Basal Access and Sampling Feasibility Study

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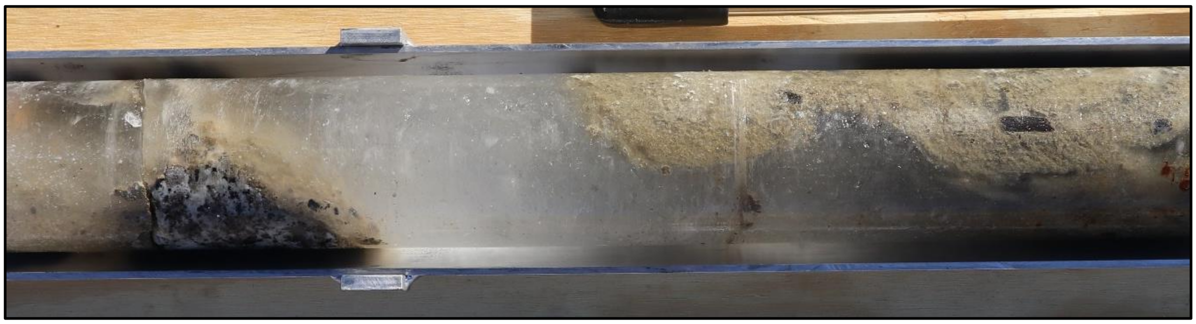

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Abstract

The U.S. Ice Drilling Program (IDP) Long Range Science Plans and community requests have shown increased interest in collecting subglacial and basal ice samples. In this paper, we explore and compare existing drill technology (tethered coring drills, rotary-pipe rigs, and hot water drills). We then discuss development needed for clean access and reducing logistics for each approach. Finally, new approaches including autonomous drills, lasers, and water jet cutting are evaluated.

Introduction

Scientific Drive

Subglacial sampling is a significant technical challenge from a drilling standpoint because of the wide range of potential basal environments. However, access to basal ice and subglacial samples (sediment or bedrock) provides critical data to better understand glacier history (Ackert et al., 1999), paleoenvironments, paleoclimate, biodiversity, and the evolutionary processes of living organisms under subglacial conditions (Tulaczyk et al., 2014). The purpose of this paper is to evaluate the technology needed to collect basal samples in a variety of subglacial environments. A variety of approaches are explored and evaluated for various basal environments. The technology is classified as existing, nearly existing or easily developed, or needing significant research and development.

Basal Environment

In order to accurately evaluate drill technologies and their capabilities in subglacial sampling, it is first important to define the environments that could be encountered through the glacier and at the ice-bed or ice-water interface (Table 1). Also considered in the evaluation is the transition from ice to the bed. Thick regions of "dirty ice" - ice mixed with silt, sand, or gravel - can complicate drilling and will limit the effectiveness of some techniques.

CLASSIFICATION	DESCRIPTION
SEALED BED	The overlying glacial ice is competent throughout, with no voids or cracks. At the bed interface, the ice is frozen to the rock through the transition. During drilling, no paths for loss of drill fluid exist.
DRY, NOT SEALED BED	The ice is frozen but voids/crevasses at the interface exist so drill fluid cannot be contained.
WET BED	Liquid water is present. This can be in the form of mud, drainage streams, or a subglacial lake at the ice-bed interface or as groundwater in the porous bedrock formations.

Table 1: Classification of glacial and interface conditions.

Wet Bed Restrictions

A drill site with a wet bed adds complexity. When exploring Antarctica, wet environments require special protections under the Antarctic Treaty (Siegert, 2018). Wet beds restrict the technology that can be used to collect basal samples because consideration needs to be made to prevent environmental contamination (for example, drilling fluid permeating the glacier, mixing with lake waters and/or leaking outward at the ice-bed interface). The Committee on the Principles of Environmental and Scientific Stewardship for the Exploration and Study of Subglacial Environments and the Scientific Committee on Antarctic Research (SCAR) Action Group outline specific recommendations for drilling into subglacial aquatic environments (SAE) (Doran, 2011). For this paper, it is assumed that any drilling program expected to encounter wet bed conditions must meet the SAE recommendations. When the bed is frozen, but voids exist, special consideration is needed to ensure future melt could not cause contamination to downstream sites. The SAE recommendations from section 4 of Doran (2011) are:

> *4. Drilling and SAE-entry*
>
> *4.1 Unless there is site-specific evidence to the contrary, drilling to the base of Antarctic ice sheets should assume that the basal ice is underlain by liquid water, and that this water forms part of a subglacial drainage network requiring a high level of environmental protection. In general, downstream sites, particularly those closest to the sea, can be viewed to have lower environmental risk than upstream sites.*
>
> *4.2 Exploration protocols should also assume that the subglacial aquatic environments contain living organisms, and precautions should be adopted to prevent any permanent alteration of the biology (including introduction of alien species) or habitat properties of these environments.*
>
> *4.3 Drilling fluids and equipment that will enter the subglacial aquatic environment should be cleaned to the extent practicable, and records should be maintained of sterility tests (e.g., bacterial counts by fluorescence microscopy at the drilling site). As a provisional guideline for general cleanliness, these objects should not contain more microbes than are present in an equivalent volume of the ice that is being drilled through to reach the subglacial environment. This standard should be re-evaluated when new data on subglacial aquatic microbial populations become available.*
>
> *4.4 The concentrations of chemical contaminants introduced by drill fluids and sampling equipment should be documented, and clean drilling technologies (e.g., hot-water) should be used to the full extent practicable.*
>
> *4.5 The total amount of any contaminant added to these aquatic environments should not be expected to change the measurable chemical properties of the environment.*
>
> *4.6 Water pressures and partial pressures of gases in lakes should be estimated prior to drilling in order to avoid downflow contamination or destabilization of gas hydrates respectively. Preparatory steps should also be taken for potential blow-out situations.*

Following these recommendations means that drilling efforts cannot include any of the chemicals currently used for drilling fluids when subglacial water may be present. Similarly, hot water drills (HWD) must include filtering and cleaning protocols to meet contamination requirements above.

Another critical consideration when drilling into a wet bed is the hydrostatic pressure of the water at the interface. When the borehole penetrates the water interface, hydrostatic pressure will either cause water to flow into the borehole, or drill fluid to flow into the SAE. Water flowing into the borehole could reach cooler temperatures further up and freeze or risk hydro fracturing the borehole when the pressure rises. If the drilling fluid flows out of the borehole, risk of washing away samples increases.

Also, maintaining an adequate fluid column for circulation is essential for some modes of drilling. Overcoming this technical challenge is critical for wet bed sampling. The hydrostatic pressure is difficult to predict so the drills must be tolerant of variable conditions.

Drilling Techniques

This paper will explore three drilling techniques that are proven for polar drilling (Table 2). Drills have varying capabilities, weights and drill penetration rates (Figures 1 and 2; Table 2). We will discuss how they can be adapted to collect basal samples or access subglacial environments.

- **Tethered Coring Drills** – Tethered drills have become the standard architecture for ice-only coring projects. The systems always include an electromechanical cable, winch, and drill sonde. The sonde is lowered on the end of the cable to collect discrete core samples. The winch pulls the sonde to the surface between each coring operation to collect the core from within the sonde.

  These drills are designed specifically to collect high quality ice cores. Advancements over decades have made them small and easily packaged for deep field deployments. They are inherently slow and are limited in power by the cable and feed pressure by the sonde weight. They require drilling fluid for deep holes, contributing to their overall logistical burden.

- **Rotary-Pipe Rigs** – These rigs generate the feed pressure and rotation needed for coring at the surface, generally leveraging hydraulic pumps, motors, and rams. The energy is transferred to the cutting head via a rigid string of drill rods. The drill string is also used as a conduit to supply drilling fluid to the cutting head, to clear chips and cool the bit.

  These rigs are designed for mineral exploration, making them capable of collecting rock samples. They are powerful, heavy, and can quickly create access holes through overlying glaciers. They also require drilling fluid.

