Earth and Space Science

TECHNICAL REPORTS: METHODS

10.1029/2020EA001327

Key Points:
- We have designed, developed, and tested a low-cost, portable hybrid Lister-type probe to measure shallow thermal gradients
- The probe consists of lightweight, quickly interchangeable/expendable components deployable to 2,100-m depth
- The probe provides high vertical and temporal temperature resolution and rapid data transmission, reducing downtime

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3

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Citation:
Hornbach, M. J., Sylvester, J., Hayward, C., Kühn, M., Huhn-Frehers, K., Freudenthal, T., et al. (2021). A Hybrid Lister-Outrigger probe for rapid marine geothermal gradient measurement. *Earth and Space Science*, *8*, e2020EA001327. https://doi.org/10.1029/2020EA001327

Received 28 JUN 2020
Accepted 18 OCT 2020
Accepted article online 3 NOV 2020

A Hybrid Lister-Outrigger Probe for Rapid Marine Geothermal Gradient Measurement

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Abstract We have successfully constructed and tested a new, portable, Hybrid Lister-Outrigger (HyLO) probe designed to measure geothermal gradients in submarine environments. The lightweight, low-cost probe is 1–3 m long and contains 4–12 semiconductor temperature sensors that have a temperature resolution of 0.002°C, a sample rate of <2 s, and a maximum working depth of ~2,100 m below sea level (mbsl). Probe endurance is continuous via ship power to water depths of ~700 mbsl or up to ~1 week on batteries in depths >500 mbsl. Data are saved on solid-state disks, transferred directly to the ship during deployment via a data cable, or transmitted via Bluetooth when the probe is at the sea surface. The probe contains an accelerometer to measure tilt, internal pressure, temperature, and humidity gauges. Key advantages of this probe include (1) near-real-time temperature measurements and data transfer; (2) a low-cost, transportable, and lightweight design; (3) easy and rapid two-point attachment to a gravity corer, (4) short (3–5 min) thermal response times; (5) high temporal/spatial resolution; and (6) longer deployment endurance compared to traditional methods. We successfully tested the probe both in lakes and during sea trials in May 2019 offshore Montserrat during the R/V Meteor Cruise 154/2. Probe-measured thermal gradients were consistent with seafloor ocean-drilling temperature measurements. Ongoing probe improvements include the addition of real-time bottom-camera feeds and long-term (6–12 months) deployment for monitoring.

1. Introduction and Background

For more than a decade, there has been a growing need for more dynamic, time-, and cost-efficient ways to measure heat flow and geothermal gradients in marine environments. This need was clearly outlined in the 2007 National Science Foundation (NSF)-sponsored workshop report, "The Future of Marine Heat Flow: Defining Scientific Goals and Experimental Needs for the 21st Century." The report highlights how marine Earth science research "suffers from a lack of access to capabilities for acquisition, processing, and interpretation of marine heat flow data," and ultimately recommended "developing and sustaining the capability for the acquisition of marine heat flow data by researchers operating on UNOLS and other (conventional) research vessels at low cost" (Harris et al., 2008). The marine heat flow community notably requested instruments that (1) allow for real-time, rapid, two-way communication with deployed instrumentation so that measurements could be "modified on the fly" and (2) provide low-cost approaches for heat flow measurements applicable to multidisciplinary research studies, where heat flow may not be the primary scientific objective (Harris et al., 2008).

Since the 1970s, the two most heavily used tools for collecting marine heat flow data have been either Lister-type multipenetration "violin-bow" heat flow probes (e.g., Hyndman et al., 1979; Lister, 1970; Nagihara & Lister, 1993) or outrigger temperature data loggers attached to coring systems (e.g., Gerard et al., 1962; Pfender & Villinger, 2002). Each of these two probe-types has advantages and disadvantages. Here, we describe a new type of probe, the Hybrid Lister-Outrigger (HyLO) probe, that is designed to maximize the advantages of each of these probe systems. The HyLO probe is specifically designed to complement (but not replace) both Lister probes and outrigger temperature loggers by providing a low-cost, low-weight, rapid, and versatile (deployable either as a stand-alone or outrigger configuration) approach for thermal gradient measurements at shallow to intermediate water depths (up to ~2,000 m) on smaller vessels (where an A-frame or gravity corer may not be available). Regarding the low cost of the new HyLO probe, the raw components used to develop the probe including all housing, data loggers, thermocouples, and cabling are less than U.S. $500. The greatest construction cost for the new probes, by far, was the labor involved in design adaptations and field testing during development. The most significant cost savings with this probe, however, is its feasibility for use on smaller vessels, with less operational personnel, less fuel cost, and less instrument downtime due to near-real-time data transmission. These efficiencies equate to tens of thousands of dollars (or more) in savings depending on ship day rate costs and cruise time. The hope is that HyLO probes will fill an important gap in understanding geothermal gradient and heat flow in continental margin and shelf settings by allowing researchers to test "on-the-fly" shallow seafloor fluid or heat flow hypotheses in dynamic marine environments on a broader range of sea-going vessels.

Heat flow and geothermal gradients are fundamental measurements that provide direct insight into plate tectonics and the thermal evolution of the seafloor and upper crust. For more than 70 years geophysicists have developed creative and often ingenious techniques for making these measurements in the demanding physical environments at the bottom of the ocean (e.g., Bullard, 1954; Hyndman et al., 1979; Lister, 1970; Pfender & Villinger, 2002). Although several marine thermal gradient and heat flow tool designs exist (e.g., Bullard, 1954; Gerard et al., 1962; Hyndman et al., 1979; Lister, 1970; Figure 1), the approach for measuring heat flow using each of these tools is similar. All probes consist of a lance containing a thermistor or string of thermistors that are inserted into the upper few meters of the seafloor (e.g., Langseth, 1965). Following initial frictional heating of thermistors in the lance during insertion into the sediments, temperature quickly decays over seconds or minutes toward a background equilibrium value. By knowing (1) steady-state temperature for each thermistor in combination with depth spacing, (2) probe dip angle, (3) seafloor bathymetry, and (4) bottom water temperature variations, it is possible to estimate the thermal gradient in marine environments. Furthermore, we can estimate heat flow by combining thermal gradient measurements with sediment thermal conductivity measurements (typically measured either in situ using a known heating source in the probe or later by measuring the thermal conductivity on a sediment core recovered at the site) (e.g., Langseth, 1965).

