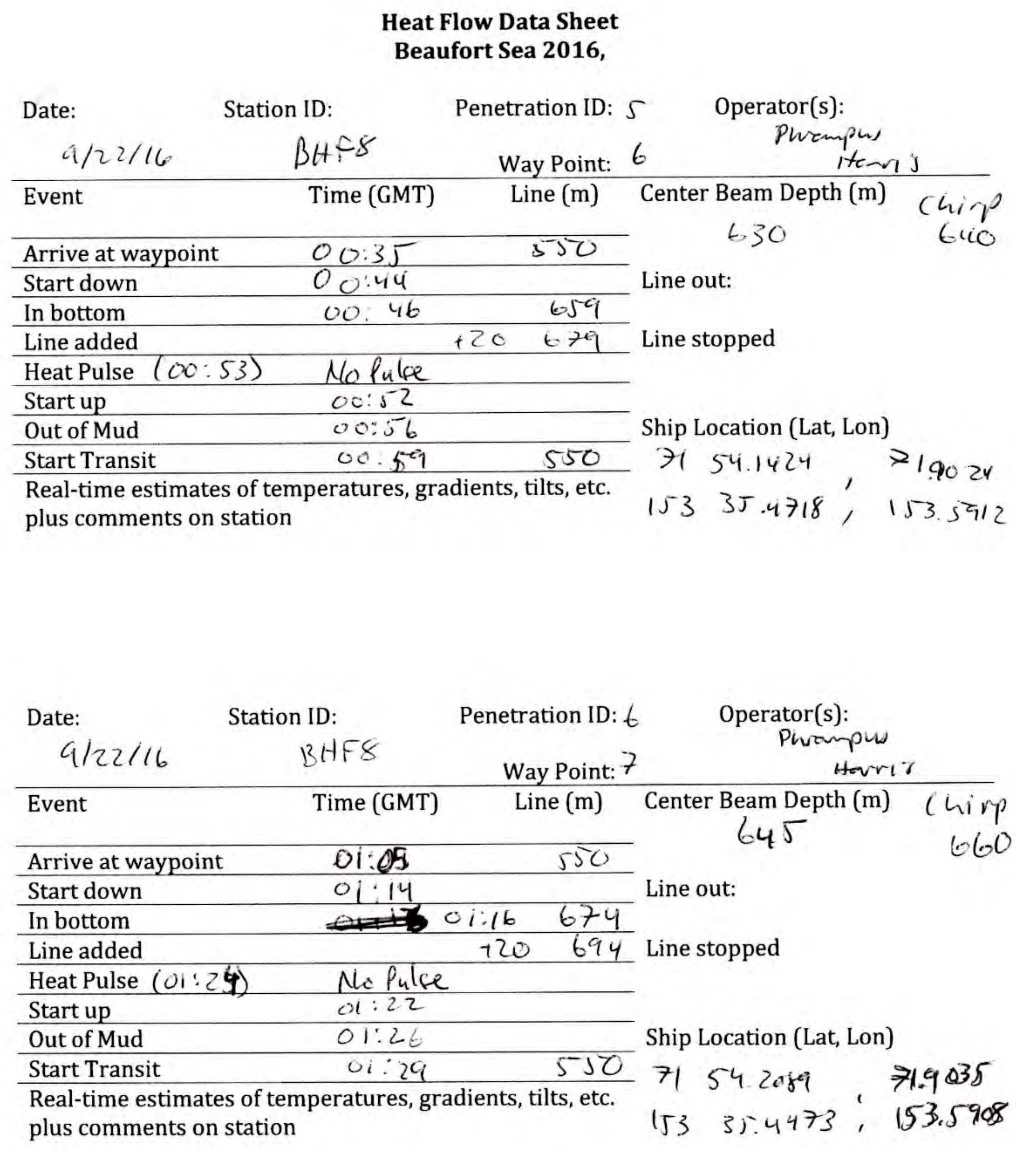
Center Beam Depth (m) 625 Chirp 618

Line out:

Line stopped

Ship Location (Lat, Lon)
71 54.0087, 71.9001
153 35.6474, 153.5941

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/22/16
Station ID: BHF8
Penetration ID: 5
Way Point: 6
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	00:35	550
Start down	00:44	
In bottom	00:46	659
Line added		+20 679
Heat Pulse (00:53)	No Pulse	
Start up	00:52	
Out of Mud	00:56	
Start Transit	00:59	550

Center Beam Depth (m) 630 Chirp 640
Line out:
Line stopped
Ship Location (Lat, Lon)
71 54.1424 , 71.9024
153 35.4718 , 153.5912

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

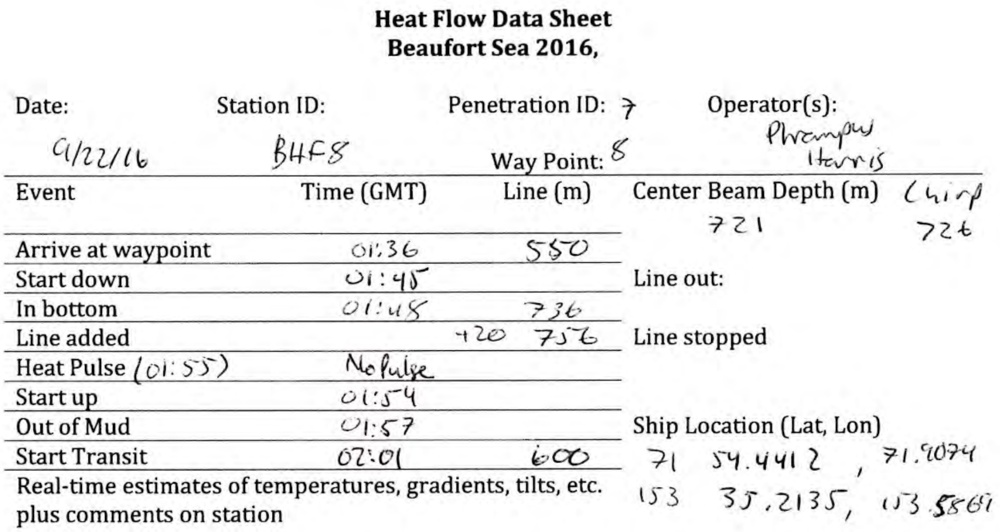
---

Date: 9/22/16
Station ID: BHF8
Penetration ID: 6
Way Point: 7
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	01:05	550
Start down	01:14	
In bottom	01:16	674
Line added		+20 694
Heat Pulse (01:24)	No Pulse	
Start up	01:22	
Out of Mud	01:26	
Start Transit	01:29	550

Center Beam Depth (m) 645 Chirp 660
Line out:
Line stopped
Ship Location (Lat, Lon)
71 54.2089 , 71.9035
153 35.4473 , 153.5908

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



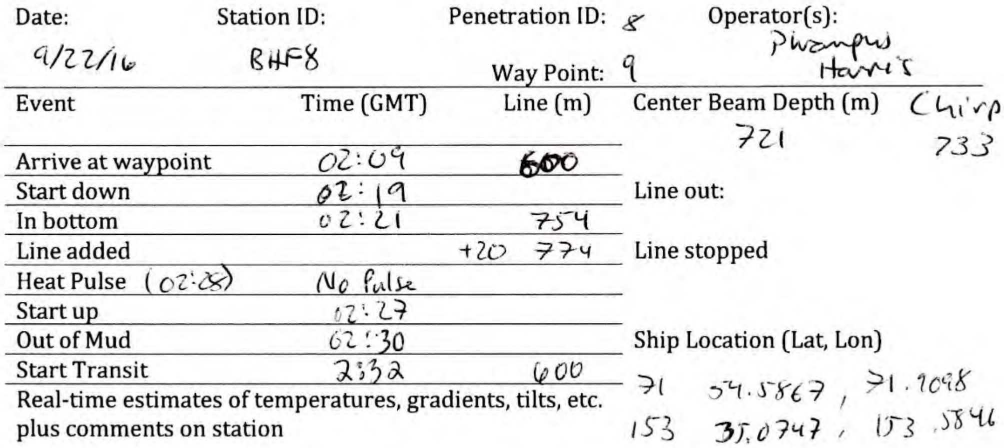
Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/22/16
Station ID: BHF8
Penetration ID: 7
Way Point: 8
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	01:36	550
Start down	01:45	
In bottom	01:48	736
Line added		+20 756
Heat Pulse (01:55)	No Pulse	
Start up	01:54	
Out of Mud	01:57	
Start Transit	02:01	600

Center Beam Depth (m) 721
Chirp 726
Line out:
Line stopped
Ship Location (Lat, Lon)
71 54.4412 , 71.9074
153 35.2135, 153.5869

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Date: 9/22/16
Station ID: BHF8
Penetration ID: 8
Way Point: 9
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	02:09	600
Start down	02:19	
In bottom	02:21	754
Line added		+20 774
Heat Pulse (02:28)	No Pulse	
Start up	02:27	
Out of Mud	02:30	
Start Transit	2:32	600

Center Beam Depth (m) 721
Chirp 733
Line out:
Line stopped
Ship Location (Lat, Lon)
71 54.5867 , 71.9098
153 35.0747 , 153 .5846

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/22
Station ID: BHF8
Penetration ID: 9
Way Point: 10
Operator(s): No Casey! MADIE/ROB/BEN/MATT

Event	Time (GMT)	Line (m)
Arrive at waypoint	02:41	600
Start down	02:50	
In bottom	02:53	807
Line added		+20 827
Heat Pulse (03:00)	No Pulse	
Start up	02:59	
Out of Mud	03:02	
Start Transit	03:07	650

Center Beam Depth (m) 770 Chirp 780

Line out:

Line stopped

Ship Location (Lat, Lon)
71 54.6960 , 71.9116
153 34.9730 , 153.5829

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

very ~~cold~~ low gradient ...