- **Hot Water Drills** – Water is heated on the surface and pumped through tubing to a nozzle at the bottom of the borehole, forming the borehole by melting the ice ahead. Water is usually recirculated through the borehole but other options are possible as well. Drilling can be continuous and all equipment but the hose and nozzle are on the surface.

  Existing systems have been used to access subglacial lakes in a clean manner per the recommendations above. The size of the systems varies greatly, but the most recent versions have been assembled into the lightest packages. They drill quickly, however, the borehole will refreeze without reaming. These drills do not generally collect cores, so subglacial sampling must be completed with different tools.

TECHNIQUE	SYSTEM NAME	GROUP	CORE DIAMETER [MM]	HOLE DIAMETER [MM]	MAXIMUM DEPTH [M]	TIME TO MAX DEPTH [DAYS]	TOTAL WEIGHT* [KG]	SOURCE
TETHERED CORING DRILLS	Stampfli Drill	U.S. IDP	57	72	100	4	222	
	Eclipse	U.S. IDP	81	113	200	15	1088	
	Foro400	U.S. IDP	98	126	400	22	1178	
	Foro1650	U.S. IDP	98	129.6	1750	98	82715	
	Foro3000*	U.S. IDP	98	129.6	2800	165	82962	*(Johnson, 2017)*
ROTARY-PIPE DRILLS	Winkie Drill	U.S. IDP	34	48	120	2	3462	
	ASIG	U.S. IDP	39	62.5	700	2	19000	

	RAID Antarctica	RAID	38.4	55.6	3300	3	115392	*(Goodge, 2016) (personal com. AJ Vecchiarelli)*
HOT WATER DRILLS	SLLID	U.S. IDP	-	250	6	1	200	
	IDP Small HWD	U.S. IDP	-	100	30	1	1500	
	BEAMISH	BAS	-	300	2200	4	33679	*(Anker, 2021)*
	EHWD	IceCube	-	600	2500	4	566108	*(Benson, 2014)*
CLEAN HOT WATER DRILLS	WISSARD	UNL	-	600	1000	3	230000	*(Rack, 2016)*
	SLCEC CHWD**	BAS	-	300	2700	6	88400	*(Makinson, 2021)*

*Table 2. Ice drilling projects have historically used one of the above four techniques. This table captures some of the defining parameters for field projects. The only systems currently capable of drilling into a bed following the cleanliness guidelines are the hot water drills. *Weight includes the drill, fluid, and fuel for a single hole; does not include contingency fuel or drilling fluid **Predicted values, these systems have not been used at the time this paper was written.*

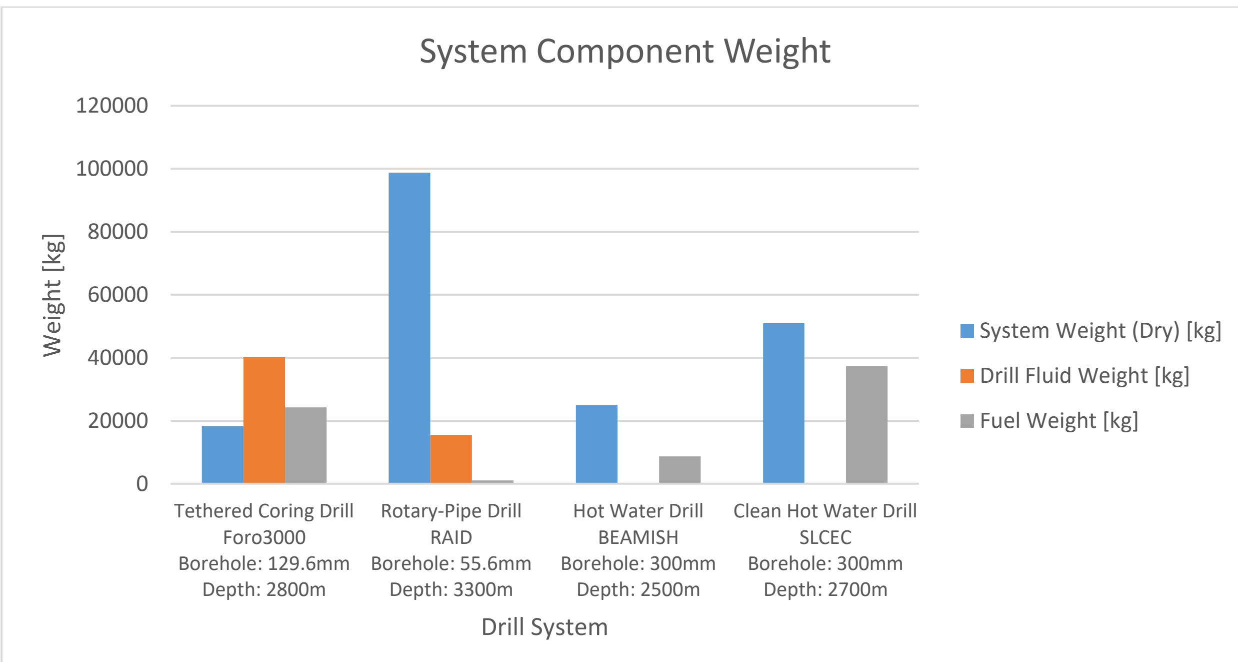

Figure 1. Drill systems with component weights. The fuel and drilling fluid is an estimate for a single borehole to maximum depth, without contingency. Fuel does not include setup or transportation.

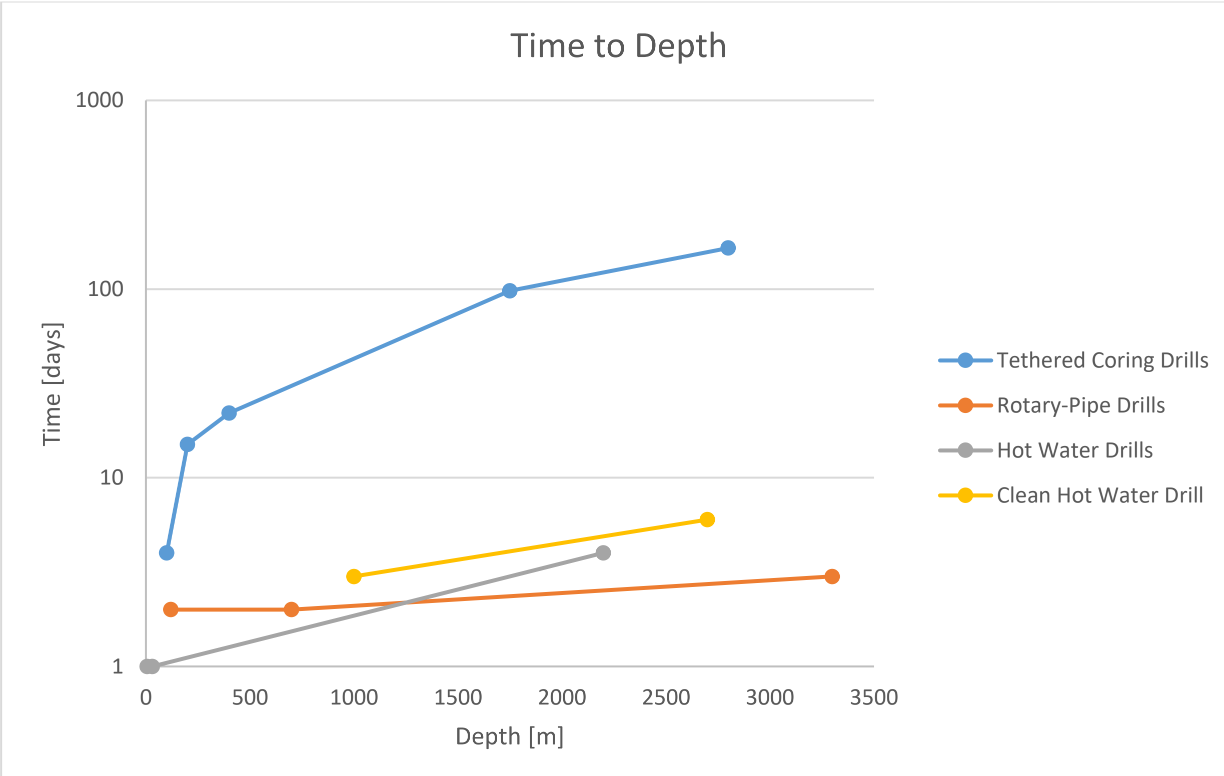

Figure 2. Note logarithmic scale. Tethered systems require long or multiple field seasons to reach depths achievable in days with either rotary-pipe or hot water drills. This is the result of collecting ice core samples – neither HWDs nor rotary-pipe drills collect continuous core samples when achieving maximum penetration rates.