The first marine heat flow probes developed, known as "Bullard" probes, are heavy and rugged with slow thermal response times. Thermistors are housed in a thick (typically 2- to 3-cm diameter) steel pipe that acts both as a sensor housing and as a strength member (Bullard, 1954, Figure 1a). The wide-diameter pipe housing the thermistors can disrupt surrounding sediment and, despite its sturdy design, will sometimes still bend or become damaged during deployment when the probe encounters a hard seafloor or nonvertical pull-out occurs (e.g., Bullard, 1954; Lister, 1970).

There are both advantages and disadvantages to Bullard-type probes. Wide-diameter pipes on Bullard probes increase probe rigidity and weight but are difficult to deploy and transport. Wider-diameter pipes also result in much slower thermal response times. A narrow-diameter pipe on a Bullard probe results in less weight required for seafloor insertion and faster thermal equilibrium as the characteristic response time for temperature change in the probe is proportional to the probe lance radius squared. For example, reducing the diameter of a Bullard probe lance from 2 to 1 cm can theoretically reduce thermal response time by ~75% (Carslaw & Jaeger, 1959). If hundreds of heat flow measurements are needed, the faster response time using a narrow diameter probe lance can save hours or even days of ship time. Furthermore, a narrow Bullard probe requires less weight to insert into the seafloor, since reduced surface area of the probe also reduces resistance of the lance while penetrating the seafloor. A narrower diameter Bullard probe therefore has both faster thermal response times, and it has the added advantage of maneuverability: Its lower weight requirements for seafloor penetration make it easier to manage during deployment, recovery, and shipping. Unfortunately, the efficiencies of a narrow diameter Bullard probe lances come with a critical drawback: Narrow diameter Bullard probes have significantly reduced probe strength which increases the risk of probe bending or failure during seafloor insertion compared to thicker and wider diameter probes (Bullard, 1954; Langseth, 1965; Lister, 1970). Bending of the probe can lead to several hours of downtime and data loss due to probe repair. Because of these problems, for the past ~40 years, the preferred tools for collecting marine heat flow and geothermal gradient data have been either Lister-type "violin-bow" probes that are outrigged from a thicker strength member (Hyndman et al., 1979; Lister, 1979) (Figure 1b) or, alternatively, Ewing-type temperature loggers that are attached to large gravity coring systems (e.g., Gerard et al., 1962;