Date: 9/22/16
Station ID: BHF8
Penetration ID: 10
Way Point: 11
Operator(s): Phrompui Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	03:20	~~750~~ 650
Start down	03:29	
In bottom	03:31	895
Line added		+20 915
Heat Pulse (03:38)	No Pulse	
Start up	03:37	
Out of Mud	03:40	
Start Transit	03:43	800

Center Beam Depth (m) 892 Chirp 915

Line out:

Line stopped

Ship Location (Lat, Lon)
71 54.9227 , 71.9154
153 34.7531 , 153.5792

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/22/16
Station ID: BHF8
Penetration ID: 11
Way Point: 12
Operator(s): Phrampus Harris

Event	Time (GMT)	Line (m)
Arrive at waypoint	03:51	800
Start down	04:00	
In bottom	04:01	910
Line added		130 940
Heat Pulse (04:08)	No Pulse	
Start up	4:07 [illegible]	
Out of Mud	4:09	
Start Transit	4:12	825

Center Beam Depth (m) 923
Chirp 938

Line out:

Line stopped

Ship Location (Lat, Lon)
71 55.0452 , 71.9174
153 34.7547, 153.5792

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9/22
Station ID: BHF8
Penetration ID: 12
Way Point: 13
Operator(s): MADIE/MATT

Event	Time (GMT)	Line (m)
Arrive at waypoint	4:17	825
Start down	4:25	
In bottom	4:26	936
Line added	+30	966
Heat Pulse	—	
Start up (4:33)	4:32	
Out of Mud	4:34	
Start Transit	4:35	900

Center Beam Depth (m) 944
Chirp 961

Line out:

Line stopped

Ship Location (Lat, Lon)

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

71 55.185 N
153 34.585 W

Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/22
Station ID: BHF8
Penetration ID: 13
Way Point: 14
Operator(s): MADIE/MATT

Event	Time (GMT)	Line (m)
Arrive at waypoint	4:44	900
Start down	4:52	
In bottom	4:53	965
Line added	+30	995
Heat Pulse	—	
Start up (5:00)	4:59	
Out of Mud	5:01	900
Start Transit	5:03	

Center Beam Depth (m) 972 chirp 987

Line out:

Line stopped

Ship Location (Lat, Lon)
71 55.4083 N
153 34.3427 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

---

Date: 9/22
Station ID: BHF8
Penetration ID: 14
Way Point: 15
Operator(s): MADIE/MATT

Event	Time (GMT)	Line (m)
Arrive at waypoint	5:10	900
Start down	5:19	
In bottom	5:21	1028
Line added	+30	1058
Heat Pulse	—	
Start up (5:28)	5:27	
Out of Mud	5:29	
Start Transit	5:33	900

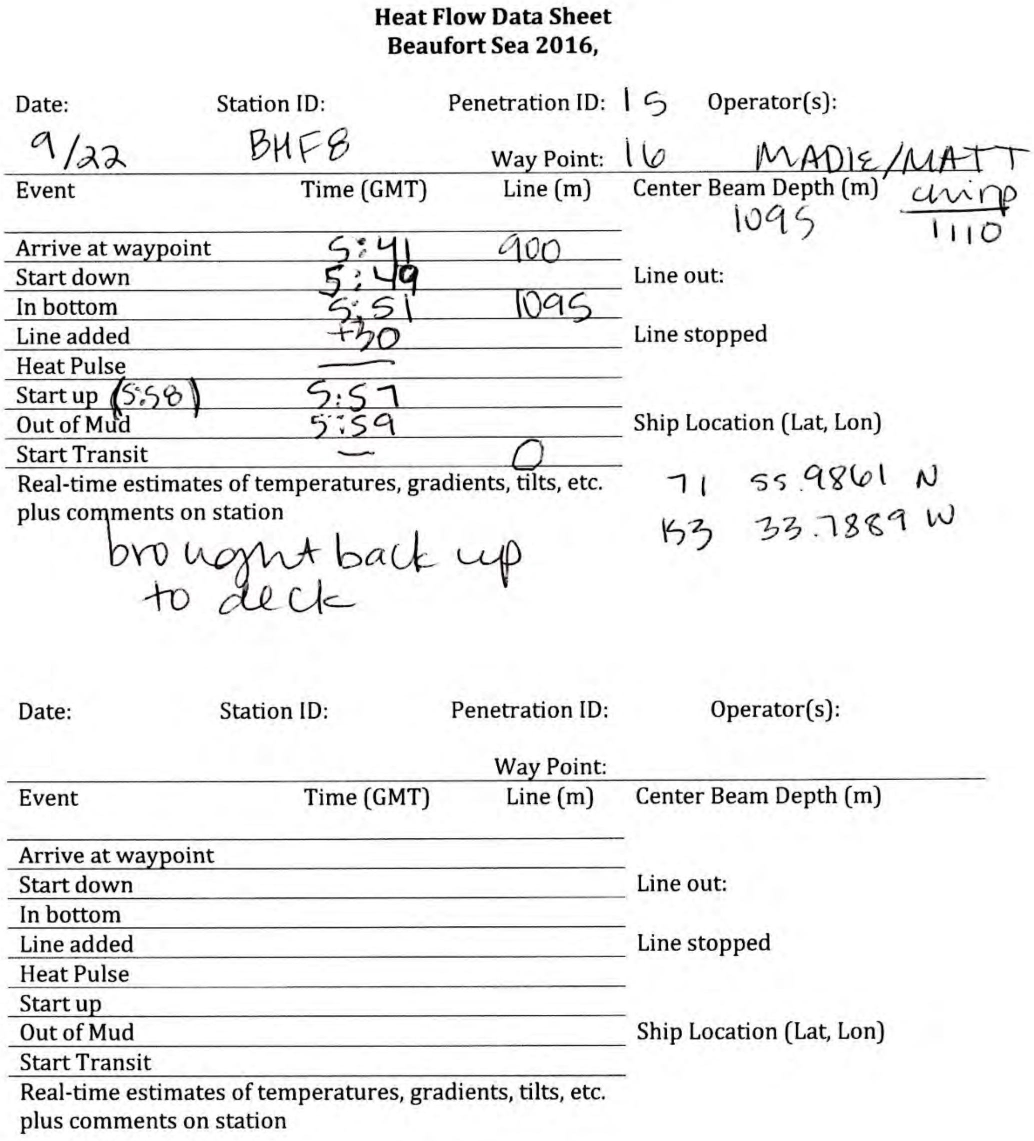
Center Beam Depth (m) 1037 chirp 1052

Line out:

Line stopped

Ship Location (Lat, Lon)
71 55.7063 N
153 34.0687 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station



Heat Flow Data Sheet
Beaufort Sea 2016,

Date: 9/22
Station ID: BHF8
Penetration ID: 15
Way Point: 16
Operator(s): MADIE/MATT

Event	Time (GMT)	Line (m)
Arrive at waypoint	5:41	900
Start down	5:49	
In bottom	5:51	1095
Line added	+30	
Heat Pulse	—	
Start up (5:58)	5:57	
Out of Mud	5:59	
Start Transit	—	0

Center Beam Depth (m) 1095 chirp 1110

Line out:

Line stopped

Ship Location (Lat, Lon)
71 55.9861 N
153 33.7889 W

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

brought back up to deck

Date:
Station ID:
Penetration ID:
Way Point:
Operator(s):

Event	Time (GMT)	Line (m)
Arrive at waypoint		
Start down		
In bottom		
Line added		
Heat Pulse		
Start up		
Out of Mud		
Start Transit		

Center Beam Depth (m)

Line out:

Line stopped

Ship Location (Lat, Lon)

Real-time estimates of temperatures, gradients, tilts, etc. plus comments on station