Each technique has its own specific advantages and shortcomings. Individual project requirements will likely drive which technique is leveraged to reach the bed for basal sampling.

Tethered Sampling

Description

The defining feature of a tethered drill is the piece-wise drilling technique; collecting one high quality, 1m to 3m core at a time and bringing it to the surface. The drill sonde can take many forms including non-rotary, thermal drills, rotary drills, and rotary percussive drills. The following sections will evaluate the most effective options for tethered subglacial sampling, inherent limitations, and recommended technology developments. Tethered drills are reliable, and the hardware is a logistically light option for accessing the subglacial environment but will require further technology development to adapt this technology for robust and adaptable subglacial bedrock sampling.

The sonde of a tethered rotary ice drill is typically comprised of four main subsystems: i) Anti-Torque; ii) Motor Section; iii) Core Barrel and Chip Conveyor; and iv) Cutter head. The anti-torque (AT) section reacts the rotational torque from drilling and contains the drill cable connection, rotational borehole anchors, and a slip ring to protect the electromechanical cable. The motor section creates the rotational motion for drilling and houses the drill motor, gear reduction, and any ancillary drill electronics such as temperature, pressure, and orientation sensors. The core barrel and chip conveyor transfer rotational motion from the motor to the cutter head, hold the collected core sample, and transport chips away from the drill head using either an auger or localized fluid circulation. At the bottom of the drill, the cutter head cores ice using sharpened cutters and breaks the core sample for retrieval using core dogs.

All of these subsystems can be tailored to core in both wet and dry borehole conditions, making this technology adaptable for different depths and drilling environments.

History

A wide array of tethered rotary coring drills has been developed and used successfully to core to bedrock since a re-conditioned rock electro-drill was adapted to drill ice in 1964 by the Cold Regions Research and Engineering Laboratory (CCREL) (Wang, 2015). Attempts at using this technology to collect subglacial material have had limited success, however, only retrieving samples on four separate instances over almost an 80-year history (Talalay, 2013). Currently under development in China, the Ice and Bedrock Electromechanical Drill (IBED) is the most current adaptation of an electromechanical drill for bedrock sampling and includes technology that addresses previously known issues.

Tethered rotary percussive drills employ the same four major subsystems described above as the rotary ice coring drills but have an optimized cutting method for drilling dry rock formations. Rotary percussive drills operate best in dry conditions and do not require drilling fluid. To fracture rock, rotary percussive drills combine rotary drilling with axial hammering. Axial impulses can be generated by a variety of methods depending on power and size constraints. Common methods include spring-cam, voice coil, and ultrasonic percussive hammer mechanisms (Timoney, 2020). Rotary percussive drills have successfully sampled rock formations on the surface of Mars and can be operated within strict power, size, and weight requirements (NASA, 2021).

Inherent Advantages

Despite limited previous success at subglacial bedrock sampling, tethered drills are still an appealing framework because of their ability to collect continuous large diameter, high quality core. By using an electromechanical cable instead of a surface driven pipe string, system power requirements and weight is reduced when collecting comparable core diameter. Replacing drill pipe with an electromechanical cable allows for an agile drill system that can be scaled easily for deep drilling while still being supported by small aircraft. In addition to reduced logistics, this technology provides the highest quality ice core when compared to surface driven pipe drilling rigs (Kuhl, 2021).

Inherent Disadvantages

Tethered drills are throttled by the restrictions of an electromechanical cable (Table 3). The cable sets the upper limit for electrical power delivery to the drill head and available mechanical pullback force to break the core. Also, tethered drills rely on gravity to generate feed pressure while coring. Compared to ice, subglacial sampling requires more drill power, pullback force, and feed pressure due to the increased mechanical strength of some bedrock. Depending on temperature and crystalline structure, ice tensile strength can range from 1.5 – 2mPa while the tensile strength of rock formations ranges from 10 – 100mPa (Schwander, 1988) (Perras, 2014).

Tethered drills designed to drill ice also currently lack the robustness necessary to sample the subglacial environment where a mixture of ice, till, and bedrock can be present. One of the key issues is the difference in drilling mechanism between bedrock and ice. When drilling ice, razor sharp hardened steel cutters are used to shear the ice into coarse chips that can be easily transported away from the drill head. In contrast, rock is typically drilled with abrasive diamond impregnated tooling and circulated drilling fluid that flushes cuttings and cools the drill bit. When traditional ice coring cutters are used to core abrasive bedrock or mixed media, carbide and steel cutters dull rapidly stalling drill penetration and generating excess heat. This excess heat is a major concern because it causes borehole melting and refreezing (Green, 2007). Variability in the chip transport dynamics between rock and ice cuttings also limits robustness. Ice chips lend themselves well to auger transport, as compared to clumping clay, till, and soft rock formations that can choke the drill head and auger flights (Timoney, 2020).

Future Development

To improve the feasibility of tethered subglacial sampling, a borehole anchor should be investigated. A borehole anchor would both counteract drilling torque (like a traditional tethered drill anti-torque) and provide axial anchoring for the drill sonde, preventing movement up and down the borehole. If this technology was implemented, higher feed and core break forces could be generated on a similar scale to a rotary surface driven rig allowing traditional abrasive rock coring bits to be implemented. Additionally, this anchor could serve a dual purpose and seal the bottom of the borehole, enabling localized fluid circulation for chip transport and bit cooling. Functionality for the anchor would include remote activation, evenly distributed anchoring pressure (to prevent borehole fracture), and ability to anchor in a variety of media. Taking these criteria into consideration, an inflatable packer similar to those used by RAID and ASIG to seal casing is an appealing option. This type of anchor is inserted down-hole (60-100m) and then inflated with compressed air from the surface using airlines(150-200psi) causing it to seal against the borehole wall and anchor in place with friction. A tethered borehole anchor would require a different inflation method because running inflation air lines to depth alongside a drill cable would be cumbersome and not feasible. A likely solution is to package a local inflation pump in the drill sonde. The pump could inflate the packer with either air or drilling fluid.

Due to the variety of environments possible during subglacial sampling, the following section of this paper will discuss the application of tethered drilling in four distinct borehole environments: dry hole sealed bed, dry hole wet bed, fluid-filled hole sealed bed, and fluid-filled hole wet bed.

Tethered Limitation	Solution	Required Development Effort
Power transfer down tether	• Increase conductor size	• Minimal
Pull-back/core break force	• Increase mechanical cable jacket strength • Non-axial core break scheme • Borehole anchor	• Minimal • Existing tech, needs to be adapted (i.e. BID, Shaw Backpack) • New application of existing technology, full development project
Feed Pressure	• Increase weight of sonde • Local sonde anchor	• Minimal • New application of existing technology, full development project

Drill rate limited by discrete sample runs	• Inherent to tethered system design	• N/A

Table 3. Tethered drill systems are inherently limited by the electromechanical cable. The above table summarizes the limitations with proposed solutions that pertain to all tethered systems

Dry hole, Sealed Bed

Regardless of drilling technique, dry holes are limited in depth to 200-500m due to borehole closure and core quality degradation (Schwander, 1988).