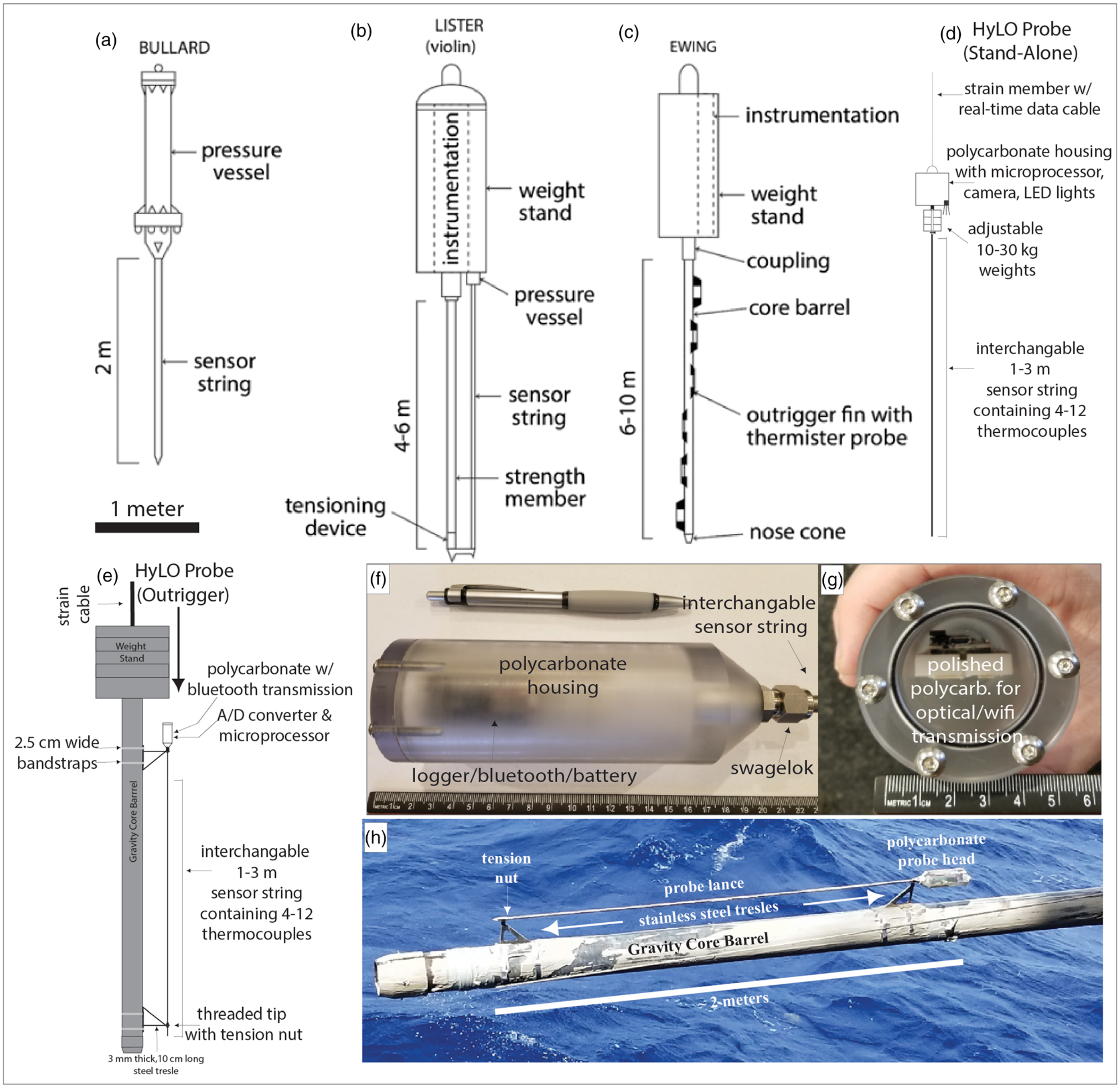

Figure 1. Mechanical configuration of the three most common marine heat flow probes (a–c) (Sclater et al., 2014) and the two HyLO probe configurations (d and e). Photo images of the polycarbonate housing and join site of the probe head and lance for HyLO probes (f and g). Thermocouple strings are quickly interchangeable (~5 min) via swageloks (h). A photo of the first recovery of the HyLO probe outrigged to a 3-m-long gravity corer during sea trials from the R/V Meteor in May 2019.

Pfender & Villinger, 2002) (Figure 1c). The Lister- and Ewing-type probes are generally preferred over the original Bullard probes because they are quite robust due to the rigid strength member, and the sensor string still has a narrower diameter thermistor housing, resulting in faster thermal response times. Below we briefly outline other important advantages and disadvantages for Lister- and Ewing-type temperature loggers.

1.1. Advantages and Disadvantages of Lister Probes

The Lister probe first discussed by Lister (1979) and perfected by Hyndman et al. (1979) has been the workhorse for shallow marine heat flow measurements for the past 40 years and remains in use today (e.g., Antriasian et al., 2019). There are several advantages to using Lister probes that have made it a fundamental marine heat flow measurement tool. First, Lister probes usually provide in situ thermal conductivity measurement. The sensor strings in these probes contain a heat element that generates a well-constrained temperature pulse, allowing in situ measurement of thermal conductivity (e.g., Lister, 1970). As a result, no coring or additional postdeployment thermal conductivity measurements are necessary. Second, these probes are durable and versatile: They can be deployed both in shallow lakes and in water depths >5,000 m. Third, many Lister probes have acoustic transponders capable of transmitting preliminary real-time data (such as probe tilt, approximate insertion depth, and preliminary temperature measurements) back to the ship which is particularly useful when working in great water depth (>2,000 mbsl) and areas with hard seafloor where insertion rate is low since these probe can inform researchers of probe success rate during deployment. Some more advanced Lister probes have coax cable connections that allow for real-time data transmission if a ship winch has sufficient coax cable available (e.g., Berndt, 2013). Fourth, Lister probes can contain several thermistors (usually more than 10), resulting in high vertical resolution temperature-depth measurements.

There are, however, several disadvantages to using Lister probes. Lister probes typically weigh more than 0.5 t and can be 3–6 m long, requiring several persons to deploy and recover and a more limited weather window than smaller instruments, as well as high transport costs. Additionally, due to their significant weight and difficult handling at sea, Lister probes are rarely longer than 6 m and cannot reach greater subseafloor depths where sediment temperatures are less impacted by bottom water temperature fluctuations. The thermal response time for Lister probes is typically half that of traditional Bullard probes; however, it still takes ~7 min following insertion to estimate steady-state temperature and an additional ~7 min (14 min total) to also measure thermal conductivity. Conductivity measurements using traditional Lister probes can also sometimes fail to produce accurate results (e.g., Berndt, 2013; Hornbach et al., 2020; Lister, 1979). If damaged or bent on the seafloor, Lister probes pose a higher risk both in terms of lost ship time and data loss, since all data are stored in a single logger, and replacement of these components or the sensor string can be expensive, time-consuming, and potentially nontrivial. Finally, the ability of Lister probes to measure thermal conductivity and transmit data acoustically means higher power consumption, with probe endurance time typically no more than 24–48 hr before probe recovery and battery replacement is required. To maximize data collection, heat flow probes are often kept deployed for hours or days at a time, sometimes with no direct access to the data. Once the instrument is recovered on board, it can take several hours more to download and process the data for each site. Thus, a key drawback of the Lister probe is the limited access to real-time data to make quick decisions regarding data character or quality.

1.2. Advantages and Disadvantages of Ewing-Type Probes

An alternative, highly effective tool for measuring heat flow and thermal gradient is the Ewing-type temperature probe. Ewing probes are attached to gravity coring systems that are routinely used in marine research (e.g., O'Regan et al., 2016). In most instances, several Ewing probes are attached to the side of gravity coring devices to measure the thermal gradient.

Perhaps the most significant advantage of Ewing probes is their low weight and portability (Clark et al., 1972). The most advanced Ewing probes consist of individual thermistor and temperature logger systems that are centimeters long and typically weigh only a few hundred grams. Therefore, unlike Lister probes, they are easy to transport to any ship that has a gravity coring system. Second, the smaller thermistor sensor tip on Ewing-type probes results in very fast thermal response time—typically a few seconds—meaning, in theory, significantly faster temperature measurements (e.g., Gerard et al., 1962), although, ideally 3- to 5-min-long measurements, provide the most reliable temperature estimates (Pfender & Villinger, 2002) using these probes. Additionally, because the Ewing probes measure only thermal gradient and conductivity is measured after gravity cores are recovered, no time is spent measuring thermal conductivity in the sea bottom. Therefore, Ewing probes reduce the time on-site by about half compared to a Lister probe deployment (at added cost of measuring core thermal conductivity later). An additional inherent advantage of Ewing probes is that the depth of penetration and sediment character (and therefore potential uncertainty) may be better constrained because normally a sediment core is recovered at the same time as the temperature measurements are made: The core provides direct insight into sediment physical properties, penetration depth, and conductivity along the entire core profile, not just at thermistor locations. Since the Ewing probes can be attached anywhere along a core barrel—including jumbo piston coring systems that are up to 75 m long (e.g., the Calypso corer)—they can be used to collect deeper—and therefore potentially higher quality—temperature measurements that are less impacted by bottom water fluctuations. Finally, Ewing probes provide a potentially lower-risk approach for collecting temperature gradient data because the thermistors and data loggers are dispersed along the core barrel: Even if some are damaged during insertion, remaining instruments and additional spares can be used or replaced relatively easily.