XIII. Complete Spreadsheet for All Deployments, Penetrations, and Heat Flow Values.

OPERATOR	DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)	BOAT REPORTED DEPTH (M)	TIME ARRIVE AT WAY POINT	TIME START DOWN	TIME IN BOTTOM	LINE OUT IN BOTTOM (M)	LINE ADDED (M)	HEAT PULSE TIME	START UP TIME	OUT OF MUD TIME	START TRANSIT TIME	LINE OUT FOR TRANSIT (M)	CHIRP DEPTH (M)	NOTES		Thermal Gradient (C/km)	Heat Flow (mW/m2)	Discards	Thermal fit NOTES
RH	####	BHF1	1	1	####	####	1470	1:00	1:28	1:30		+15	1:38	1:49	2:14	2:17	1350		ALL TIMES UTC		22	27	7, 6, 4, 2	"Ratty" data
BP	####	BHF1	2	2	####	####	1427	2:52	3:18	3:20		+25	3:27	3:34	3:41	3:44								No frictional heating, thus no fit
BP	####	BHF1	3	3	####	####	1440	4:21	4:31	4:33	1441	+29	4:41	4:49	4:52	4:57	1300				52	58		
BP	####	BHF1	4	4	####	####	1430	5:31	5:31	5:33	1430	+30	5:40	5:47	5:51	5:55	1300				24	28	1, 2, 3	"Ratty" data
MJ	####	BHF1	5	5	####	####	1458	6:23	6:30	6:34	1458	+92	6:41	6:48	6:53	7:00	1300		EXTRA LINE LET OUT TO ACCOMMODATE BOAT DRIFTING IN STRONG CURRENT					Cannot find fit, stranger things are occuring
MJ	####	BHF1	6	6	####	####	1400	7:30	7:31	7:33	1467	+30	7:40	7:47	7:50	7:55	1300	1400			43	44	1, 2, 3, 4	
MJ	####	BHF1	7	7	####	####	1380	8:29	8:34	8:35	1435	+30	8:42	8:49	8:53	8:58	1250	1384			37	49	4, 8	
MJ	####	BHF1	8	8	####	####	1320	9:25	9:29	9:31	1380	+30	9:39	9:46	9:49	9:55	1200	1320			44	47	1	
MJ	####	BHF1	9	9	####	####	1305	10:35	10:36	10:38	1318	+30	10:46	10:53	10:56	11:01	1150	1305			44	45		
MJ	####	BHF1	10	10	####	####	1210	11:33	11:38	11:41	1288	+30	11:48	11:55	11:58	12:05	1050	1210	WEAK PINGER SIGNAL		33	35		
CPB	####	BHF1	11	11	####	####	1148	12:36	12:41	12:44	1172	+30	12:50	12:58	12:59	13:04	1000	1151	STRONG SIGNAL		57	64		
CPB	####	BHF1	12	12	####	####	1157	13:28	13:31	13:34	1196	+30	13:41	13:50	13:52	13:58	1000	1149	STRONG SIGNAL		61	71		
CPB	####	BHF1	13	13	####	####	1155	14:27	14:30	14:31	1200	+30	14:36	14:43	14:45	14:57	850	1140			83	96		
CPB	####	BHF1	14	14	####	####	1105	15:56	16:04	16:06	1085	+30	16:14	16:21	16:27	16:34	850	1116	WAITED 10 MIN FOR PROBE TO STABILIZE		53	68	3, 5	
CPB	####	BHF1	15	15	####	####	1035	17:10	17:22	17:24	1032	+30	17:32	17:38	17:44	17:49	850	1060	WAITED 10 MIN FOR PROBE TO STABILIZE		56	63		
CPB	####	BHF1	16	16	####	####	936	18:13	18:23	18:25	1010	+20	18:32	18:39	18:43	n/a	surface	963	being brought back on deck for checkup and data dump		95	110		
MJ	####	BHF2	1	A	####	####	1100	6:17	6:36	7:12	1108	+30	NO PULSE	7:22	7:24	7:30	900	1158	WENCH FREE FALL SPEED REACHED 90-100 M/MIN		72	79	8, 9, 10, 11	Assumed k of 1.1 to calc HF

OPERATOR	DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)	BOAT REPORTED DEPTH (M)	TIME ARRIVE AT WAY POINT	TIME START DOWN	TIME IN BOTTOM	LINE OUT IN BOTTOM (M)	LINE ADDED (M)	HEAT PULSE TIME	START UP TIME	OUT OF MUD TIME	START TRANSIT TIME	LINE OUT FOR TRANSIT (M)	CHIRP DEPTH (M)	NOTES		Thermal Gradient (C/km)	Heat Flow (mW/m2)	Discards	Thermal fit NOTES
MJ	####	BHF2	2	B	####	####	1107	7:50	8:06	8:08	1095	+30	NO PULSE	8:17	8:20	8:37	500	1120			77	85	9, 10, 11	Assumed k of 1.1 to calc HF
MJ	####	BHF2	3	C	####	####	1031	9:12	9:15	9:26	1020	+30	NO PULSE	9:34	9:37	9:43	850	1050			74	81		Assumed k of 1.1 to calc HF
MJ	####	BHF2	4	D	####	####	890	9:58	10:10	10:11	871	+30	NO PULSE	10:19	10:21	10:27	700	910			26	29	11	"Ratty" data, Assumed k of 1.1 to calc HF
MJ	####	BHF2	5	17	####	####	810	10:42	10:48	10:50	824	+30	NO PULSE	10:57	11:01	11:08	600	820	POSSIBLE SUBMARINE HEADWALL SLIDE IN CHIRP DATA BETWEEN D AND 17, PINGER SIGNAL DISAPPEARED WHEN HEAT FLOW PROBE HIT THE BOTTOM					Fell over, NO DATA
CPB	####	BHF3	1	18	####	####	726	11:27	14:20	14:23	772	+30	NO PULSE	14:31	14:34	14:42	500	738	FIRST DEPLOY AFTER BATT CHARGEON PINGEROnly 1 temp ping showedfrictional heating signal. Deployed after changing batts in pinger. Relatively steep slope here.		28	31		"Ratty" data, Assumed k of 1.1 to calc HF
CPB	####	BHF3	2	19	####	####	647	15:02	15:06	15:08	683	+30	NO PULSE	15:15	15:18	15:24	450	669	POSSIBLY HIT HARD BOTTOM, LITTLE TO NO FRICTIONAL HEATING AND JUMP IN TILT METER		42	46		Assumed k of 1.1 to calc HF
CPB	####	BHF3	3	20	####	####	613	15:47	15:59	16:03	652	+39	NO PULSE	16:09	16:15	16:22	400	631			46	51		Assumed k of 1.1 to calc HF
CPB	####	BHF3	4	21	####	####	526	16:41	16:48	16:50	561	+30	NO PULSE	16:56	17:00	17:06	300	535	APPARENTLY HIGH TILT		39	43		Assumed k of 1.1 to calc HF, Curved potentially showing warming waters
CPB	####	BHF3	5	22	####	####	477	17:24	17:33	17:35	507	+30	NO PULSE	17:41	17:45	17:52	250	500			39	43	1, 10, 11	Warming water with depth results in bad fits
CPB	####	BHF3	6	23	####	####	449	18:09	18:19	18:21	473	+30	NO PULSE	18:26	18:31	18:36	250	460	CLOSE TO SMALL HORST AND GRABEN ON RIDGE		13	14	1, 2, 3, 4, 5, 11	Warming water with depth results in bad fits

OPERATOR	DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)	BOAT REPORTED DEPTH (M)	TIME ARRIVE AT WAY POINT	TIME START DOWN	TIME IN BOTTOM	LINE OUT IN BOTTOM (M)	LINE ADDED (M)	HEAT PULSE TIME	START UP TIME	OUT OF MUD TIME	START TRANSIT TIME	LINE OUT FOR TRANSIT (M)	CHIRP DEPTH (M)	NOTES		Thermal Gradient (C/km)	Heat Flow (mW/m2)	Discards	Thermal fit NOTES
CPB	####	BHF3	7	24	####	####	424	18:52	19:01	19:03	446	+30	NO PULSE	19:09	19:13	19:17	250	435	REAALLY NICE STRATA APPROX 5 METERS BELOW sf, APPARENT FOLDING IN STRATA		20	22	1	Warming water with depth results in bad fits, curvature (warming trend)
CPB	####	BHF3	8	25	####	####	400	19:34	19:43	19:45	420	+30	NO PULSE	19:51	19:55	####	200	410			27	30		Warming water with depth results in bad fits
BP	####	BHF3	9	26	####	####	378	20:18	####	####	397	+30	NO PULSE	####	####	####	200	388			26	29		Warming water with depth results in bad fits
BP	####	BHF3	10	27	####	####	360	21:01	21:10	21:12	348	+30	NO PULSE	21:18	21:23	21:28	150	370			38	42	1	Warming water with depth results in bad fits
BP	####	BHF3	11	28	####	####	330	21:45	21:54	21:56	347	+30	NO PULSE	####	####	22:11	150	341			52	57	1, 10, 11	Warming water with depth results in bad fits
BP	####	BHF3	12	29	####	####	298	####	####	####	284	+30	NO PULSE	####	####	####	150	308			69	76	1	Warming water with depth results in bad fits
BP	####	BHF3	13	30	####	####	271	####	23:17	23:19	257	+30	NO PULSE	####	####	####	100	281			87	96	1	Warming water with depth results in bad fits
BP	####	BHF3	14	31	####	####	205	0:02	0:11	0:12	190	+30	NO PULSE	0:18	0:24	RECOVERED	0	215	RECOVER PROBE		184	202		Assumed k of 1.1 to calc HF
CPB	####	BHF4	1	2	####	####	203	18:12	18:21	18:23	208	30	NO PULSE	18:30	18:34	18:36	125	209	1ST DEPLOY ON BHF4 WAYPOINT 1 WAS LESS THAN 200 M		122	134	11	Assumed k of 1.1 to calc HF
CPB	####	BHF4	2	3	####	####	290	18:53	19:03	19:05	294	30	NO PULSE	19:11	19:16	19:18	200	300			51	56	1	Warming water with depth results in bad fits
CPB	####	BHF4	3	4	####	####	400	19:34	19:44	19:47	421	30	NO PULSE	19:53	19:57	####	300	412	TILT IN WATER COLUMN IS ERATIC		-51	-56		Neg grad
BP	####	BHF4	4	5	####	####	540	####	####	####	531	30	NO PULSE	####	####	####	450	550	ENTERED SEDIMENT AT ~60 M/MIN		24	26	1, 11	Assumed k of 1.1 to calc HF
BP	####	BHF4	5	6	####	####	648	21:13	21:23	21:26	682	35	NO PULSE	21:32	21:37	21:41	550	662			22	24	11	Assumed k of 1.1 to calc HF
BP	####	BHF4	6	7	####	####	783	####	22:13	22:17	798	40	NO PULSE	####	####	####	700	761	LOWER PROBE TO 600 M AND HOLD		37	41	10, 11	Assumed k of 1.1 to calc HF
BP	####	BHF4	7	8	####	####	810	####	####	####	800	30	NO PULSE	####	23:14	23:17	700	753			-35	-39		Neg grad
BP	####	BHF4	8	9	####	####	1030	####	####	####	1062	30	NO PULSE	####	0:04	0:07	950	1036			51	56		Assumed k of 1.1 to calc HF