Rotary Percussive

In a dry hole frozen bed environment, tethered rotary percussive drills enable clean access while reducing downhole power requirements, torque, and feed pressure. Tethered rotary drill technology is in the advanced developmental stage and many design aspects can be leveraged, including core barrel with auger flights for chip transport, anti-torque design, and winches. However, tethered rotary percussive drills are not yet field proven for subglacial access. The leading example of a terrestrial tethered rotary percussive drill for subglacial access is the British Percussive Rapid Access Isotope Drill (P-RAID). Table 4 compares the estimated required power consumption and torque between conventional rotary vs. rotary percussive drilling in igneous and metamorphic rock formations (Timoney, 2020). Rotary percussive drilling fits within the resources-limited environment of tethered subglacial access making this a promising technology for future development.

Drill Parameter	Conventional Rotary	Rotary Percussive Drilling
Torque (Nm)	50	3.5-7
Motor Power Consumption (W)	3000-4000	15-100

Table 4: Comparison of drilling parameters between rotary and rotary percussive drills (Timoney, 2020)

Although rotary percussive drilling is an effective way to reduce power consumption and downhole forces, there are existing issues with heat generation and robustness of the percussive drilling mechanism in varied subglacial environments. Rotary percussive drills are able to operate without drilling fluid because the hammering impulse generates less heat compared to conventional rotary rock drills. Despite reduced heat generation, borehole melt and drill freeze-in are one of the biggest limitations of dry drilling (Green, 2007). To minimize this risk, drills such as P-RAID use temperature and electrical resistivity sensors paired with autonomous feed pressure controls to limit borehole melting (Timoney, 2020). In the event of melting, the P-RAID drill is able to retract the cutter head to prevent freeze-in and drill loss.

In addition to the disadvantage of borehole melting, rotary percussive drilling has limited robustness in rock formations and substrates that absorb percussive impulses such as ice, clay, and mixed media. In soft rock formations such as limestone or consolidated sand, auger choke is a common failure mode (Timoney, 2020). Testing of the Honeybee Robotics rotary percussive Auto Gopher drill on Mt. Hood, Oregon and at Lake Vida, Antarctica also confirmed ineffectiveness of rotary percussive drills at penetrating solid ice (Badescu, 2006). To manage drill/auger choke in varied substrates, advanced controls are needed to monitor drill power consumption, weight on bit, and penetration rate. Further development and testing will be needed to tune these parameters appropriately for subglacial sampling. In order for rotary percussive drills to be a robust option for subglacial bedrock sampling, further technology development is needed to decrease borehole melt and improve adaptability to substrate.

Due to the inherent difference in effective cutting techniques of ice vs. rock, technology needs to be developed that allows the drill to operate in either rotary mode for ice and mixed media or rotary percussive mode for bedrock sampling. The rotary percussive drill used on the NASA JPL Perseverance rover has drill technology capable of both drill modes, but further development and field testing is needed to make the drill adaptable to the wide range of possible substrates found in the subglacial environment (Moeller, 2021). To combat drill melt-in, development of technology that enables compressed air chip transport and bit cooling should be considered. This technology could be adapted from the Perseverance Rover which uses compressed air to flush chips during pure rotary drilling. Experience with the IDP Rapid Air Movement (RAM) Drill can be leveraged to calculate air loss into firn and required lift velocity.

Another development that would increase bedrock sampling effectiveness is an eccentric core break mechanism. This would allow a tethered system to break bedrock samples without relying on an electromechanical cable or borehole anchor. Multiple designs for eccentric core break mechanisms have been suggested, such as eccentric core catchers or core barrels, but further testing is needed to field prove these designs (Talalay, 2021).

To sample the subglacial environment of a dry hole, rotary percussive drilling is the most effective option because reduced downhole torque, feed pressure, and power required align within the constraints of cable suspended electromechanical drills. Further testing and development are required to understand how this type of drill will perform in mixed media including subglacial till and clay. The biggest limitations to this drill style are its formation-specific design, refreezing concerns, and inherent depth limitations in a dry hole (Table 5).

Tethered Limitation	Solution	Required Development Effort
Borehole Melt and Drill Freeze-in	• Resistivity and temperature sensor on sonde instrumentation • Autonomous feed pressure controls	• Minimal • New technology, full development project
Low robustness in ice, clay, and other impact absorbing media	• Separate rotary and rotary percussive operation modes • Compressed air chip transport	• New technology, full development project • Existing technology, needs to be adapted

Table 5. Summary of limitations of tethered drill systems and proposed solutions specific to dry hole, sealed bed environments.

Fluid-Filled Hole, Sealed Bed

The tethered rotary drilling platform is well suited for fluid-filled and sealed bed subglacial sampling. Having a fluid-filled hole is an inherent advantage for conventional drilling of mixed media and rock because the drilling fluid facilitates both bit cooling and chip transport. Modular rock drilling technology can be packaged into a tethered drill sonde for reliable sampling of subglacial mixed media. The IBED system follows this design concept and has been developed to accommodate both a traditional ice cutter head for basal access, and a small diameter rock drilling stinger to collect bedrock cores (Talalay, 2021). Leveraging the existing fluid column from ice coring, this drill uses local circulation to flush chips and collect them in a filtration module.

Filtration capacity limits the amount of subglacial sample a tethered drill platform can recover per run. Since tethered drills are not plumbed to the surface with drill pipe, all drilling fluid filtration must occur locally at the sonde. Taking into consideration borehole size constraints, fluid filtration and circulation must be compact. The PICO 5.2" Drill and the DISC Drill are two examples of tethered drills that successfully implemented compact down-hole local circulation (Giles, 1994). Even with an optimized filtration system, capacity is limited for a tethered platform when compared to a surface driven rig which typically employs a combination of shaker tables and melter tanks to process rock and ice chips. Without proper chip transport and filtration, there is high risk of a tethered drill becoming stuck. Downhole drilling fluid filtration is a significant limitation of the tethered platform for subglacial bedrock sampling.

The length of rock core sample is limited by the length of the "stinger", which varies from 0.3m to 2m on existing systems (Talalay, 2021) (Timoney, 2020). A stinger is a rock coring barrel assembly (smaller in diameter) that extends past the end of the ice coring head. The small diameter rock corer is critical to concentrate the available power and feed pressure produced by the drill sonde. For example, the IBED system produces a 135mm ice borehole diameter but only a 60mm rock borehole diameter (Talalay, 2021). With each rock core that is collected, the stinger needs to be extended further out the bottom of the sonde. The stinger length is limited by surface operation (tilting tower), drill string weight, and fluid circulation constraints.

It is worth noting that limited stinger length has large impacts on the ability of a tethered system to collect bedrock. To penetrate effectively to bedrock, standard ice coring heads are absolutely dependent on the subglacial interface transitioning directly from clean ice to rock. If mixed media is present, penetration with a standard coring head may stop well short of bedrock. If the stinger cannot be extended far enough to reach through the mixed media then it will be impossible to sample the bed below.

Solutions Needed

Future development of a tethered platform for fluid-filled holes with sealed bed access should focus on continued improvement of downhole chip filtration/circulation along with borehole anchoring techniques to facilitate bedrock core breaks and elevated drilling torques (Table 6). Future local circulation development can be informed by existing drill designs including the 5.2", DISC, and IBED drills. Circulation development should be focused on making systems robust and capable of handling mixed media and clay, which prove difficult to transport because of their propensity to clump and clog filters and fluid passageways. One potential solution to aid with transport of mixed media such as clay are chemical drilling fluid additives such as surfactants, encapsulators, flocculators, and thinners (Quintero, 2002).

Due to the increased power requirements associated with rock drilling, further testing needs to be conducted to evaluate if standard bladed Anti-Torques are strong enough anchors to react drilling torques. Future work should evaluate alternative anchors such as inflatable packers, which can both resist drilling torque and act as an axial anchor and circulation isolator.