Nonetheless, Ewing probes also have several disadvantages. Ewing probes are usually only attached to gravity corers and therefore require large vessels with gravity coring systems available. Additionally, Ewing probes generate lower spatial resolution thermal gradient results than Lister probes. This is because each Ewing probe typically houses only a single thermistor. Adding more Ewing probes to the core barrel increases spatial resolution, but at the risk of greater sediment disturbance, as adding more Ewing probes disrupt more sediments surrounding the core barrel. Ewing probes are therefore typically staggered around the core barrel in a helix pattern, often a meter or more apart, to avoid disrupting sediment (e.g., Gerard et al., 1962; Pfender & Villinger, 2002; Sclater et al., 2014). The staggered spacing and long distances between probes mean that if probe penetration is limited (only a few meters), the thermal gradient measurements may consist only of very few measurements, resulting in higher gradient uncertainty compared to Lister probes that often have thermistors spaced every 0.33 m. An additional disadvantage is that Ewing probes must have each individual logger attached and removed to the core barrel during deployment and final recovery, with each data logger requiring individual data downloading. Ewing probes can therefore take more time to prepare and compile/process data than Lister probes once data are acquired.

2. Instrumentation Development Methods and Results

The probe described here is specifically designed to collect near-real-time geothermal data at high sample rates (<2 s) on small vessels in water depths <2,000 mbsl. Advances in material science combined with low-cost microprocessor and microchip technology allow for the construction of inexpensive, transportable probes that acquire and transmit data in real time at high samples rates for extended periods of time (weeks to years).

Development of the new probes presented here was motivated by the desire to (1) obtain rapid, ideally near-real-time temperature gradient data using (2) a low-cost, lightweight, highly portable tool. The new probe builds on previous designs and in many ways represents a hybrid adaptation of Bullard, Ewing, and Lister probes. For brevity, the probe described here represents only the final product of more than a year of incremental probe design adjustments and remodeling to ensure rapid thermal response time, an ~2,000-mbsl water depth pressure rating, near-real-time data transmission, and easy instrument transport and construction. While the new probe is inexpensive and provides rapid data transmission, its water depth and penetration range is limited. The stand-alone version of the probe, which weighs <40 kg even with full added weight, can be deployed rapidly by one to two people and requires no A-frame or crane. The probe also provides either real-time or near-real-time temperature data so that results are known within minutes. The primary disadvantage of the new probe is that it (1) currently operates in water depths shallower than 2,100 m, (2) has shorter probe lengths (1–3 m) resulting in 1 to 2 times higher uncertainty than the conventional 3- to 6-m-long marine heat flow probes, and (3) requires separate thermal conductivity measurements. The probe therefore does not replace traditional Ewing and Lister probes, but it represents a potentially important, rapid, lightweight alternative for measuring thermal gradient with high vertical resolution and near-real-time results on continental margins and in shallow water settings using smaller vessels.

2.1. Basic Design and Construction

In its simplest form, the new probe represents a miniaturized, portable Bullard-type heat flow probe that can be either outrigged to the side of a gravity corer (like an Ewing probe but with a longer sensor string with more thermocouples) or, alternatively, deployed as a stand-alone device. The Probe consists of two physical components that can be quickly and easily attached, detached, or interchanged. These include (1) a stainless steel sensor string housing the thermocouples and (2) a polycarbonate probe head housing the electronics/power/data logger package.

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2.1.1. Probe Sensor String

The probe's sensor string consists of a 1- to 3-m-long stainless steel tube with an outer diameter of 0.95 cm and an inner diameter of 0.5 cm. It houses 8 to 12 analog thermocouples. The thermocouples are spaced 0.12 to 0.3 m apart. The number and spacing depend on the sensor string length used. Once the sensors and their power and data cables were inserted into the tube, we vacuumed out all air and injected highly thermally conductive (~1 W/m/K) epoxy into the sensor strings. We also tested other materials including mineral oil and thermal grease as a possible injection material for the sensor strings, but epoxy doped with high-conductivity materials (silver thermal grease or diamond paste) works best because it provides (1) fast thermal response time, (2) locked sensor locations that cannot move during seafloor impact, (3) greater structural rigidity compared to an oil-filled center, and perhaps most importantly, (4) quick and easy sensor string attachment and replacement from the probe head, since epoxy, once hardened, does not leak from the string. The doped thermal epoxy filling the temperature string has a thermal conductivity >1 W/m/K, nearly an order of magnitude greater than mineral oil often used to fill Lister probes. The bottom of the sensor string is threaded on the inside, and after epoxy injection, a small threaded screw machined with a sharp tip and rubber O-ring is screwed into the bottom of the probe lance. The top of the sensor string contains the data, power, and ground wires from the thermocouples. A single, 0.95-cm stainless steel Swagelock connection is used to provide a watertight seal, connecting the sensor string to the electronics in the probe head.

2.1.2. Probe Head and Electronics

The probe head consists of a 12-cm-long, 6.4-cm diameter hollowed-out polycarbonate cylinder that has an inner diameter of 3.8 cm and a total payload storage volume of 113 cm^3 (Figures 1d–1h). The probe head is made of polycarbonate. This makes it durable, corrosion resistant, low-cost to purchase and machine compared stainless steel (approximately one third the cost), and most importantly, transparent to light and microwaves, allowing data transfer using wireless frequencies. The bottom of the probe head is tapered to reduce drag during insertion. At its base there is a port threaded with a watertight O-ring Swagelock pipefitting. We use this port to thread through the data and power lines to the sensor string, which is connected mechanically to the probe head with a single Swagelok nut. We cap the probe head with a circular, approximately 1-cm-thick piece of polished polycarbonate that is grooved to hold an O-ring. Some of these caps are polished and capable of optical transmission; others have data cable ports using watertight O-ring Swagelock fittings.