OPERATOR	DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)	BOAT REPORTED DEPTH (M)	TIME ARRIVE AT WAY POINT	TIME START DOWN	TIME IN BOTTOM	LINE OUT IN BOTTOM (M)	LINE ADDED (M)	HEAT PULSE TIME	START UP TIME	OUT OF MUD TIME	START TRANSIT TIME	LINE OUT FOR TRANSIT (M)	CHIRP DEPTH (M)	NOTES		Thermal Gradient (C/km)	Heat Flow (mW/m2)	Discards	Thermal fit NOTES
BP	####	BHF4	9	10	####	####	1220	0:47	0:55	0:58	1256	30	NO PULSE	1:04	1:10	1:15	1100	1220			88	97		Assumed k of 1.1 to calc HF
BP	####	BHF4	10	11			1247	1:38	1:47							1:58	1150	1225	PROBE FELL OVER, MOVE TO NEXT POINT					Fell over, NO DATA
BP	####	BHF4	11	12			1321	2:28								RECOVERED	0	1254	STEEP SLOPE, PROBE FELL OVER, RECOVER					Fell over, NO DATA
MJ	####	BHF5	1	1	71.4	151	207	11:18	11:23	11:24	206	20	NO PULSE	11:31	11:32	11:35	125	207	LOOKS LIKE IT SEES SEASONAL EFFECTS (MUCH WARMER DEEPER)		142	156	11	Curvature, Assumed k of 1.1 to calc HF
MJ	####	BHF5	2	2	71.4	151	211	11:52	11:55	11:56	219	20	NO PULSE	12:03	12:04	12:06	150	222	LOOKS LIKE IT SEES SEASONAL EFFECTS (MUCH WARMER DEEPER)		151	166		Curvature, Assumed k of 1.1 to calc HF
CPB	####	BHF5	3	3	71.4	151	226	12:21	12:26	12:26	231	22	NO PULSE	12:33	12:35	12:37	150	237	LOOKS LIKE IT SEES SEASONAL EFFECTS (MUCH WARMER DEEPER)		119	131	10, 11	Warming water with depth results in bad fits, Assumed k of 1.1 to calc HF
CPB	####	BHF5	4	4	71.4	151	250	12:57	13:02	13:03	251	20	NO PULSE	13:09	13:11	13:13	175	258	SOME DECAY IN TEMP WITH TIME, BUT STILL SEASONAL EFFECTS PERHAPS.		84	92		Warming water with depth results in bad fits, Assumed k of 1.1 to calc HF
CPB	####	BHF5	5	5	71.4	151	294	13:31	13:37	13:38	317	21	NO PULSE	13:44	13:47	13:48	225	305	High thermal grad, possibly still seeing seasonal effects.		23	25		Warming water with depth results in bad fits, Assumed k of 1.1 to calc HF
CPB	####	BHF5	6	6	71.4	151	381	14:10	14:16	14:17	377	23	NO PULSE	14:24	14:25	14:27	300	390	steep slope		25	28		Warming water with depth results in bad fits, Assumed k of 1.1 to calc HF
CPB	####	BHF5	7	7	71.4	151	511	14:48	14:53	14:55	508	22	NO PULSE	15:02	15:03	15:05	450	524	steep slope, probe might have fallen over.		20	22	9, 10, 11	Assumed k of 1.1 to calc HF
CPB	####	BHF5	8	8	71.4	151	660	15:19	15:25	15:27	663	22	NO PULSE	15:34	15:36	15:37	600	680	STEEP SLOPE		29	32	10, 11	Assumed k of 1.1 to calc HF
CPB	####	BHF5	9	9	71.4	151	820	16:12	16:21	16:24	843	30	NO PULSE	16:29	16:33	16:37	700	863			41	45	10, 11	Assumed k of 1.1 to calc HF
CPB	####	BHF5	10	10	71.5	151	965	16:43	16:53	16:56	977	30	NO PULSE	17:02	17:06	17:10	850	973	STEEP SLOPE 0.5 KM		66	73	11	Assumed k of 1.1 to calc HF
CPB	####	BHF5	11	11	71.5	151	1060	17:17	17:26	17:28	1050	35	NO PULSE	17:34	17:39	17:42	950	1089	possibly high tilt		86	95		Assumed k of 1.1 to calc HF
CPB	####	BHF5	12	12	71.5	151	1144	17:58	18:08	18:10	1148	50	NO PULSE	18:16	18:22	18:22	0	1188	.5 KM MOVE BEING BROUGHT ON DECK		83	91		Assumed k of 1.1 to calc HF
BP	####	BHF6	1	13	71.5	151	1270	0:20	1:05	1:08	1242	35	NO PULSE	1:14	1:21	1:22	1200	1280			76	84		Assumed k of 1.1 to calc HF
BP	####	BHF6	2	14	71.5	151	1320	1:47	1:56	1:57	1315	35	NO PULSE	2:03	2:08	2:12	1200	1334			101	111		Assumed k of 1.1 to calc HF