Tethered Limitation	Solution	Required Development Effort

Filtration Capacity	• Develop and test effectiveness	• Minimal, single runs inherent to procedure
Downhole Power	• Optimize coring parameters • Optimize filtration design	• Existing technology, some specialized testing • Existing technology, some specialized testing
Stinger Length	• Light weight drill rods • Surface procedure for adding rods ahead of sonde	• Existing technology • New procedure, minor development
Anti-Torque holding strength	• Articulating AT blades • Borehole anchor	• New technology, full development program • New application of existing technology, full development project

Table 6. Summary of limitations of tethered drill systems and proposed solutions specific to fluid-filled hole, sealed bed environments.

Electromechanical drilling in a fluid-filled hole with a sealed bed is a promising method of subglacial bedrock drilling. Cooling, chip transport, and lubrication all provided by the drilling fluid are advantageous for subglacial sampling of rock and mixed media. The unique challenge of this drilling environment is the transport and filtration of chips downhole with local fluid circulation and the limited sample length possible with a modular rock drilling stinger.

Dry Hole, Wet Bed

There is not a single style of tethered drilling platform that can reliably collect basal samples from the entire range of potential media in a dry hole wet bed environment (Table 7). For evaluation of performance, it is easiest to divide the dry hole, wet bed scenarios into two media categories; unconsolidated sediment, sediment and bedrock. Tethered drills that excel in these different categories of media function differently at a fundamental level.

Unconsolidated clay and sand in wet environments are best sampled using either vibra-core or piston corer technology. These styles of drills rely on impact/vibration to penetrate a solid tube into soft sediment for collection. This type of sampling has successfully been used for both oceanographic research and subglacial sampling (Talalay, 2013). Since this technology has a proven history, little development would be required for implementation. This style of drill will not penetrate solid media and is not a viable option if mixed media exists. For this reason, this style of tethered drill should only be considered if the basal environment is known to be unconsolidated clay and sands (e.g., subglacial lake, sub-ice-shelf ocean basin, etc.).

For subglacial rock formations, tethered rotary drilling becomes the only solution for sampling. Due to the inherent issues with chip transport and drill freeze-in with a wet environment, there is high risk associated with this option and low chance of success. Forced air chip circulation could be considered as a solution, but there is no existing technology that uses this in a wet bed scenario, meaning development costs would be high. Rotary percussive drilling could be a promising alternative, but percussive drilling in wet environments is not proven and would need to undergo thorough testing and development before it could be implemented in a field setting. One of the biggest uncertainties of rotary percussive drilling in a wet environment is how much fluid immersion would dampen the hammering mechanism. If the impulse is dampened by fluid immersion, this style of drilling is ineffective. Sampling hard formations in a dry hole wet bed environment represents a substantial challenge with high risk of failure for a tethered platform.

Tethered Limitation	Solution	Required Development Effort
Poor chip transport and freeze in due to dry hole	• Forced air for chip circulation and cooling	• New technology, full development program
Fluid dampening of rotary percussive drills	• Test a submerged rotary percussive drill	• New technology, full development program

Table 7. Summary of the limitations of tethered drill systems and proposed solutions specific to dry hole, wet bed environments.

Fluid-Filled Hole, Wet Bed

Tethered sampling of a fluid-filled hole, wet bed environment is only possible if a clean drilling fluid is discovered. Currently, there is no proven technology capable of reliably sealing the interface. To create a reliable seal to prevent drilling fluid loss, standard options such as burn-in casing and packers require either fluid tight bedrock or borehole walls. Given the high uncertainty of the wet subglacial interface, neither of these conditions can be guaranteed, which limits their potential for future development. Aside from mechanical seals, passive options also exist and include freeze-in casing and bore hole "cement". These options are slower and can be difficult to verify proper seal. If the borehole cannot be sealed, the only other option is to drill with the one known clean drilling fluid, water. This adds significant complexity because the borehole must be kept above 0°C. In a polar environment, maintaining warm water requires energy intensive equipment, such as a hot water drill system. If ethanol could be considered "clean" and the glacier is non-isothermal, another option is to prevent freezing by using an ethanol/water mixture, however, ethanol may affect any organisms present in the wet bed. If the glacier is isothermal, the best tethered option to cleanly access the subglacial environment is an electro-thermal drill. This drill platform performs best in solid ice where consistent heat transfer from the heating element is possible. Drilling mixed media and dirty ice is not reliable because small rock particulates accumulate at the bottom of the borehole and can insulate the heating element, slowing drill rate. Rocks (12-25mm) can completely stop progress (Boeckmann, 2019). Traditional tethered rotary ice core drills should not be considered for access because warm ice cuttings frequently stick together and do not transport well, causing auger choke. Drilling a subglacial access hole in a fluid-filled, wet bed environment is possible with a tethered thermal drill only if a clean ice-bedrock transition without mixed media exists.

After creating an access borehole to the subglacial environment, success of bedrock drilling is dependent on maintaining a consistent unfrozen fluid column. If hot water access is used, additional reaming may be necessary to prevent freeze-back during basal sampling. The hot water reaming process is well known, with little required development (Greenler, 2014) (Talalay, 2019).

Overall, fluid-filled hole, wet-bed tethered drilling is limited to water as the only currently viable clean drilling fluid. Future work is needed to identify other geochemical and biologically "clean" drilling fluid options that have a low freezing point. Theoretically, it is possible to sample bedrock with a tethered drill and warm water drilling fluid, but is considered high risk, would require technology development, and necessitate heavy logistics for the accompanying hot water system; ultimately this currently is the most complicated and least feasible application of the tethered drilling platforms (Table 8).

Tethered Limitation	Solution	Required Development Effort
Treated water is the only known clean drilling fluid	• Identify and implement an alternative clean drilling fluid with low freezing point	• New technology, full development program
Thermal drills become less effective in mixed media. Cannot drill through rock.	• Debris vacuum	• Existing technology under development
Drilling fluid loss	• Burn-in casing • Freeze-in casing • Borehole cement	• Exists, application testing needed • Preliminary design exists • New application, extensive development needed

Table 8. Summary of the limitations of tethered drill systems and proposed solutions specific to fluid-filled hole, wet bed environments.

Rotary-Pipe Rigs

Description

Several surface-driven drilling systems have proven successful in accessing and sampling the subglacial environment (Table 2). These systems are generally either rotary-pipe drilling rigs similar to those used in the minerals exploration industry or hot water systems.

Rotary-pipe drills operate by advancing a segmented pipe drill string tipped with one of a variety of different types of drill bits via rotation provided by a drive mechanism that remains on the surface. A pressurized drilling fluid, usually liquid but sometimes compressed air, is used to convey cuttings from the bit face to the surface where they can be removed with filtration equipment.

History

The history of subglacial sampling via rotary pipe drill systems has been well summarized by Talalay et al. (2012). Progress in the field has been made since that time with the development of the Rapid Access Ice Drill (RAID) system and its successful testing at Minna Bluff, Antarctica to retrieve subglacial rock cores (Goodge, 2021). A smaller but similar system, the Agile Sub-Ice Geological (ASIG) Drill, composed of human-portable components for remote field sites, was also developed and used to retrieve subglacial cores at Pirrit Hills, Antarctica in 2016 (Kuhl, 2021).

Inherent Advantages

These types of drills can quickly create an access hole to depths of scientific interest, and then be used to core and retrieve ice and subglacial material, in a single field season. They are especially adapted for sampling significant lengths of rock or other consolidated formations (e.g., multiple meters) due to the large amount of feed/pullback force, torque, and fluid flow available.

Inherent Disadvantages

The major disadvantage of this type of drill is the large size/weight of the drill system (Table 2; Figure 1). The cores are also generally smaller than tethered systems; on the order of 40mm vs 100mm. Other disadvantages include the increased complexity of the drill rigs, risk to drill operators from hydraulically-powered equipment, increased number of personnel required, and the risk of hydrofracture of the surrounding ice from the pressurized drilling fluid. Currently, this style of drill can only be used in sites where the subglacial environment is frozen, although future development may allow “wet” subglacial environments to be accessed (see next). Samples recovered with rotary-pipe drills are exposed to the drilling fluid, and therefore may not be considered biologically clean unless the interior of the cores can be subsampled in a clean way.

