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Hot water drilling in the firn layer of Greenland's percolation zone

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Abstract

The intermixed thermal and structural framework of cold firn, water-saturated firn and ice layers in Greenland's percolation zone can be challenging to penetrate with core drills. Here, we present our experiences using a hot water drill for research on the firn layer of the percolation zone. We built and deployed a lightweight and easily transportable system for drilling a transect of ∼15 cm diameter boreholes through the full firn column thickness, to depths exceeding 100 m. An instrumented drill stem provides a scientific measurement of the firn properties while drilling. The system was successful at gaining rapid access to the firn column with mixed wet and cold conditions, was easily transported to the site and across the glacier surface, and required a small field crew to operate. The boreholes are well suited for in situ investigations of firn processes in Greenland percolation zone.

1. Introduction and purpose

The 'percolation zone' of the Greenland ice sheet is broadly defined as the region of the accumulation zone where surface meltwater is generated regularly (Benson, 1962). Meltwater from the lower percolation zone may run off from its point of origin (Machguth and others, 2016), while at higher elevations the water may simply infiltrate into cold snow and firn to fill underlying pore space, forming ice when it refreezes (Braithwaite and others, 1994; Harper and others, 2012) or remaining liquid if it does not (e.g., Humphrey and others, 2012; Forster and others, 2014). As Greenland's climate warms, scientific research has increased emphasis on the meltwater processes and structural framework of the firn layer in the percolation zone.

Since ice core reconstruction of paleoclimate is challenging in places strongly influenced by melt, the subsurface of the percolation zone has received very little direct investigation. A relatively small handful of locations in the percolation zone have been the focus of field campaigns. Furthermore, studies have been restricted to shallow depths (typically <20 m) which can be accessed by snow pits or shallow hand-drilled cores. Substantial challenges to drilling arise in firn that is wet or fully water-saturated, but intermixed with cold conditions. Wet drilling equipment will freeze up when encountering cold firn, saturated firn is difficult to cut, heated cutters tend to spin on slushy ice layers, and further up the hole, the unheated drill arrangement is highly susceptible to freeze-in. Due to these issues, recent investigations targeting the Greenland Perennial Firn Aquifer have employed two drills: a mechanical drill for the dry firn and an electro-thermal drill for the saturated firn (e.g., Koenig and others, 2014). This overcomes issues related to mixed cold and wet, but at the cost of requiring two drills, and electro-thermal drills often have slow drilling speeds and make holes that can be far out of vertical.

Here, we present an alternative method for drilling boreholes in the firn layer of the percolation zone: the hot-water drill. Prior hot water drilling projects in Antarctica have penetrated the firn layer en route to deeper objectives (e.g., Engelhardt and others, 1990), but here we focus on holes solely targeting the firn layer. The firn layer in Greenland's percolation zone has highly variable thickness depending on location but is generally less than about 70 m (Leone and others, 2020). We designed a simple and effective system which is easily transportable in a small aircraft or helicopter, can be moved over the snow surface by hand, and can be operated by a small (2 or 3 persons) field team. Our system includes an instrumented drill stem which provides structural information about the firn during penetration. We describe the drill system and stem, and discuss our experiences deploying the equipment to install a transect of 100 m deep boreholes in the percolation zone of the Greenland ice sheet.

2. Hot water drill for firn

2.1. Overview

We focus here on a generalized overview of our drilling system since hot water drilling is not new and many different commercial options are available for purchasing the various components. To target boreholes in firn, our hot water system needed to be cable of drilling a minimum 15 cm diameter access hole through 100 m of −20 °C firn containing ice layers centimeters to meters thick, and potentially containing liquid water in firn aquifers. The project's science objectives required that we collect as much information as possible about the structural framework of the firn (i.e., ice layers and density variations) while drilling.