OPERATOR	DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)	BOAT REPORTED DEPTH (M)	TIME ARRIVE AT WAY POINT	TIME START DOWN	TIME IN BOTTOM	LINE OUT IN BOTTOM (M)	LINE ADDED (M)	HEAT PULSE TIME	START UP TIME	OUT OF MUD TIME	START TRANSIT TIME	LINE OUT FOR TRANSIT (M)	CHIRP DEPTH (M)	NOTES		Thermal Gradient (C/km)	Heat Flow (mW/m2)	Discards	Thermal fit NOTES
BP	####	BHF6	3	15	71.5	151	1330	2:32	2:41	2:43	1348	30	NO PULSE	2:49	2:54	2:57	1250	1363			107	118		Assumed k of 1.1 to calc HF
BP	####	BHF6	4	16	71.5	151	1379	3:09	3:18	3:20	1384	30	NO PULSE	3:27	3:33	3:37	1250	1360			101	111		Assumed k of 1.1 to calc HF
BP	####	BHF6	5	17	71.5	151	1371	4:00	4:09	4:10	1375	30	NO PULSE	4:16	4:19	4:22	1275	1409			71	78		Assumed k of 1.1 to calc HF
MJ	####	BHF6	6	18	71.5	151	1405	4:41	4:50	4:52	1395	30	NO PULSE	4:59	5:01	5:05	1275	1421	JUST PASSED OVER A 100M RIDGE, MAY SEE EVIDENCE IN HEAT FLOW		83	91		Assumed k of 1.1 to calc HF
MJ	####	BHF6	7	19	71.5	151	1420	5:22	5:30	5:32	1410	30	NO PULSE	5:39	5:41	5:44	1300	1435	ALSO NEAR A SMALL SEAMOUNT/RIDGE		88	97		Assumed k of 1.1 to calc HF
MJ	####	BHF6	8	20	71.5	151	1431	6:03	6:12	6:13	1420	30	NO PULSE	6:20	6.:23	6:25	1350	1453			84	92		Assumed k of 1.1 to calc HF
MJ	####	BHF6	9	21	71.5	151	1454	6:42	6:50	6:51	1435	30	NO PULSE	6:59	7:01	7:03	1350	1470			76	84		Assumed k of 1.1 to calc HF
MJ	####	BHF6	10	22	71.5	151	1460	7:23	7:32	7:33	1455	30	NO PULSE	7:40	7:42	7:45	1350	1480			82	90		Assumed k of 1.1 to calc HF
MJ	####	BHF6	11	23	71.5	151	1485	8:06	8:12	8:14	1467	30	NO PULSE	8:21	8:23	8:25	1400	1505			84	92		Assumed k of 1.1 to calc HF
MJ	####	BHF6	12	24	71.5	151	1505	8:59	9:04	9:05	1485	30	NO PULSE	9:12	9:14	9:17	1400	1505	5-10 MIN DRIFT TEST BETWEEN P11 AND P12		82	90		Assumed k of 1.1 to calc HF
MJ	####	BHF6	13	25	71.5	151	1496	9:31	9:39	9:41	1485	30	NO PULSE	9:48	9:50	9:53	1400	1515	INCORRECT BOAT DEPTH HERE		80	88		Assumed k of 1.1 to calc HF
MJ	####	BHF6	14	26	71.5	151	1507	10:03	10:11	10:12	1514	30	NO PULSE	10:19	10:21	10:23	1400	1535			86	95		Assumed k of 1.1 to calc HF
MJ	####	BHF6	15	27	71.5	151	1530	10:45	10:51	10:52	1525	30	NO PULSE	10:59	11:01	11:05	1400	1557			97	107		Assumed k of 1.1 to calc HF
MJ	####	BHF6	16	28	71.5	151	1550	11:18	11:24	11:26	1563	30	NO PULSE	11:33	11:36	11:39	1450	1575			95	105		Assumed k of 1.1 to calc HF
MJ	####	BHF6	17	29	71.5	151	1580	11:48	11:54	11:56	1593	30	NO PULSE	12:03	12:06	12:10	1475	1600			86	95		Assumed k of 1.1 to calc HF
CPB	####	BHF6	18	30	71.5	151	1575	12:19	12:28	12:29	1593	30	NO PULSE	12:36	12:39	12:41	1500	1620			76	84		Assumed k of 1.1 to calc HF
CPB	####	BHF6	19	31	71.5	151	1580	12:57	13:04	13:06	1605	30	NO PULSE	13:12	13:15	13:18	1500	1648			73	80		Assumed k of 1.1 to calc HF
CPB	####	BHF6	20	32	71.5	151	1640	13:36	13:44	13:46	1640	30	NO PULSE	13:52	13:55	13:58	1550	1692	ECHO TEMP SIGNAL		44	48	2, 3	"Ratty" data, Assumed k of 1.1 to calc HF
CPB	####	BHF6	21	33	71.6	151	1670	14:14	14:22	14:23	1660	30	NO PULSE	14:30	14:33	14:36	155O	1695			81	89		Assumed k of 1.1 to calc HF
CPB	####	BHF6	22	34	71.6	151	1680	14:54	15:03	15:04	1660	30	NO PULSE	15:10	15:13		0	1699	LAST POINT ON BHF6 AND LINE, BROUGHT UP ON DECK		80	88	11	Assumed k of 1.1 to calc HF
BP	####	BHF7	1	1	71.9	154	194	####	23:31	####	204	30	NO PULSE	####	####	####	100	204			112	123	10, 11	Warming water with depth results in bad fits, Assumed k of 1.1 to calc HF

OPERATOR	DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)	BOAT REPORTED DEPTH (M)	TIME ARRIVE AT WAY POINT	TIME START DOWN	TIME IN BOTTOM	LINE OUT IN BOTTOM (M)	LINE ADDED (M)	HEAT PULSE TIME	START UP TIME	OUT OF MUD TIME	START TRANSIT TIME	LINE OUT FOR TRANSIT (M)	CHIRP DEPTH (M)	NOTES		Thermal Gradient (C/km)	Heat Flow (mW/m2)	Discards	Thermal fit NOTES
BP	####	BHF7	2	2	71.9	154	207	####	0:02	0:04	215	30	NO PULSE	0:10	0:14	0:17	100	212			83	91	10, 11	Warming water with depth results in bad fits, Assumed k of 1.1 to calc HF
BP	####	BHF7	3	3	71.9	154	216	0:26	0:35	0:37	217	20	NO PULSE	0:41	0:44	0:47	100	223			95	105		Warming water with depth results in bad fits, Assumed k of 1.1 to calc HF
BP	####	BHF7	4	4	71.9	154	226	0:56	1:05	1:07	228	20	NO PULSE	1:13	1:18	1:21	100	237			59	65		Warming water with depth results in bad fits, Assumed k of 1.1 to calc HF
BP	####	BHF7	5	5	71.9	154	248	1:30	1:39	1:41	253	20	NO PULSE	1:47	1:50	1:53	150	273	WARM WATER TRANSITION		40	44		Warming water with depth results in bad fits, Assumed k of 1.1 to calc HF
BP	####	BHF7	6	6	71.9	154	287	2:03	2:12	2:14	290	20	NO PULSE	2:20	2:23	2:26	200	298			29	32		Warming water with depth results in bad fits, Assumed k of 1.1 to calc HF
MJ	####	BHF7	7	7	71.9	154	350	2:32	2:41	2:43	365	20	NO PULSE	2:49	2:53	2:56	250	361			25	28		Assumed k of 1.1 to calc HF
BP	####	BHF7	8	8	71.9	154	376	3:03	3:12	3:14	372	20	NO PULSE	3:20	3:23	3:26	250	386			8	9	10, 11	"Ratty" data, Assumed k of 1.1 to calc HF
BP	####	BHF7	9	9	71.9	154	389	3:35	3:44	3:46	390	20	NO PULSE	3:52	3:54	3:56	300	410	Evidence of seafloor diapir at seafloor.		-26	-29		Neg grad
MJ	####	BHF7	10	10	71.9	154	491	4:15	4:21	4:23	505	30	NO PULSE	4:29	4:31	4:37	300	510	looks very cold. Tilt ok, bu not much warming		15	17	9, 10, 11	
MJ	####	BHF7	11	A	71.9	154	370	4:55	4:56	4:57	374	30	NO PULSE	5:04	5:06	5:07	325	380	WENT BACK TO FAULT/DIAPIR FEATURE SEEN IN CHIRP PROFILE BETWEEN P9 AND P10		9	10	9, 10, 11	
MJ	####	BHF7	12	11	71.9	154	658	5:33	5:42	5:42	654	30	NO PULSE	5:49	5:50	5:54	550	672	BASED ON CHIRP, WE PUNCHED THE PROBE THROUGH A SUBMARINE SLIDE					Uninterpretable, Large curvature
MJ	####	BHF7	13	12	71.9	154	845	6:11	6:17	6:18	819	30	NO PULSE	6:25	6:27	6:29	750	840	Very steep slope. Good chirp penetration--60 mbsf! Suggests very soupy sediments.				10, 11	Curvature
MJ	####	BHF7	14	13	71.9	154	965	6:50	6:56	6:58	942	30	NO PULSE	7:05	7:07	7:09	850	973			21	23	10, 11	Assumed k of 1.1 to calc HF