Non-frozen Subglacial Environment

Accessing a non-frozen (i.e. “wet”) subglacial environment poses a serious challenge to conventional rotary-pipe drilling systems due to the drilling fluids involved. Loss of drilling fluid to the subglacial environment can halt drilling operations due to a lack of return fluid to the surface and can result in a stuck drill string if cuttings accumulate in the hole. In addition, environmental regulations in most operating regions do not allow access to the subglacial environment with biologically contaminated equipment/fluids. It is currently not feasible to operate rotary-pipe type drilling systems in a clean manner.

Future Development

Surface driven rotary-pipe rigs are in use and have proven to be successful. As with all polar region equipment, system weight is a consideration. Future development could focus on several items (Table 9), including reducing system and drilling fluid weight.

Subglacial access in a non-frozen condition presents a challenge in terms of drilling fluid circulation and environmental contamination. Rotary-pipe drilling rigs generally require drilling fluid to circulate between the surface and the drill bit. Fluid lost to the formation must be replaced to maintain flushing at the bit, and in deep boreholes, to prevent the hole from closing. Any lost fluid increases the logistical requirements of the project. Loss of return fluid can also cause cuttings from the bit to accumulate in the borehole and eventually impede drilling operations. Conventional drilling fluids are also environmental contaminants that will alter subglacial biological communities and geochemistry. Therefore, they are unlikely to be approved for use if substantial quantities will be released into the subglacial environment.

An environmentally “clean” drilling fluid may be possible, but the unique requirements of fluids suitable for ice drilling makes this difficult. A more promising method would be to quickly seal a casing to a competent subglacial formation with minimal drilling fluid release to the environment. The specifics of this process would depend on the site and are unlikely to be applicable to all subglacial formations (such as thick sediment deposits). The use of casing-advancer equipment and specialized cements/muds may make this possible, but significant experimentation and development is needed. A recent paper details one possible scheme that leverages a drillable plug in the end of the casing and inflatable packer (Talalay, 2021).

Subglacial sampling using a surface-driven rotary-pipe drill in a previously created hot-water-drill borehole (for clean access) does not likely represent a major technical challenge but has not yet been attempted. A casing would be lowered to the base of the HWD borehole and drilled into a competent formation to create a fluid-tight conduit to the surface. Conventional drilling fluid would replace the water inside the casing, and normal drilling could commence from there. A suitable formation to seal the casing to would be needed, or other cementing/sealing technologies would need to be explored. Environmental restrictions will likely limit the types of testing and drilling that can be attempted given the experimental nature of the drilling technology needed and the risk of accidental drilling fluid release.

In some circumstances, warm water (>0°C) can suffice as the drilling fluid. A system being developed by the University of Victoria in Wellington, New Zealand would use a hot water drill to create an access hole through an ice shelf, and then use a rotary pipe coring drill to sample the sea floor through the access hole (Alex Pyne, personal communication 2021). Warmed seawater will provide the drilling fluid in a lost-circulation mode (water and cuttings will be ejected to the sea and be replaced with sea water pumped from below the ice sheet). A similar concept is theoretically possible on a grounded ice sheet in a closed circulation loop, with return water and cuttings routed to the surface for filtration and reuse. Special attention will be needed to keep surface equipment from freezing, similar to what is done in existing HWDs. Over-reaming around the casing may be necessary to prevent freeze back around the casing.

Rotary-Pipe Limitations	Solution	Required Development Effort
System Weight	• Lighten components	• Known solutions • Engineering effort and development funds needed
Drilling fluid weight	• Foam Drilling • Air Drilling	• Extensive development/testing needed to adapt existing technology
Drilling fluid Contaminates Wet Bed	• Biologically Clean Drilling fluid • Seal Casing to Formation • HWD Access Hole, Seal Casing • Circulate Hot Water as Drilling fluid	• Extensive development and testing effort needed

Table 9. The above table summarizes the limitations and development effort needed to overcome these limitations for rotary pipe drills.

Hot Water Drills

Description

Hot water drill (HWD) systems have been used in the past to cleanly access the subglacial environment, allowing for samples to be retrieved without contamination from the drilling equipment/fluid (Tulaczyk, 2014; Priscu, 2021). HWDs utilize fuel-fired heaters to melt and heat ice/snow, which is then pumped through a hose/nozzle to create a borehole in ice. These systems vary greatly in size and complexity according to their depth capacity. The largest systems can relatively rapidly create an access hole to the subglacial environment even in the thickest ice sheets (Figure 2).

History

Various sizes of HWDs have been used for decades in polar regions. Biologically clean access and subglacial sampling via clean HWD (CHWD) was accomplished at Whillans Subglacial Lake, Antarctica with the WISSARD system in 2013 (Rack, 2013) and at subglacial Lake Mercer, Antarctica with a slightly modified WISSARD system in 2018 (Priscu, 2021). The British Antarctic Survey (BAS) developed a clean HWD system to access Antarctic subglacial lakes. The initial attempt to cleanly access subglacial Lake Ellsworth was unsuccessful due to equipment failures (Makinson, 2016). In 2019, BAS successfully drilled the deepest subglacial access hole so far (2154m) with a HWD in the Rutford Ice Stream. Biologically clean access was not required because the ice streams flushed directly to the adjacent ocean, however, if biological sampling is an element of the research project, this remains a critical element and the equipment can be used with existing filter and UV sanitation equipment from the Lake Ellsworth project for clean subglacial access (Anker, 2021).

Inherent Advantages

A major advantage of HWDs, besides speed, is the ability to drill in a biologically and geochemically clean manner with the use of filtration/sterilization equipment, making them especially applicable to sites with above-freezing subglacial environments. A variety of sampling tools ranging from cameras to sediment corers can be run into the access hole. Sampling of subglacial rock or other difficult formations can be accomplished with a surface-driven rotary-pipe drill (running in a casing drilled into the bedrock) or with other cable-deployed coring equipment (see previous sections).

Inherent Disadvantages

The main disadvantage of hot water drilling systems is the size, complexity, and energy-intensiveness of the drilling equipment (see Table 3). The size of the largest systems with clean-access equipment exceeds 450 Tonne, which would roughly double if a rotary-pipe drill was also included for bedrock sampling. Hot water boreholes also freeze back relatively rapidly and must be kept open via water circulation and/or hot water reaming as long as borehole access is required, increasing the system fuel requirements. The borehole diameter will vary with drilling parameters and ice temperature so any drilling technique that leverages the borehole for anti-torque would need to accommodate large variations.

Future Development

Hot-water drill access to and sampling of unfrozen subglacial environments has been demonstrated. However, application of the proven filtration/sterilization techniques in past CHWD projects to smaller projects with limited logistics presents a major challenge. Current filtration/sterilization equipment is so large it is only suitable for traverse-supported projects. Smaller/lighter/less-complex filtration equipment will be needed for aircraft-supported projects.

Subglacial sampling of true bedrock and rocky sediments in a HWD hole requires additional research and experimentation (Table 10). Current oceanographic sampling tools are not well suited to these formations. Existing seafloor piston corers, vibra-corers, etc. are best suited for soft sediments lacking coarse components. Tethered rock coring sondes designed for fluid-filled holes may hold some promise (see previous section) in a HWD hole, especially robotic-type seafloor drills currently in use, in coarse sediments and bedrock.

HWD Limitation	Solution	Required Development Effort
Oceanographic tools	• Adaptation to subglacial environment	• Minimal development effort for existing seafloor sampling equipment in soft sediments • Major development effort to sample rocky formations
Fuel weight/volume	• Microturbines • Minimize hole size required	• Moderate effort to incorporate new technology
Filtration Equipment weight/complexity	• Simplify as much as possible	• Significant research, design, and testing of new components

Table 10. The current limitations of hot water drills and necessary development to overcome these limitations is shown.