Our build criteria revolved around minimizing weight and maximizing mobility. The drill needed to be broken into small components (Table 1) easily loaded and unloaded by hand into a Twin Otter aircraft, occupying less than a single load. The components needed to be easy to move across the glacier surface by human power. Finally, the system needed to be operable by a small crew: in theory, our system is automated and the drill can create the hole by itself. In practice, we devoted one person to mind the power plant and hose payout, and one person to monitor the speed and behavior of the drill (Fig. 1).

2.2. Power plant

A small electric sump pump moves water from the reservoir to the intake for the pressure pump. A 6.7 kW gasoline engine powers the triplex direct drive plunger pump. The water then enters a pressure-washer style coil water heater, consuming 11–15 L h^{-1} of diesel fuel. From the heater, water enters the 120 m section of drill hose. A 3 kW gasoline generator provides the electric power for the drill system including the water heater, sump pump and drill tower motor. Through pump-motor speed and nozzle selection (section 2.5), we pressurize the system at 5500–8000 kPa.

The overall gasoline (MoGAS) to Arctic grade diesel (DFA) consumption ratio is about 1–4 throughout the process of generating water and drilling. Melting snow to generate drilling water requires ~55 L of DFA and 8–11 L of MoGAS, per 3800 L of water. One nuisance is that our approach requires two types of fuel for the field campaign. However, while we have successfully used a diesel generator and pump-engine in prior builds, this does not eliminate the need for MoGAS to power snow machines and a camp power generator. Furthermore, MoGAS engines are typically lighter in weight for a given horsepower.

2.3. Water

Drilling water is generated by melting snow in a 5500 L portable firefighting tank. Water is recirculated with a small sump pump through the heater to generate hot water used to melt snow that is shoveled into the tank. To avoid duplication of equipment, we opted to drill in series: first generating the water, then drilling the hole. Parallel water production/drilling is certainly possible, but will require a larger power plant including a second heater. Our melt system generates water at a rate of about 750 L h^{-1}. During drilling the system consumes about 30 L min^{-1} of water.

With 3000–3400 L required to drill to 100 m depth, generating the drilling water is the most time consuming aspect of drilling a borehole. Water is easily stored in the tank overnight. We found it unnecessary to bury the tank in the snow: over one night at −15 °C air temperature, a shell of ice formed across the surface and around the sides of the tank, but the internal body of water remained unfrozen. Having access to the water in the morning is actually advantageous for thawing frozen equipment such as the sump pump.

2.4. Drill tower

The drill tower provides a fully powered system to drive the hose both down and back up the hole. The drive system is designed for constant speed operation with a permanent magnet DC motor/controller driving an infinite variable speed mechanical drive. This allows slow speeds while lowering the hose, typically on the order of 60 m h^{-1}, and high-speed retrieval (~20 m min^{-1}) of the hose after the hole is completed. A load cell on the tower measures the weight of the hanging drill stem in the hole, providing feedback to the driller. The tower is mounted on a devoted sled for easy transport to different drilling locations while leaving the power plant fixed. The drill tower can be located up to 100 m away from the power plant by use of power extension cords and a drilling hose extension.

2.5. Drill hose

We use a Synflex thermoplastic 1.27 cm ID hose, which has a neutral density in the water. For drilling in firn, we use a single 120 m section of drill hose. Separate shorter sections provide the option of extending the distance from the power plant to the drill tower. Prior to drilling, the hose is placed on a tarp and coiled in a figure of eight pattern (i.e., no hose reel) to prevent it from melting into the snow and to minimize heat loss. The hose can also be transported coiled as a figure of eight, eliminating the weight and bulk of a hose reel. Ice tends to form in the hose at night, despite efforts to gravity drain and expel the water with compressed air. When pressurized with water after freezing overnight, the small amount of ice on the walls accumulates to clog exit coupling. An easy way to solve this problem is to thaw the hose by submerging it in the water tank.