OPERATOR	DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)	BOAT REPORTED DEPTH (M)	TIME ARRIVE AT WAY POINT	TIME START DOWN	TIME IN BOTTOM	LINE OUT IN BOTTOM (M)	LINE ADDED (M)	HEAT PULSE TIME	START UP TIME	OUT OF MUD TIME	START TRANSIT TIME	LINE OUT FOR TRANSIT (M)	CHIRP DEPTH (M)	NOTES		Thermal Gradient (C/km)	Heat Flow (mW/m2)	Discards	Thermal fit NOTES
MJ	####	BHF7	15	14	71.9	154	1079	7:26	7:33	7:35	1053	30	NO PULSE	7:42	7:44	7:48	900	1086			82	90		Assumed k of 1.1 to calc HF
MH	####	BHF7	16	15	71.9	154	1180	8:06	8:13	8:16	1160	30	NO PULSE	8:23	8:25	8:35	900	1191			79	87		Assumed k of 1.1 to calc HF
MH	####	BHF7	17	16	71.9	154	1206	8:47	8:54	8:57	1180	30	NO PULSE	9:04	9:06	9:13	950	1218			79	87	10, 11	Assumed k of 1.1 to calc HF
MH	####	BHF7	18	17	71.9	154	1207	9:21	9:28	9:31	1187	30	NO PULSE	9:38	9:39	9:44	1050	1219			64	70	6, 10, 11	Assumed k of 1.1 to calc HF
MH	####	BHF7	19	18	72	154	1220	9:52	10:00	10:01	1195	30	NO PULSE	10:08	10:09	10:17	950	1231	GOING BACK TO THE SITES WE SKIPPED		45	50		Likely fell over, Assumed k of 1.1 to calc HF
MH	####	BHF7	20	19	71.9	154	1115	11:02	11:06	11:08	1118	30	NO PULSE	11:15	11:17	11:24	850	1162			70	77		Assumed k of 1.1 to calc HF
MH	####	BHF7	21	20	71.9	154	1012	12:06	12:12	12:13	990	30	NO PULSE	12:20	12:22		0	1039	BEING BROUGHT BACK ON DECK		92	101		Assumed k of 1.1 to calc HF
BP	####	BHF8	1	2	71.9	154	402	####	####	####	411	20	NO PULSE	####	####	####	300	412	SKIP FIRST WAY POINT TO GET AWAY FROM POLAR BEARS		10	11	10, 11	Assumed k of 1.1 to calc HF, good curvature
BP	####	BHF8	2	3	71.9	154	419	23:12	23:18	23:19	430	20	NO PULSE	####	####	####	300	430						Assumed k of 1.1 to calc HF, good curvature, uninterpretable
BP	####	BHF8	3	4	71.9	154	565	####	####	####	597	20	NO PULSE	####	0:00	0:04	450	575						Assumed k of 1.1 to calc HF, good curvature, uniterpretable
BP	####	BHF8	4	5	71.9	154	625	0:05	0:15	0:17	653	20	NO PULSE	0:23	0:27	0:29	550	618						Assumed k of 1.1 to calc HF, good curvature but seems less, uninterpretable
BP	####	BHF8	5	6	71.9	154	630	0:35	0:44	0:46	659	20	NO PULSE	0:52	0:57	0:59	550	640						Assumed k of 1.1 to calc HF, good curvaure
BP	####	BHF8	6	7	71.9	154	645	1:05	1:15	1:16	674	20	NO PULSE	1:22	1:26	1:29	550	660						Assumed k of 1.1 to calc HF, curvature
BP	####	BHF8	7	8	71.9	154	721	1:37	1:46	1:48	736	20	NO PULSE	1:54	1:58	2:01	600	726			47	52	1, 10, 11	Assumed k of 1.1 to calc HF, curvature
BP	####	BHF8	8	9	71.9	154	721	2:09	2:19	2:21	754	20	NO PULSE	2:27	2:31	2:32	600	733	temp looks a little ratty following frictional decay. Values look cold.					Assumed k of 1.1 to calc HF
BP	####	BHF8	9	10	71.9	154	770	2:41	2:50	2:53	807	20	NO PULSE	2:59	3:02	3:03	750	780						Assumed k of 1.1 to calc HF, curvature all down thermistors
BP	####	BHF8	10	11	71.9	154	892	3:20	3:29	3:31	895	20	NO PULSE	3:37	3:40	3:41	800	915			59	65	10, 11	Assumed k of 1.1 to calc HF

OPERATOR	DATE	STATION ID	PENETRATION ID	WAY POINT	LAT (decimal degrees)	LON (decimal degrees)	BOAT REPORTED DEPTH (M)	TIME ARRIVE AT WAY POINT	TIME START DOWN	TIME IN BOTTOM	LINE OUT IN BOTTOM (M)	LINE ADDED (M)	HEAT PULSE TIME	START UP TIME	OUT OF MUD TIME	START TRANSIT TIME	LINE OUT FOR TRANSIT (M)	CHIRP DEPTH (M)	NOTES		Thermal Gradient (C/km)	Heat Flow (mW/m2)	Discards	Thermal fit NOTES
BP	####	BHF8	11	12	71.9	154	923	3:51	4:00	4:01	910	30	NO PULSE	4:07	4:09	4:12	825	938	May have sunk probe head.		69	76	1, 11	Assumed k of 1.1 to calc HF
MJ	####	BHF8	12	13	71.9	154	944	4:17	4:25	4:26	936	30	NO PULSE	4:32	4:34	4:35	900	961	light fluff drape on seafloor in chirp		85	94		Assumed k of 1.1 to calc HF
MJ	####	BHF8	13	14	71.9	154	972	4:44	4:52	4:53	965	30	NO PULSE	4:59	5:01	5:03	900	987	appears ajacent to fault or margin slope breaK. Thin apron veneer. Looks like shallowest thermistor went in perhaps		52	57	1, 11	Assumed k of 1.1 to calc HF
MJ	####	BHF8	14	15	71.9	154	1037	5:10	5:19	5:21	1028	30	NO PULSE	5:27	5:29	5:33	900	1052	likely weakly reflective drape at bottom		64	70		Assumed k of 1.1 to calc HF
MJ	####	BHF8	15	16	71.9	154	1095	5:41	5:49	5:51	1095	30	NO PULSE	5:57	5:59		0	1110	more drape on seafloor. Possible slope failure.		75	83		Assumed k of 1.1 to calc HF
																					repick 8 11			

Appendix: Overview Report on Atlantic Margin Methane Hydrate Dynamics

Prepared by C. Ruppel, USGS, June 2017

Under USGS-DOE Interagency Agreement DE-FE0005806 and as part of a subaward from DE-FE0010180 to Rick Colwell at Oregon State University, the US Geological Survey, OSU, and collaborators from UCLA, Geomar, and MARUM (Bremen), conducted a 13-day cruise aboard the *R/V Hugh R. Sharp* in September 2015 to acquire piston cores, multicores, limited amounts of informal heat flow data (outriggers on the piston corer), water column imagery, and some sub-bottom data on U.S. Atlantic margin seeps between Washington Canyon and the southern New England margin.

The purpose of the cruise was to study gas hydrate dynamics on the upper slope of the northern U.S. Atlantic margin, with emphasis on water depths of 300 m to 1200 m. Calculations completed by Ruppel as part of DE-FE0006781 provide finer-scaled details about the landward limit of gas hydrate stability on this margin, but the nominal depth from *D. Brothers et al*. (2014) and *Skarke et al*. (2014) is ~550-575 meters.

The cruise track, which is shown in purple in Figure A1, sampled the upper slope offshore Virginia in the area of concentrated seeps, worked in part of Hudson Canyon, cored along an older seismic line that was the subject of the *D. Brothers et al*. (2014) paper, and then acquired data on the New England upper slope before heading into Woods Hole to remove the cores from the ship.

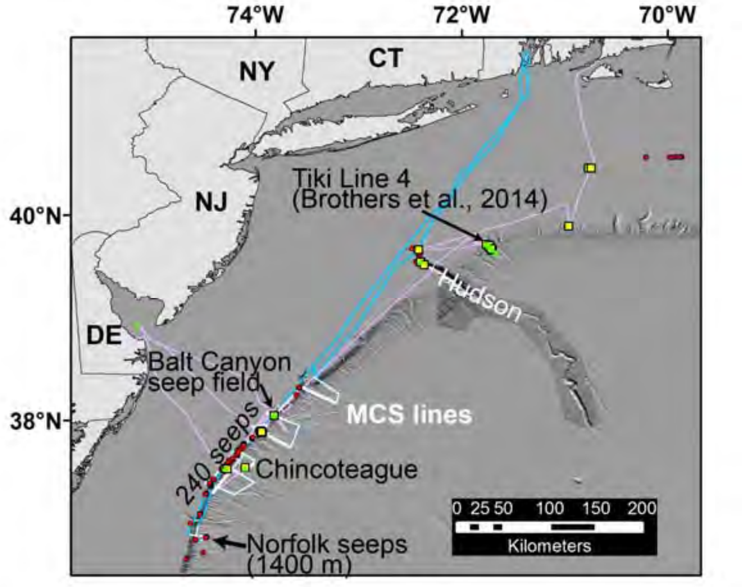


Figure A1. Ship tracks for September 2015 multidisciplinary cruise on the *R/V Hugh R. Sharp* are shown in pink. The blue ship track and the white MCS lines are from a spring 2015 cruise conducted by the USGS under the auspices of a different agreement. Seeps from the *Skarke et al*. (2014) database are shown in red. The other colored dots correspond to piston cores and CTDs.

The locations of the discrete samples (e.g., piston cores, multi-cores, and CTDs) acquired on the cruise are shown in Figure A2.

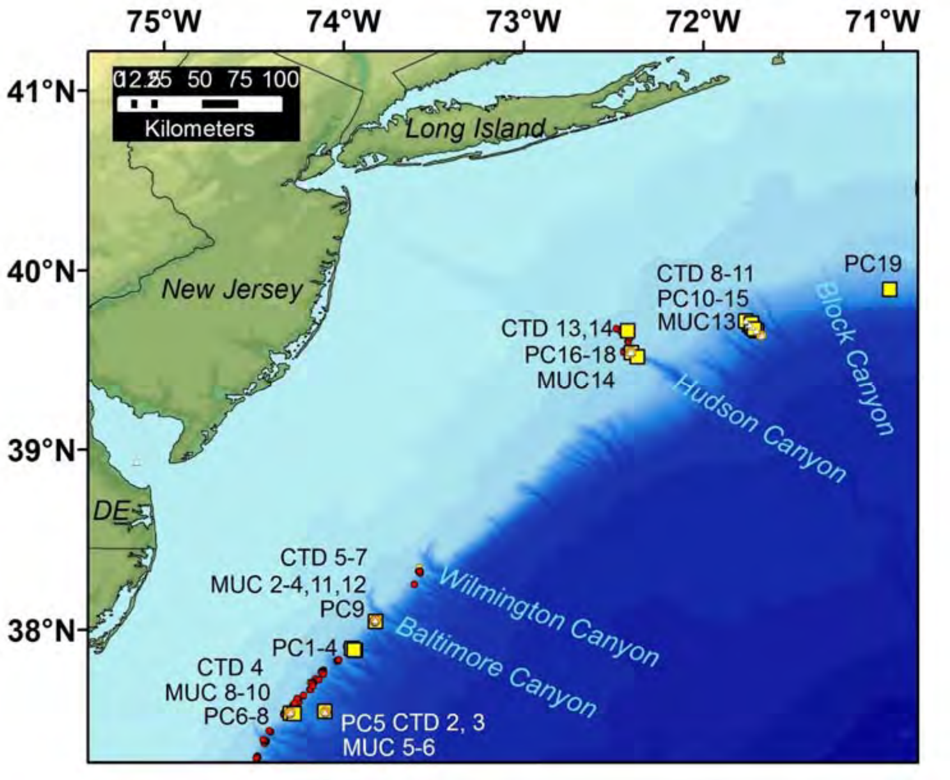


Figure A2. Piston cores (PC), multicores (MUC), and CTDs obtained during the R/V Sharp cruise. Not included are two piston cores acquired on the part of the New England margin not visible here. Numbers are not consecutive due to unsuccessful piston or multi-coring attempts.