To determine the effective operating depth of the probe head, we performed a series of pressure tests in which the probe head, with a short (0.1 m) probe sensor string attached to it, was submersed and pressurized in a stainless steel containment vessel. To assess deformation of the polycarbonate housing during pressurization, we placed a pressure and temperature sensor inside the probe and increased pressure in a stepwise manner. Results from repeat pressure tests on the probe head demonstrated that the air pressure in the payload space of the probe head increased approximately linearly with external pressure, with an ~1% increase in atmospheric pressure for every ~5×10^6 Pa of added external pressure (equivalent to ~500-mbsl water depth). For pressure below 2.1×10^7 Pa, deformation of the probe head appears to be elastic, with pressure inside the probe head responding linearly to any change in external pressure. At pressures above 2.1×10^7 Pa (equivalent to ~2,100-mbsl water depth), we saw no obvious damage to the probe head and the internal pressures remained low (~4% above atmospheric pressure) but we noticed that probe screw threads seemed tighter, perhaps due to minor plastic deformation and compression, making screws slightly more difficult to remove. Close inspection under a microscope revealed microcracks emanating from cap screw points that appeared once pressure exceeded ~2.1×10^7 Pa. Based on these observations, we conclude that probe heads with this design should not be deployed deeper than ~2,100-mbsl water depth without jeopardizing the mechanical integrity of the probe and that probes should be analyzed routinely after every few uses to check for material fatigue.

The probe head houses an 18-bit analog-to-digital converter that digitizes all analog voltages from the thermocouples (up to 12 channels), an accelerometer/tilt meter, a humidity and internal pressure sensor, a microprocessor for controlling sample rate, data storage, and when needed, a Bluetooth or 70-cm microwave radio transmitter. The microprocessor is an 8-bit ATmega32u4 that consists of a low-precision ceramic clock, with an accuracy of 70 ppm (or drift of up to 6 s/day) for a temperature range of 0°C to 40°C. To improve timing accuracy when operating autonomously on battery power, we have added a DS3231 temperature compensated crystal precision clock that is accurate to ±2 ppm (0.17 s/day). The wires carrying power, ground, and analog temperature data from the thermocouples connect to the 18-bit digitizer quickly and easily using 2.5-mm jumpers. As a result, changing the thermocouple sensor string on the probe head takes ~5 min. All digitized temperature data are saved to an SD card attached to the microprocessor. If a data line is connected from the top port of the probe head to the ship, the data are also transmitted real time to the ship and integrated with high-precision computer-based clocks. Power requirements for the probe during data collection are low (<0.07 W). During operations where temperature measurements are sampled at 0.5 Hz, the probe draws ~20 mA using 3.3 V. The probe can therefore operate continuously for ~4 days using only a single, small 2-Ah lithium-ion battery. For sample rates of 0.1 Hz (the sample rate often used for Lister probes), the probe can operate for more than a week. Alternatively, as we describe below, if the probe is connected to a combined data/strength cable, it can operate indefinitely using shipboard power.

2.2. Instrument Deployment Approach

The probe can be deployed either as an outrigged instrument attached to a heavy gravity corer or as a stand-alone instrument on smaller vessel where no A-frame, crane, or associated gravity coring equipment is available. The two deployment approaches have advantages and disadvantages that we outline below.

2.2.1. Stand-Alone Deployment

On small vessels where no crane or A-frame is available, we can deploy the probe as a stand-alone system attached to a cable. In this instance, we add a small weight (10–40 kg) to the top of the probe, which can be deployed by a single person. Where the seafloor consists of uncompacted silt or mud, we find that only 10–20 kg of added weight is necessary to achieve ~2 m of penetration into the seafloor, primarily because the thermocouple lance has a very narrow diameter that reduces surface friction. For a cable, we use a lightweight 0.005-m diameter cable with three conductors that we connect to the top port of the probe head. This cable not only acts as a strength member for deploying and recovering the probe but also provides power, ground, and a data line for real-time data transmission. The combined data, power, and strength cable are rated to 136 kg (1,333 N), well above the maximum weight of the total system of ~40 kg in air (including the probe, probe weights, and entire 200-m-long cable). The cable is also rated above the average pullout force (~300 N) needed to recover the probe. On the ship, the cable is connected to a microprocessor that provides a real-time data feed to a laptop computer.

2.2.2. Outrigger Deployment

On larger vessels where gravity coring capabilities exist, the thermal gradient tool can also be deployed as an outrigger attached to a gravity corer. For this approach, we secure the probe to the gravity corer by attaching two stainless steel metal brackets to the core barrel with stainless steel, 2.54-cm-wide, band straps. Each bracket has a stainless steel trestle extending 10 cm from the core barrel that has at its end a 1-cm-long, ~1-cm diameter, welded stainless steel pipe (Figures 1e and 1h). The probe is secured to brackets by simply sliding the sensor string through the ~1-cm diameter stainless steel pipe attached to the end of each of the two brackets and tightening a nut at the base of the sensor string against the bottom bracket pipe so that the sensor string is put under tension, similar to Lister-type probe systems. For this deployment approach, no data cable is attached to the top of the probe. Instead, the probe collects data continuously and autonomously while the core barrel is deployed. All temperature data can be transferred via Bluetooth/radio transmission once the probe head is above the water line. Additionally, with this approach, the probe can be removed and replaced with a spare probe in under a minute, as it requires only the removal of a single nut at the base of the probe. The probe therefore differs from a traditional Ewing probe in three ways: (1) the probe can be removed, adjusted, or replaced and data downloaded rapidly (~1 min) with only a single data logger requiring removal or downloading and (2) a greater number of thermistors and thermistor spacing options exist in the probe lance that result is less sediment disturbance around the core barrel compared to Ewing probe deployments.