2.6. Drill stem and nozzle

A heavy (~30 kg) drill stem acts as a gravitational plumb bob, ensuring vertical holes in any firn medium (firn, ice layer, aquifer, etc.) as long as the full load of the stem is supported by the drill tower. Our holes in ice have been checked by inclinometer and are vertical within the limits of our instrumentation. The nozzle diameter is critical for producing a straight high-pressure jet, rather than a spray. Nozzle selection also factors into the operating pressure of the hose. We use nozzles in the range of 2.5 mm diameter, with our pump system and 120 m hose length.

2.7. Sensing drill stem

One section of our drill stem includes a water-tight pod with electronic sensors and a data logger for measuring down-hole conditions as the drill hole is advanced. This is done to improve drilling efficiency, and to collect information about the structural framework of the firn column.

The pod is a 5 cm diameter stainless steel shell with a through-flowing central pressure pipe that can be inserted into the top of the stem or a small section of hose above the stem (Fig. 2). The air space in between the pressure pipe and the outer shell contains the instrumentation, consisting of lithium batteries, an analog pressure sensor connecting to the outside of the shell, two temperature sensors (I2C protocol) and a minimal data logger/controller based on a Texas Instruments MSP430 MCU and an ATMEL flash memory chip.

In most cases, we choose to mount section 200 cm above the drill tip to reduce disturbance of the pressure record from turbulence. The outer-wall temperature sensor measures the upwelling water in the borehole, but in an air-filled hole, the temperature is poorly constrained as a result of the very low heat capacity of air compared to the stainless steel shell. The temperature in the air tends to oscillate mainly depending on the shell touching the ice walls of the borehole. In water, the upwelling water temperature can be compared to simultaneous measurements of downgoing drill water, measured by the inner sensor. Thus, the transfer of heat between outgoing drill water at the nozzle and upwelling water in the hole can be determined (Humphrey and Echelmeyer, 1990). Heat loss is relatively minimal in the shallow firn holes, but in prior projects drilling to >800 m in the ice, we have found this information useful for optimizing drilling speeds and system pressure. Additional measurements from a water pressure transducer with its diaphragm open to the borehole yields a record

Table 1. Specifications of components in hot water drill system. Total weight is 550 kg

Item	Specification	Approximate Weight (kg)
Pressure pump	*General triplex pump, TSF2021*	20
Pump motor	*Honda gx630, 20 hp, (operated derated)*	44
Generator	*Honda 3 kW*	59
Drill motor	*¾ hp permanent magnetic DC motor, with Galco controller*	15
Transmission	*C-face ringcone mechanical transmission, right angle reduction and chain drive*	25
Heater	*Amazing Machinery pressure washer coil heater, 120 kWh*	105
Hose	*1.27 cm ID, thermoplastic, nonconductive, 120 m*	30
Drill stem	*Lead filled, stainless steel, diameter 5 cm, length 175 cm*	30
Water storage	*FireTak 5000 L (fire storage tank)*	25
Drill tower	*Three-wheel serpentine/capstan hose drive, with hose brake*	120
Miscellaneous	*Sump pumps, connection hoses, extension cords, tools*	75

of the height of water column above drill tip. All sensor data are logged at 1 s intervals downhole and retrieved after drilling. A time stamp is used to synchronize the downhole with the drilling depth in drilling logs.

3. Discussion and conclusions

3.1. Performance

We found that a hot water drill is an efficient and successful tool for gaining 100 m access holes in the firn layer of Greenland's percolation zone. The highly mixed structure of this region's firn, including firn with variable density, water-saturated firn and thick ice layers, is easily penetrated. Drill freeze-in due to contrasting wet and subfreezing conditions creates no barriers to drilling. The drill is easily deployed in situations where the surface working conditions are wet and slushy, but the subsurface firn is >10 °C below freezing. With our system that is optimized for lightweight and easy transport, the water supply for a 100 m borehole can be generated in a few hours, and the borehole can be drilled in well under 2 h.