Other Systems

Various other techniques for drilling through ice and collecting subglacial samples are discussed below. The technology has limited or no previous use in glacial environments or would require substantial development effort. Advantages and limitations are discussed.

Robotic sea-floor drill

Remote controlled, robotic rotary-pipe sea-floor drills have become a proven technology for rapid sampling of the ocean floor up to 150m deep. Industry leaders of remote sea-floor drilling include:

- Williamson & Associates, Seattle, WA
- The Center for Marine Environmental Sciences at the University of Bremen, Germany

These drill systems are large (on the order of 10 Tonne, 2.5m x 2.5m x 6m) but include a fully automated rotary-pipe rig suspended from a cable (Freudenthal, 2013). However, smaller form factors of these drills do exist that can be mounted on submersible remotely operated vehicles. Recently, Williamson & Associates have developed the Remotely Operated Core Sampler (ROCS) which leverages a smaller design form for flexible and economic deep seafloor coring.

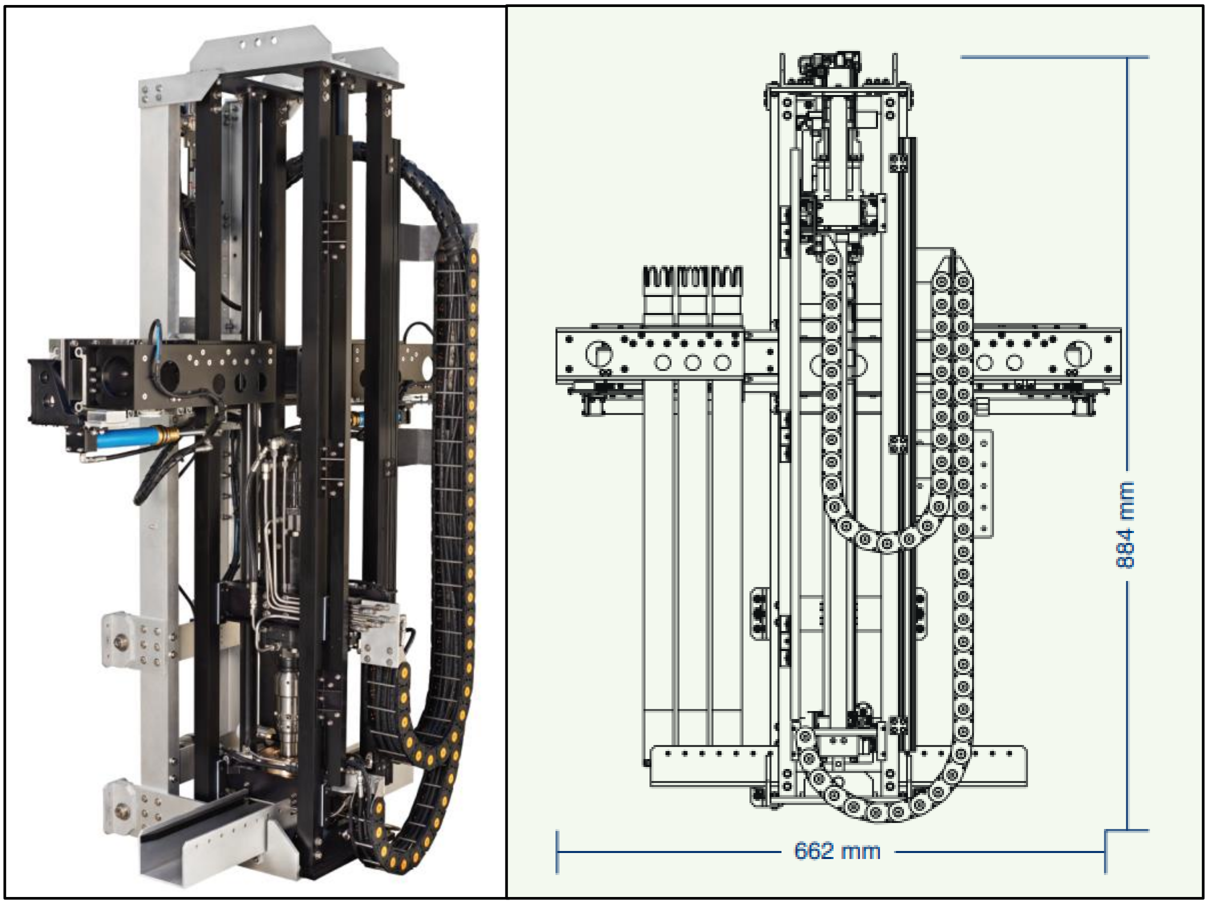

Figure 3. The Williamson & Associates ROCS is a remotely operated coring system designed for mounting to a ROV for subsea core sampling (Williamson, n.d.)

If adapted for basal sampling, this drill technology would be best suited for sampling below an ice shelf or subglacial lake. The advantage of this approach is that the coring rig does not require interaction with the borehole wall (Anti-torque, fluid circulation). Likely, the access hole would be drilled with a CHWD due to the clean requirements previously discussed. Hot Water Drills produce the largest boreholes of the techniques explored in this paper; however, a realistic borehole diameter limit is 1m. Repackaging these drills to fit in an ice borehole is a significant challenge.

The cost to adapt this drill technology for subglacial sampling would be high because of the high starting cost of the equipment. Any modifications to the complex automation processes would also require large time and financial investment. Clean subglacial sampling of lake or ocean beds would be difficult.

Lasers

Laser drilling of ice has been demonstrated by several research institutions and companies. Various penetrators and corers have been proposed, with a handful being tested with positive results (Talalay, 2021). Laser drilling in ice is similar to other thermal ice drilling methods, except that the laser energy is absorbed and transferred only a very short distance, limiting the extra melting and warming of the ice normally associated with thermal drilling.

Rock cutting via laser has also been demonstrated and is done commercially (laser engraving, etc.). Earth boring with laser energy has been proposed in the oil and gas industry. Initial laboratory testing has been done using various types and wavelengths of lasers with promising results (Xu, 2004). The potential advantage of laser drilling is the reduction in drill system size and weight. A laser boring machine would not require rotation or downforce, and the laser energy could be redirected to cut the core free from the formation, thus allowing the downhole and surface systems to be much lighter. Laser boring/coring may also allow for faster hole completion as the same downhole equipment could potentially be used to cut both ice and rock, reducing the amount of time needed to trip the drill string in and out for bit changes, etc.

A laser sonde could be deployed by an electromechanical cable or lightweight drill string with wireline core retrieval, depending upon the characteristics of the project. The same laser sonde could potentially drill in a coring or non-coring manner in various substrates without changing downhole equipment, depending upon the complexity of the beam focusing equipment.

Significant technical and physical challenges impede the immediate adoption of lasers for ice/rock drilling. Known issues include meltwater/cuttings/steam removal, reduced efficiency of the laser in a fluid filled borehole, efficient power delivery to the cutting head in deep drilling, laser optimization for various formations, packaging the laser system components into a useful form-factor for drilling, and cold-hardening the sensitive electronics necessary. Multiple unknown challenges are certain to arise during the development of any laser drilling system as well. Large scale development and funding would be needed, along with the involvement of specialized personnel and/or companies active in this area of research.

Abrasive Water Jet

A variety of manufacturing industries use abrasive water jets to process difficult materials without a heat-affected-zone. The process cuts by directing a high velocity stream of water, often containing an abrasive, toward the work piece. The process is well developed and is used for many applications including hard rock, such as granite counter tops.

Water jet coring is especially well suited for basal sampling for several reasons:

- *Media Flexibility* – Water jets have the ability to cut through any media encountered downhole. Unlike mechanical coring techniques that require specialized bits for ice, rock, and some type of compromise for mixed media, the water jet can cut through any media. Cutting rock is readily done in industry. Water jets for cutting ice have successfully been tested (Cold Regions Research and Engineering Laboratory, 1973). Frozen fine-grain soil samples have also successfully been cut with water jets (Lee, 2002).
- *Fluid Flexibility* – The high-pressure stream could be drilling fluid or water, depending on clean requirements or borehole temperature.
- *Configurable for Sampling or Fast-Access* – The nozzle could cut either a core sample or full borehole for fast access.