2.3. Temperature Calibration and Field Tests

Probe calibration tests were performed both in the lab and in the field. For thermocouple resolution and stability tests, we submerged the thermocouple strings in a series of different temperature baths. We recorded both the absolute temperature using high-resolution (0.001°C) NIST-traceable thermistors and the associated millivolt reading from the 18-bit digitizer attached to the thermocouples. The digitizers provide a temperature precision of 0.0007°C, and the thermocouples show a near linear temperature-voltage response for values of 0–40°C. To estimate resolution, we submerged the instrument in a constant temperature bath for

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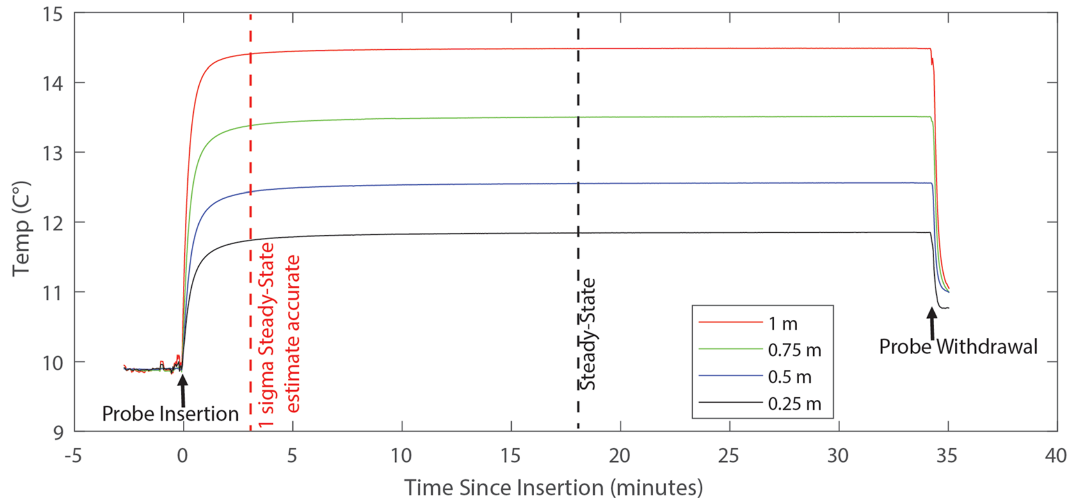

Figure 2. Probe response following insertion into the lake floor at Fincastle Lake, Texas. The probe lance used here consisted of four thermocouples spaced 25 cm apart, on a 1.25-m-long probe filled with high-conductivity epoxy. The deepest thermocouple (solid red line) penetrated ~1 m below the lake floor and the shallowest penetrated ~0.25 m below the lake floor. Steady-state values (to within thermocouple precision of 0.0025°C) were achieved rapidly (~18 min). Using the reduction algorithm of Villinger and Davis (1987), we calculate steady-state temperature to within 1 sigma uncertainty at each thermocouple depth using the first 3 min of data after insertion into the lake bottom (all raw data are in the supporting information).

~10 min and calculated the standard deviation of recorded temperatures during this time interval. The standard deviation averages 0.0025°C. Later, during field tests, we rechecked probe calibrations in the field with ice bath tests.

2.4. HyLO Stand-Alone Deployment Field Tests

We conducted two HyLO stand-alone deployment field tests: the first in an onshore abandoned oil well used as a preliminary pressure test and the second in a shallow lake to test thermocouple equilibrium response time. For both deployments, we attached the combined data/strength cable to the top of the probe head, providing a real-time data feed to the surface. For the deployment into the abandoned oil well, the 1-m-long instrument reached a maximum depth of ~200 mbsf before it encountered a thick layer of paraffin that prohibited any further penetration. Significant force (~250 N) was needed to free the probe from the paraffin, and during this time, the probe continued collecting data without incident.

For the second stand-alone field test, we deployed the instrument into a lake floor from a dock and a small (5 m long) boat in a maximum water depth of ~6 m. For this deployment, we used an ~1.25-m-long instrument with four evenly spaced thermocouples, weighted with an additional 7 kg to help probe penetration into the soft (silty) sediment. For deployment and recovery, the instrument was again attached to a combined data/strength cable that provided a real-time feed of temperature and probe tilt. During this deployment, we inserted the probe multiple times at different locations from both a dock and a boat, monitoring probe tilt angle in the process to guard against probe bending during insertion or pullout.

We used the first lake deployment to test the thermal response time of the probe for different thermally conductive materials injected into the thermistor string. These initial tests were conducted from a dock in approximately 1-m water depth at Fincastle Lake, Texas, in the winter of 2019. The probe was weighted with ~7 kg at the probe head and consisted of a 1.25-m lance with thermocouples spaced 25 cm apart. Clear water enabled us to ensure the probe experienced full 1-m vertical penetration during the test. We left the probe in the lake floor for ~35 min and monitored results in real time with a data cable, with temperature readings acquired at each thermocouple every 2 s. Results show that probe thermocouples reached steady-state values to within thermocouple resolution (0.0025°C) within ~18 min (Figure 2). Using the steady-state reduction algorithm of Villinger and Davis (1987) where the first 2 min of recorded data are ignored due to uncertainties in origin time and nonideal heat flow conditions, we were able to calculate steady-state temperature to

1-sigma uncertainty using data collected during the third minute of recording after insertion. Repeat measurements on the lake both from the dock and from small watercraft further verified these results, indicating that 3- to 5-min insertion times combined with the Villinger and Davis (1987) reduction algorithm approach provide robust subsurface temperature estimates using this probe.