The cruise attempted 21 piston cores with the USGS coring rig. Recovery ranged from 1.15 to 9.43 meters in the successful cores. One core attempted near the shelf-break in Hudson Canyon recovered nothing, most likely due to the predominance of sand in the shallow sedimentary section. Coring transects were attempted at 3 upper slope locations (2 with seeps on the Virginia margin and 1 lacking seeps at the site of the Tiki seismic line north of Hudson Canyon—Figure A3), with additional cores taken at other upper slope sites. Overall, the upper slope was highly indurated and/or had a strong sand component that frustrated attempts to obtain full cores. Methane and near-seafloor anoxic sediments were missing from most of the piston cores, underscoring the heterogeneous nature of the seep systems even within meters of known methane emission points. The cores were sectioned into small whole rounds for microbiology, geochemistry, and other studies. In some cases, this left little material for MSCL. However, MSCL analyses were run at URI for the subset of core material that was complete enough to make the analyses worthwhile. The USGS and URI also split these cores and produced calibrated photographs of them.

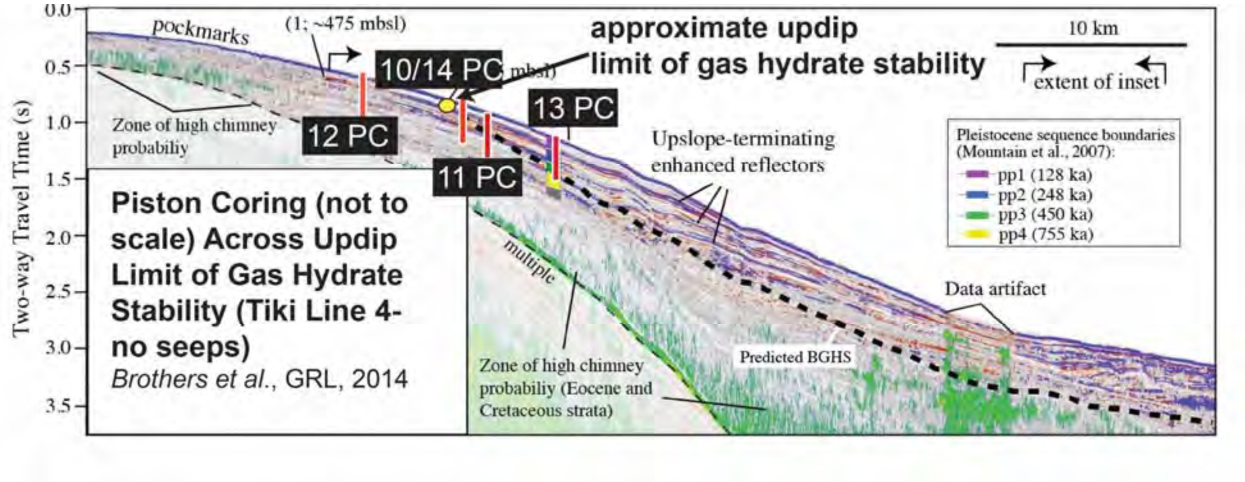


Figure A3. Upper slope piston coring transect across the updip (landward) limit of gas hydrate stability north of Hudson Canyon, superposed on the Tiki seismic data from the D. Brothers et al. paper published in 2014. Core lengths are not to scale.

The cruise also conducted 14 multicorer runs (12 successful) with real-time fiberoptic video support devised by USGS engineer Gerry Hatcher to guide the multicoring locations. The multicorer apparatus was supplied by Tina Treude at UCLA. The goal of the multicore work was to obtain relatively undisturbed samples that could be used for analyzing the rate of anaerobic methane oxidation in the near-seafloor sediments. Samples from the multicores were also used for microbiological studies (by OSU and Geomar), lipid biomarker studies (at MARUM in Germany), and biogeochemistry and physical property analyses (USGS). In addition, some multicores were sampled for paleoceanography to catalyze potential future upper slope studies by Delia Oppo at WHOI. The lack of anoxic sediments even very close to known seafloor seepage rendered analysis of the multicores challenging. The AOM rates that have emerged so far will require more analysis to fit into the framework of seep vs. background microbial processes.

Figure A4. Mini-multicoring rig provided by UCLA for the R/V Sharp cruise being retrieved off the port stern of the ship. The fiberoptic cable available at this location on the ship was used to provide real-time video feeds from the seafloor using a camera system built by USGS engineer G. Hatcher. See Hatcher et al., 2015.

Fourteen CTD casts were completed during the cruise, with attempts made to sample both within methane plumes (as guided by the water column imagery) and outside of plumes (background). The water samples have supported a wide range of studies, including analyses of dissolved CH_4 and CO_2, DIC, and $\delta^{13}C$ of methane and carbon dioxide to delineate sources of these gases. Owing to equipment problems, the DOC analyses are still in process and will be completed as soon as the USGS DOC analyzer is returned from repair.

The CTD data also provided discrete temperature-depth profiles that could be used to find the depth to the top of the hydrate stability zone in the water column (for deeper water locations) and the predicted thickness (if any) of the gas hydrate stability zone in the sediments. In Hudson Canyon, the CTD data revealed substantial warming of the water column between the September 2015 cruise and a cruise that Ruppel participated in on the R/V Endeavor in July 2014 (see Weinstein et al., 2016). This warming should theoretically have resulted in a substantial downslope (to deeper waters) shift of the landward limit of gas hydrate stability during the intervening period, although gas hydrate dynamics are not necessarily expected to keep pace with bottom water temperature changes in localized areas.

On-the-fly heat flow measurements were attempted at 15 locations on the cruise using outriggers attached to the piston core barrel, a method used decades ago at the start of heat flow measurements in the oceans. Typically three or sometimes four penetrating thermistors were used, along with the bottom water temperature measurement made on the weight stand. Given that only three of the piston cores achieved within 1.5 meters of complete penetration, the heat flow data are at best sparse and typically do not allow for determination of a robust gradient. The type of heat flow acquisition done on the cruise does not permit the in situ determination of thermal conductivities.

The cruise used the USGS EK60 38kHz transducer mounted in the *R/V Sharp's* retractable keel to survey for water column gas plumes. The EK60 is a split-beam system with only a narrow cone of ensonification, so the ship must be nearly directly over a water column methane plume to detect it. During the cruise, the USGS discovered new plumes that were not included in the original *Skarke et al.* (2014) database, documented the ephemerality of plume seepage (e.g., *Scandella et al*., 2016) by conducting repeated surveys at some upper slope sites over the course of a few days, had an unverified (by direct sampling) inference of minor seepage near an upper slope pockmark north of Hudson Canyon, and noted that some plumes with high quality factors from the original database were not seeping at the time of the surveys. Attempts to link the ephemerality of the plumes to common oceanographic/atmospheric phenomena have so far not proved productive. Data from a survey near Baltimore Canyon was used in *Prouty et al.* (2016).

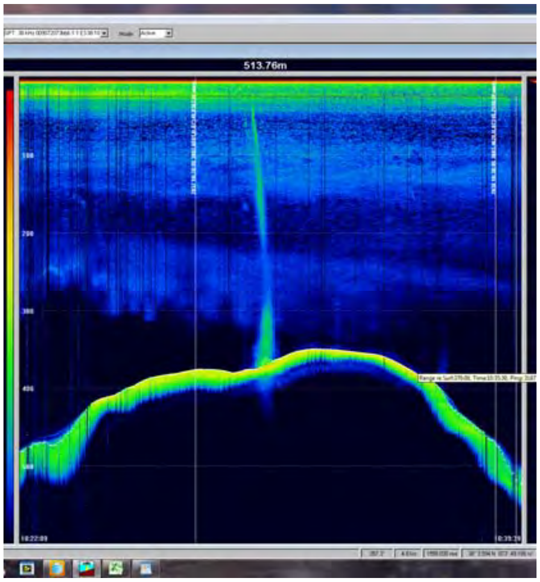


Figure A5. Raw EK60 record of a gas plume emanating from the seafloor at ~375 m water depth near Baltimore Canyon as recorded during the R/V Sharp cruise. Although the bubbles clearly continue to 40 m or shallower within the water column, the bubbles should by then have lost all of their methane to the surrounding waters.