Logging of the boreholes with a steerable borehole video camera revealed the characteristics of the boreholes. While the nominal 15 cm diameter of the hole was achieved, the specific diameter of the borehole changes with depth due to variable roughness of the wall. At shallow depths (i.e., <10 m), the firn layer has strongly contrasting density boundaries: ice layers, with a density of about 843 kg m^{-3} (Harper and others, 2012) are centimeter to tens of centimeters thick, and the firn density varies from 300 to 600 kg m^{-3}. The first ~3 m of the hole is wide and irregular, created as the drill stem was put in place and brought up to operating temperature. Below that, despite the variability of ice/firn mix, the hole becomes relatively symmetric and regular (Fig. 3a). Individual ice layers are easily identified in the borehole walls with a down-hole video camera. At ~25 m depth each of our boreholes (at all sites) gained an unusual pitted or 'cauliflower' texture (Fig. 3b), which existed for the next ~10–15 m. This texture is linked to hydraulic properties of specific thermal and density conditions, and is the subject of the detailed scientific analysis presented in another paper. By about 40 m depth, the borehole again becomes smooth and symmetrical, similar to hot water drilled holes in ice (Fig. 3c).

Logs from the instrumented drill stem reveal real-time interactions between drilling water and the surrounding firn as the drill

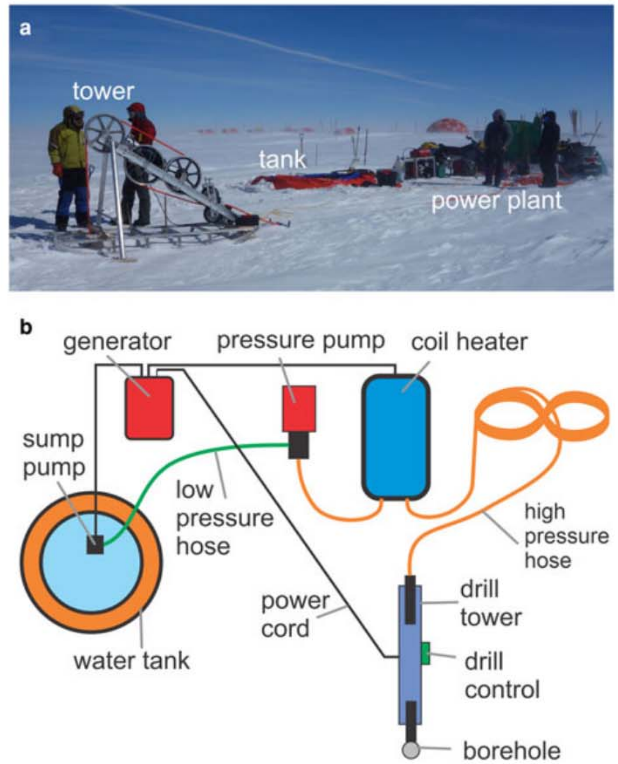

Fig. 1. Simple hot water drill for firn. (a) Photograph showing drill lower (left), water reservoir (center) and power plant (right); (b) schematic diagram showing components of the drill.

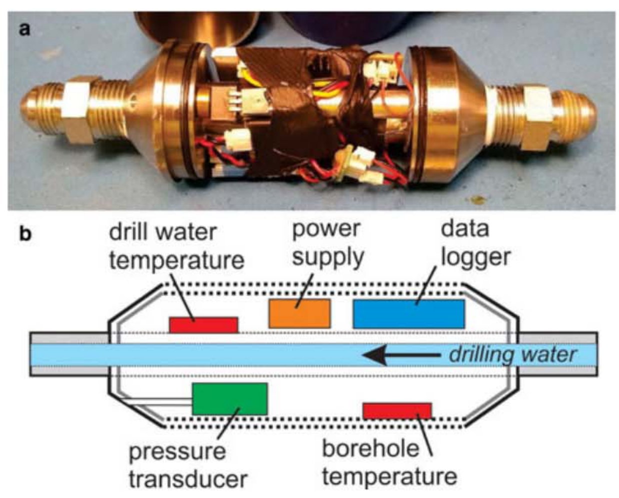

Fig. 2. Instrumented drill stem. The 5 cm diameter stainless steel pod has pressure couplings at both ends to allow mounting inline on the hose or stem. (a) Photograph showing stem with outer housing removed to show internals and sealing gaskets. (b) Generalized schematic diagram showing electronic components. Data logger includes clock and com port.