2.5. Outrigger Deployment Field Test

To test the ability of the probe to collect thermal gradient and heat flow data in deeper water (>1,000 mbsl) environments, we deployed the instrument as an outrigger on a gravity corer in the Caribbean Sea at a site of known high heat flow. Deployment occurred ~25 km southeast of the island of Montserrat in a water depth of 1,166 mbsl, from the German research vessel *Meteor* on 11 May 2019. For the field tests, we secured a 2-m-long HyLO probe, containing eight thermocouples to an ~1-t, 3-m-long gravity corer (Figure 1h). We secured the ~2-m probe to the bottom 2 m of the gravity corer to increase the chance of full probe penetration, reducing the influence of bottom water temperature variability on subsurface temperature, and to test whether the probe would survive potential burial and recovery from the seafloor. The initial test site at 16.5087°N, 61.9757°W is an area of known high heat flow located within 50 m of Site GeoB23702, where drilling and borehole logging were conducted with the seafloor drill rig MARUM-MeBo70 (Freudenthal & Wefer, 2013). Downhole temperature logging in the upper 9 m at this drill site using a single thermistor attached to the acoustic logging tool reveals a temperature gradient of 213 ± 130°C/km (Figure 3). Thermal gradient uncertainty is estimated using the MeBo data by conducting a Monte Carlo approach that randomly samples temperature-depth measurement points to estimate the thermal gradient. The scatter in the temperature data from the MeBo logging and associated high uncertainty is likely due to temperature measurements made during acoustic logging immediately following drilling. The MeBo70 thermal gradient at this site represents a lower bound because during drilling we cooled the borehole by flushing seawater from the seafloor (Riedel et al., 2018). The MeBo thermal gradient results are consistent with the high thermal gradients of approximately ~100°C/km measured ~5 km southeast at Integrated Ocean Drilling Program (IODP) site U1395 (Manga et al., 2012).

We conducted the outrigger deployment test by lowering the gravity corer with the outrigged HyLO tool attached using the crane on the R/V Meteor starboard waist deck. Following initial temperature calibration of the probe both on the ship and in the water column above the seafloor, we dropped the probe and gravity corer at a rate of 1 m/s until impact with the seafloor. Upon impact, we deployed additional slack line from the crane, and the probe and gravity corer were left in the seafloor for ~6 min, while the *Meteor* held station. During gravity corer pullout, we observed an increase in tension consistent with significant probe penetration into the seafloor, and recovery of the gravity corer at the surface showed clear evidence of full probe penetration, as the gravity corer had mud caked on the core barrel to the weight stand. Additionally, we obtained a nearly full 3-m-long gravity core at the site. The HyLO probe head was therefore buried 1 m below the seafloor during seafloor insertion. The experiment demonstrated that the probe head can withstand at least a meter of burial and extraction through hemipelagic sediment while resisting bending and maintaining full functionality.

Upon gravity corer recovery on deck, we first inspected the HyLo probe for mechanical damage. With the exception of a minor (~1 mm) amount of bending of the bottom outrigger coupling band strap that attaches the probe to the gravity corer, we observed no damage, with the probe and lance unscathed. After adding an additional band strap to the base of the coupling and quickly downloading the data, we redeployed immediately at additional gravity coring stations. Following the success of the first deployment, five additional deployments occurred during an ~5-hr period along an ~9-km transect. All but one of these deployments collected useable data. (No penetration occurred on the final deployment due to hard seafloor. However, the probe continued to function properly) The results from these five additional deployments will be highlighted in a developing manuscript that merges these data with IODP and MeBo drilling data to provide new insights into heat flow in the Lesser Antilles.

Results for the first outrigger test deployment show clear evidence of frictional heating of all eight thermocouples during probe insertion, followed by exponential temperature decay with time for the 6 min the probe was in the seafloor. The observations are consistent with analytic solutions for cylindrical cooling (e.g., Carslaw & Jaeger, 1959). For this first deployment, we calculated the thermal gradient using the method of Villinger and Davis (1987) of 260 ± 10°C/km (Figure 3), a value slightly higher than the MeBo results but

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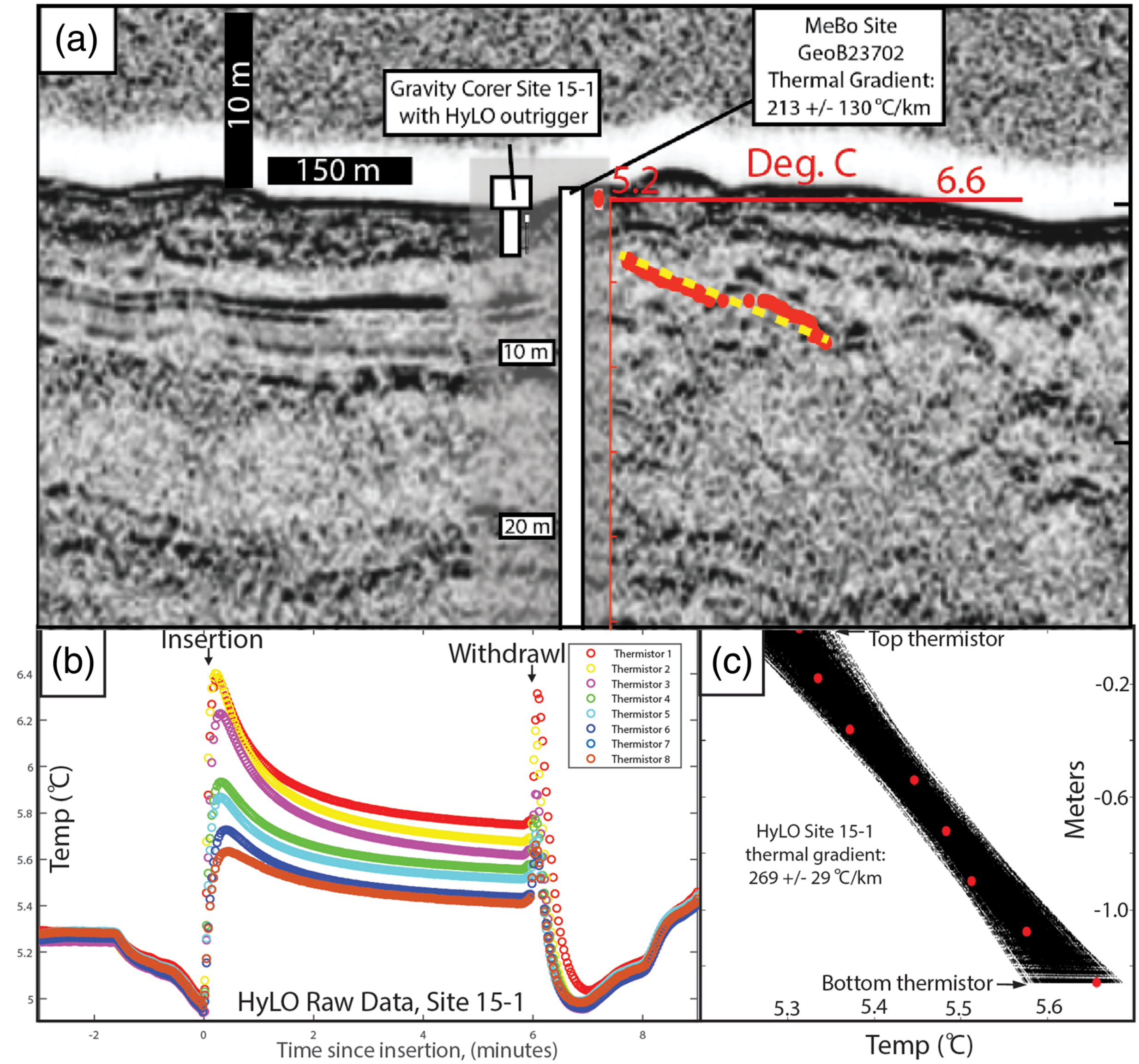