The USGS used its Edgetech 512 towed Chirp system to image below the seafloor along a portion of the ship's trackline. In some places, these data complement MCS data acquired by the USGS earlier in 2015 or older MCS data in the USGS archives. The Chirp data provide constraints on the distribution of shallow gas, fluid conduits, and stratigraphic relationships, in some cases imaging over 0.1 s (about 75 m) below the seafloor even at water depths over 1000 m. Data from the Hudson Canyon survey was used in *Weinstein et al.* (2016).

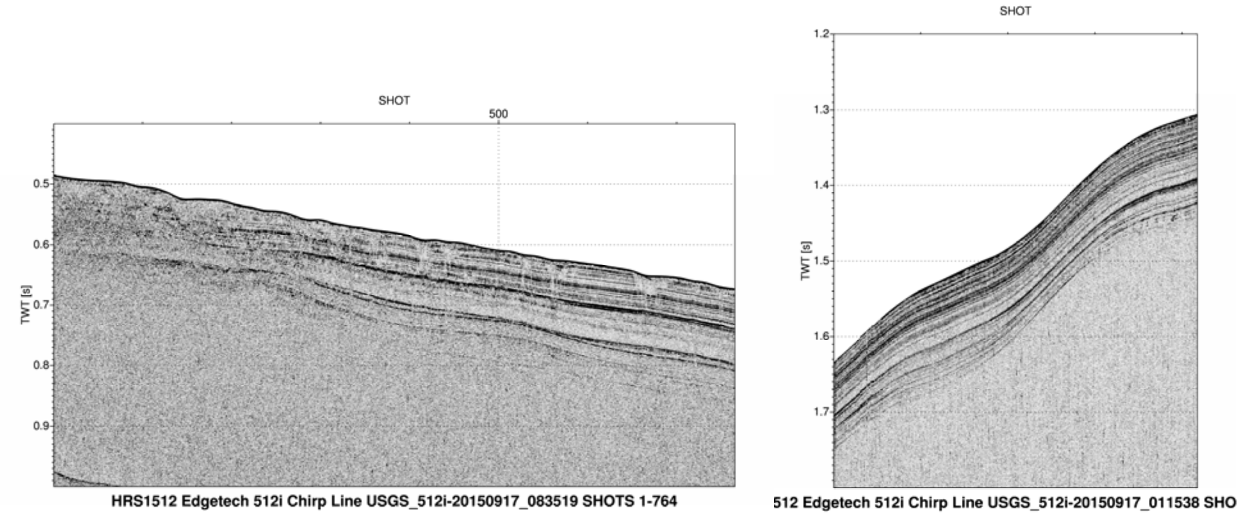


Figure A6. Examples of Edgetech 512 Chirp data obtained by the USGS during the R/V Sharp cruise, showing good penetration at both shallow and deep water depths. Imaging was more challenging on the uppermost slope due to gas charging, the presence of sand, or both factors. Note gas migration features in the section at the left.

Some of the findings to date have been described in previous reports that OSU has completed for DOE or are alluded to above. Others are listed here for the first time:

- Heterogeneity in methane emissions and biogeochemical properties occurs at the scale of centimeters near mid-Atlantic margin upper slope seeps. In many cases, pore water methane and/or anoxic sediments were lacking even very close to loci of active seepage.
- Deep-water mid-Atlantic seeps seem to emit methane more consistently than some upper slope seeps, where emissions are more ephemeral or episodic. Some upper slope seeps turn on and off within days, but the driving forces for these changes have not yet been identified. Every survey of the seep province reveals previously-undiscovered seeps, underscoring seep ephemerality and/or the initiation of new seeps (as yet, no determination of which is the prevailing process).
- Subbottom profiling reveals gas conduits beneath some seep sites and potential carbonate hardgrounds in the vicinity of particularly upper slope seeps.
- The seep methane analyses conducted so far largely pin its mechanism of origin, which is consistent with the original interpretation advanced in the Skarke et al. (2014) paper.
- In most places, the rates of AOM in the acquired samples are too low to be linked to seep activity.
- (From a previous report) When complex microbial communities are compared using 16S rDNA community sequence data (either with universal DNA primers or archaeal primers) or methane cycling archaea are compared using mcrA sequences, the seep communities along the margin form three distinct groups. These groups are defined by the site or location of the seeps.
- (From a previous report) Organic carbon content and seep dynamics may be primary drivers of microbial community structure within seep sediments. Organic carbon determines sulfate utilization and the nature of the organotrophic community both of which, in turn, control the substrate availability of methanogens.
- Hudson Canyon samples suggest that the SMTZ has recently migrated upwards in the sediments, as might be expected if flux rates have increased with time.

References/Products

(reference) Brothers, Daniel S., Ruppel, C., Kluesner, J.W., ten Brink, U.S., Chaytor, J.D., Hill, J.C., Andrews, B.D. and Flores, C., 2014, Seabed fluid expulsion along the upper slope and outer shelf of the U.S. Atlantic continental margin, Geophys. Res. Lett., doi: 10.1002/2013GL058048

Graw, M.W., Pohlman, J.W., Treude, T., Ruppel, C., and F.S. Colwell, 2016, Microbial communities in methane seep sediments along US Atlantic Margin are structured by organic matter and seepage dynamics, Fall Meeting American Geophysical Union, San Francisco.

Graw, M.W., Solomon, E., Krause, S., Treude, T., Pohlman, J.W., Ruppel, C., Colwell, R.S., 2015. Towards Biogeochemical Modeling of Anaerobic Oxidation of Methane: Characterization of Microbial Communities in Methane-bearing North American Continental Margin Sediments. American Geophysical Union. Dec. 14-18, San Francisco, CA.

Hatcher, G., J. White, P. Dal Ferro, and C. Ruppel, 2015, Sampling methane seeps and plumes on the US Atlantic margin, *Sound Waves*, USGS newsletter, Oct/Nov 2015.

Pohlman, J.W., Ruppel, C., Colwell, R..S., Treude, T., Graw, M., Casso, M., Boze, L.G., Buczkowski, B., Brankovits, D., 2015. Sediment and water column geochemistry related to methane seepage along the northern US Atlantic margin. American Geophysical Union. Dec. 14-18, San Francisco, CA.

Prouty, N.G.; D. Sahy, C.D. Ruppel, E.B. Roark, D. Condon, S. Brooke, S.W. Ross, A.W.J. Demopoulos, 2016, Insights into methane dynamics from analysis of authigenic carbonates and chemosynthetic mussels at newly-discovered Atlantic Margin seeps, Earth and Planetary Science Letters, doi:10.1016/j.epsl.2016.05.023.

Quattrini AM, Nizinski MS, Chaytor JD, Demopoulos AWJ, Roark EB, France SC, Moore JA, Heyl, T, Auster, PJ, Kinlan, B., Ruppel, C., Elliot, K.P., Kennedy, B.R.C., Lobecker, E., Skarke, A., and Shank, T.M., 2015, Exploration of the canyon-incised continental margin of the northeastern United States reveals dynamic habitats and diverse communities. *PLoS ONE* 10(10): e0139904. doi:10.1371/journal.pone.0139904

Ruppel, C., Kluesner, J, Danforth, B., Casso, M., Pohlman, J.W. 2015. Subseafloor to Sea-Air Interface Characterization of the northern US Atlantic Margin Seep Province. American Geophysical Union. Dec. 14-18, San Francisco, CA.

Ruppel, C., Kluesner, J., Pohlman, J., Brothers, D., Colwell, F., Krause, S., and Treude, T., 2015, Methane hydrate dynamics on the Northern US Atlantic margin, *DOE NETL Fire in the Ice* newsletter, pp 10-13.

(reference) Scandella, B. P., L. Pillsbury, T. Weber, C. Ruppel, H. F. Hemond, and R. Juanes, 2016, Ephemerality of discrete methane vents in lake sediments, Geophys. Res. Lett., 43, 4374-4381, doi:10.1002/2016GL068668.

(reference) Skarke, A., C. Ruppel, M. Kodis, D. Brothers, and E. Lobecker, 2014, Widespread methane leakage from the seafloor on the northern US Atlantic margin, Nature Geoscience, doi:10.1038/ngeo2232.

Treude, T., Krause, S., Colwell, R.S., Graw, M., Pohlman, J.W., Ruppel, C. 2015 Anaerobic oxidation of methane related to methane seepage along the northern US Atlantic margin. American Geophysical Union. Dec. 14-18, San Francisco, CA.

Weinstein, A., L. Navarrete, C. Ruppel, T. C. Weber, M. Leonte, M. Y. Kellermann, E. C. Arrington, D. L. Valentine, M. I. Scranton, and J. D. Kessler (2016), Determining the flux of methane into Hudson Canyon at the edge of methane clathrate hydrate stability, Geochem. Geophys. Geosyst., 17, 3882–3892, doi:10.1002/2016GC006421.