stem advanced through the firn column (Fig. 4). The drill-stem pressure and temperature records can thus be used to distinguish whether the drill stem was hanging in an air-filled or water-filled hole as it advanced. When the hole is air-filled, the pressure reads zero and relatively warm temperatures are erratic because the drill stem occasionally touches the rough firn walls of the hole. Once the drill stem becomes submerged, the temperature is fixed at the freezing point and the pressure steadily increases as the hydraulic head is added as drill advances deeper into a water column.

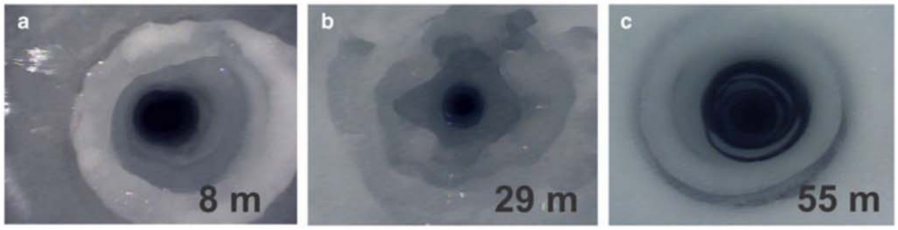

Fig. 3. Images of drill home from borehole video camera. Depths show in lower right of each image. Interbedded low-density firn and ice layers at shallow depth; irregular borehole geometry at intermediate depths; and, smooth borehole in deep high-density firn.

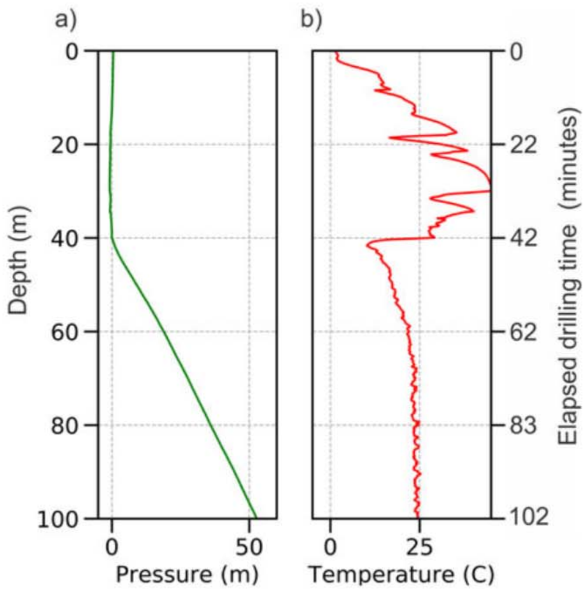

Fig. 4. Data collected by the sensing drill stem while drilling a 100 m borehole in firn. (a) water level in the borehole above the drill tip. The hole was air filled until reaching 40 m and then became water filled; (b) borehole temperature. The borehole was warm and variable while drilling in an air-filled hole, but cooled once the hole became water filled.

Practical considerations for operating in the percolation zone include nightly freeze-up and strong wind. We have found that pumping an antifreeze solution through the drill system, particularly the high-pressure pump and heater coils, to be effective. The antifreeze can be captured and reused many times such that only a few gallons are needed. Greenland's percolation zone is notoriously windy due to strong katabatic winds, so equipment for building wind breaks or snow walls is essential for combating spindrift.

3.2. Strengths and weaknesses

The obvious merits of a hot water system for percolation zone studies include the ability to gain rapid access through the entire firn layer, with a relatively small amount of equipment and crew. This permits efficient installation of borehole instrumentation. Unless there is a failure of the power plant, there is essentially no possibility of getting the drill stem frozen in the hole while penetrating the complex thermal/structural framework unique to the percolation zone. With a drilling time of well under 2 h, the number of holes drilled per day is mainly limited by time to melt snow. This typically takes about twice as long as drilling but could be reduced if needed by adding another coil heater. The system is easily moved from site-to-site by hand or with snow machines, and an experienced crew of four can set up the drill in about 1 h.