Figure 3. Comparison of thermal gradient measurements obtained from borehole temperature measurements with MeBo at depths of 5–9 mbsl versus the HyLO probe that measured thermal gradient in the upper 3 m of sediment. Parasound seismic data show a cross section of the subsurface and the location of HyLO gravity corer deployment within 50 m of MeBo drill Site GeoB23702 (a). MeBo temperature measurements on the acoustic borehole logging tool in Figure 3a (red) indicate a high thermal gradient of approximately 213°C/km (dashed yellow line) from 5 to 9 m below the seafloor. (b) There were eight temperature recordings on the ~2-m-long HyLO probe that was outrigged to a 3-m-long gravity corer at Site 15-1, with thermocouples in the probe spaced ~0.18 m apart. Frictional heating observed both during probe insertion and withdrawal, as well as temperature decay for approximately 6 min after insertion, indicates that all eight thermocouples penetrated the seafloor (b). Calculated steady-state temperature with depth (c) using the method of Villinger and Davis (1987) (red circles) that incorporate uncertainties for 1,000 Monte Carlo realizations (black lines) generate a thermal gradient of 269 ± 29°C/km, consistent with deeper MeBo measurements. HyLO raw data are in Data Set S2; MeBo raw data are in Data Set S3.

within the estimated uncertainty of the MeBo thermal gradient measurements. As previously noted, the MeBo thermal gradient underestimates true steady-state thermal gradient, since MeBo temperature measurements were made following drilling during which cold seawater fluids circulate in the borehole.

3. Conclusions and Future Development

Field tests of the prototype HyLO thermal gradient probe—both as a stand-alone unit and outrigged to a gravity corer—proved successful with the probe meeting or exceeding expectations. The HyLO thermal gradient probe provides a new, dynamic, time- and cost-efficient way to measure heat flow and geothermal gradients in shallow (<2,100 mbsl) marine environments. The stand-alone system is especially well suited for smaller, lower-cost vessels and was deployed successfully six times offshore Montserrat. The versatility of the tool as an outrigger and transportability of the instrument reduces shipping and personnel/operation costs, making it a potentially valuable "add-on" instrument that fills important gaps in marine heat and fluid flow studies with minimal additional investment. Additionally, there is the potential to deploy multiple stand-alone HyLO probes via remotely operated vehicle (ROV). Since the stand-alone HyLO probes are essentially autonomous (with their own power and data loggers), an ROV could deploy several at a time and would not lose time hovering or waiting in place for probe temperatures to approach thermal equilibrium. This approach could therefore reduce ROV downtime for thermal gradient data collection as well.

The real-time data provided by the system in water depths <700 mbsl also yield rapid insight into subsurface environments, allowing scientists to make better-informed on-site decisions. Improvements to the probe system continue and include machining a titanium housing for the probe head so that the system can be deployed at greater depths, a larger probe head for long-term (months-to-years) system deployment and monitoring, and a camera/light system for stand-alone HyLO deployments that provide real-time video feeds for pinpointing probe insertion points at key sites of interest. Camera tests have already been conducted successfully to depths of ~100 m at a test well and in a shallow lake, and the goal is to deploy a shallow (~100 m) long-term monitoring HyLO system within the next year in a deeper lake. Continued advancement of the HyLO probe should further facilitate a low-cost, rapid-response approach for addressing emerging problems in shallow marine geophysics.

Conflict of Interest

The authors declare no conflict of interest or competing interests with respect to this work.

Data Availability Statement

All raw heat flow data presented in this research are publicly available at the Interdisciplinary Earth Data Alliance (now the MGDS) website maintained by Lamont-Doherty Earth Observatory at http://www.iedadata.org/, where processed data will also be available on GeoMapApp. Additionally, we have included the raw data as supporting information associated with this manuscript.

Acknowledgments

The authors thank Captain Hammacher and crew of the R/V Meteor for their support during instrument sea trials. We especially thank Klaus Dehning, Christian Hilgenfeld, and Birgit Meyer-Schack for their expertise and professionalism with gravity coring outrigging and deployment. We thank Kira Homola and an anonymous reviewer for constructive reviews. Funding for the development and initial testing of the instrument was provided by the United States National Science Foundation, Division of Ocean Sciences Grant no. 1926729. Funding for ship time and MeBo testing/calibration was provided by Deutsche Forschungsgemeinschaft (The German Research Foundation).

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