Using a hot water drill for firn investigations has palpable drawbacks. First is that no core is taken and therefore the hole yields no density profile. Larger ice layers can be mapped in the borehole walls with a down-hole camera, but firn density cannot be determined. The hole is thus best suited for installation of instrumentation or active experimentation (e.g. determining hydraulic characteristics of the firn column (Miller and others, 2017).

Unavoidable is that water and heat are added to firn column during drilling, thereby altering the structural framework of the firn column under investigation. However, the density alteration is perhaps not as severe as one might imagine. Drilling through firn at a rate of about 60 m h^{-1} with a water flux at the drill tip of about 30 L min^{-1}, a 100 m borehole takes about 100 min of drilling time. This adds 3 m^3 of liquid water averaged over the 100 m column, and up to ~1 m^3 of this water is used to partially fill the borehole itself, depending on the firn density. Ice layers will not absorb water, whereas firn will. The radius of water penetration around the borehole depends on the thermal and density structure of the firn. However, assuming an 80 m of firn column at a mean density of 0.6, and an average of 1 m radius of water penetration, 2 m^3 will fill only 2% of the available pore space.

Finally, hot water holes also create a thermal disturbance. However, with such a large heat sink in the surrounding firn column, the disturbance decays away completely over a period of weeks. The steady-state thermal profile is well estimated from thermal decay curves measured over just a few days (Humphrey and Echelmeyer, 1990). Furthermore, the thermal disturbance created by drilling actually presents an opportunity to constrain the firn density through modeling of thermal decay.

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References

Benson CS (1962) *Stratigraphic studies in the snow and firn of the Greenland ice sheet.*, Res. Rep. U. S. Army Corps of Eng., Hanover, N. H.

Braithwaite RJ, Laternser M and Pfeffer WT (1994) Variations of near-surface firn density in the lower accumulation area of the Greenland ice sheet, Pakitsoq, West Greenland. *Journal of Glaciology* **40**(136), 477–485.

Engelhardt H and 6 others (1990) Physical conditions at the base of a fast moving antarctic Ice stream. *Science* **248**(4951), 57–9.

Forster RR and 12 others (2014) Extensive liquid meltwater storage in firn within the Greenland ice sheet. *Nature Geoscience* **7**(2), 95–98.

Harper JT, Humphrey N, Pfeffer WT, Brown J and Fettweis X (2012) Greenland ice-sheet contribution to sea-level rise buffered by meltwater storage in firn. *Nature* **491**(7423), 240–3.

Humphrey N and Echelmeyer K (1990) Hot-Water drilling and bore-hole closure in cold ice. *Journal of Glaciology* **36**(124), 287–298.

Humphrey NF, Harper JT and Pfeffer WT (2012) Thermal tracking of meltwater retention in Greenland's accumulation area. *Journal of Geophysical Research* **117**(F1), F01010.

Koenig LS, Miège C, Forster RR and Brucker L (2014) Initial in situ measurements of perennial meltwater storage in the Greenland firn aquifer. *Geophysical Research Letters* **41**(1), 81–85.

Leone R, Harper J, Meierbachtol T and Humphrey N (2020) Advection impacts the firn structure of Greenland's percolation zone. *The Cryosphere* **14**, 2020(October), 1703–1712.

Machguth H and 9 others (2016) Greenland Meltwater storage in firn limited by near-surface ice formation. *Nature Climate Change* **6**(4), 390–393.

Miller OL and 9 others (2017) Hydraulic conductivity of a firn aquifer in southeast Greenland. *Frontiers in Earth Science* **5**, 1–13.

density profile. Larger ice layers can be mapped in the borehole

southeast Greenland. *Frontiers in Earth Science* 5, 1–15.