A CRREL report (The Cold Regions Research and Engineering Laboratory, 1973) explored configurations of jointed pipe drill rigs with water jet modifications for coring. They concluded that it would be feasible to implement such a system using mostly commercially available equipment, with only a few requirements for custom parts, including high pressure swivels and dual-wall drill rods. However, for the purposes of basal sampling, this does not provide advantages. There already exists rotary-pipe rigs that can collect basal samples.

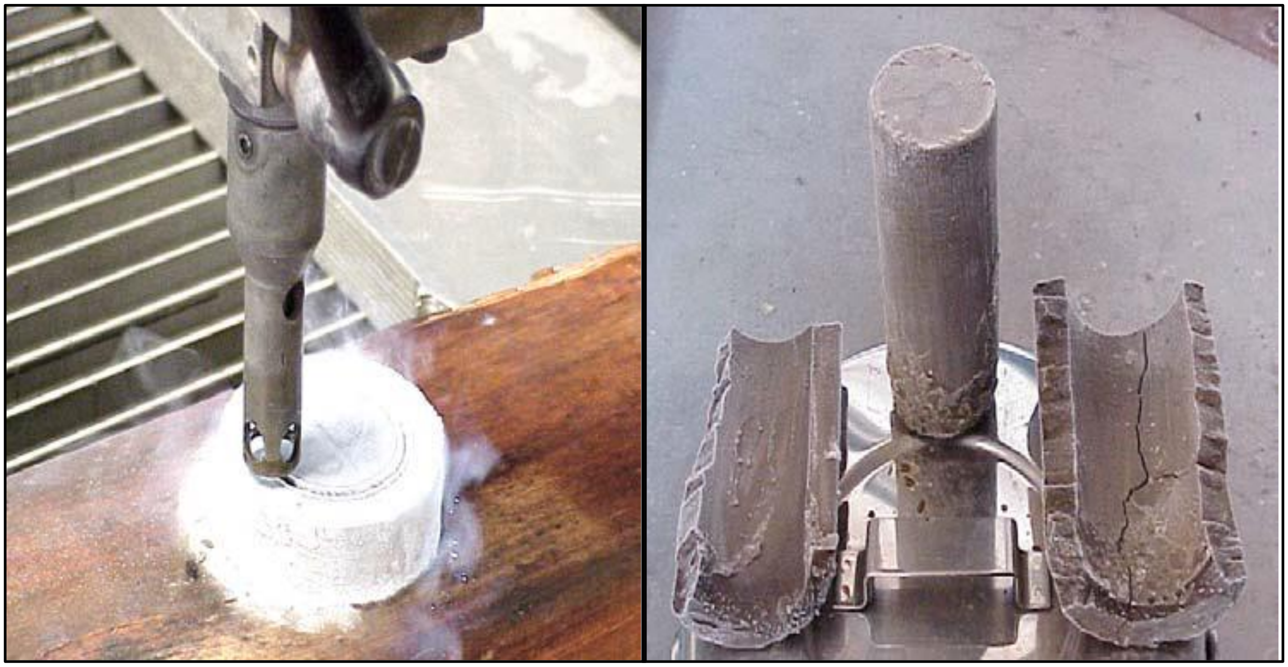

Figure 4. Water jets have been used to subsample frozen soil samples (Lee,2002)

The potential advancements from using water jets come when the approach is applied to a lightweight tethered system. This could be lowered into a HWD access hole. A water jet does not have high feed pressure requirements, resulting in a corer that can drill a full-diameter hole rather than advance a stinger. Without a stinger the drill is not limited in sample length.

If we focus on tethered systems, many challenges exist:

- *High Pressure Generation* – Packaging of hydraulic pumps and intensifiers into the borehole diameter is a challenge, though this has been explored in several previous studies and is deemed technologically possible (Kolle, 2008) (Cold Regions Research and Engineering Laboratory, 1973)
- *Power Requirement* – Experiments by Stoxreiter, (2018) reveal hydraulic power requirements to cut hard rock in the range of 20 kW or more. Transferring this much power downhole would require an increase in cable and conductor size. Alternatively, pressurized fluid could be sent downhole to an intensifier.
- *Filtration* – Chips, whether ice or rock, need to be evacuated from the borehole. This could be done continuously with full-borehole circulation, or in batches if a local fluid circulation loop is established.

Limited testing and data for a tethered application exist. A significant amount of research, development, and testing would need to be conducted to determine the feasibility of this approach. It is also a possibility that this technology could be added to assist in mechanical coring, such that feed pressure is no longer a limitation for basal rock sampling.

Conclusion

The drilling technique chosen to collect basal samples is a function of many factors:

- Clean access requirements
- Continuous ice core sampling
- Bed sample material
- Desired bed sample depth
- Core size
- Available field time

The requirements above will drive the drilling technique used. Advancements to each technique have been discussed in the body of this paper and include:

Tethered Drills	Borehole Anchors, Rotary Percussive Heads, Rock Coring Stinger and Filtration, Casing Advancers, Autonomous Corers
Rotary Pipe Rigs	Weight Reduction, Clean Fluids, Sealing Casing, CHWD Access, Warm Water Circulation
Hot Water Drills	Weight Reduction, Integration of Tethered Rock Corers, Remote Seabed Corers

Novel advancements to coring various media also show potential but would require significant investment in development. These include autonomous coring systems, lasers, and wet jet technology. There is no single solution to collecting basal samples that can be uniformly applied to all bed conditions and sampling requirements. However, there exists solutions that can be readily adapted. And in many cases, there are options to advance the technology for better sample collection and lighter logistics.

References

Ackert, R. P., Barclay, D. J., Borns, H. W., Calkin, P. E., Kurz, M. D., Fastook, J. L., & Steig, E. J. (1999). *Measurements of past ice sheet elevations in interior West Antarctica*. *Science*, *286*(5438), 276-280.

Anker, P. G., Makinson, K., Nicholls, K. W., & Smith, A. M. (2021). *The BEAMISH hot water drill system and its use on the Rutford Ice Stream, Antarctica*. *Annals of Glaciology*, 1-17.

Badescu, M., Sherrit, S., Olorunsola, A., Aldrich, J., Bao, X., Bar-Cohen, Y., ... & Song, T. (2006, March). *Ultrasonic/sonic gopher for subsurface ice and brine sampling: analysis and fabrication challenges and testing results*. In Smart Structures and Materials 2006: Industrial and Commercial Applications of Smart Structures Technologies (Vol. 6171, p. 617107). International Society for Optics and Photonics.

Benson, T., Cherwinka, J., Duvernois, M., Elcheikh, A., Feyzi, F., Greenler, L., ... & Paulos, R. (2014). IceCube enhanced hot water drill functional description. *Annals of Glaciology*, *55*(68), 105-114.

Boeckmann, G., De Vitry, A., Koehler, J. (2019). (rep.). *Juneau Icefield Research Program (JIRP) IDP Test Season End of Season Project Report*.

Boeckmann, G. and Moravec, E. (2020). (rep.). *Mt. Murphy Winkie Drill End Of Season Project Report*.

Cold Regions Research and Engineering Laboratory (US), & Shvaishtein, Z. I. (1973). *Cutting ice with a continuous high-pressure water jet*.

Doran, P. T., & Vincent, W. F. (2011). *Environmental protection and stewardship of subglacial aquatic environments*. Antarctic subglacial aquatic environments, 192, 149-57.

Freudenthal, T., & Wefer, G. (2013). *Drilling cores on the sea floor with the remote-controlled sea floor drilling rig MeBo*. Geoscientific Instrumentation, Methods and Data Systems, 2(2), 329-337.

Giles, D., Hancock, W., Kelley, J., Koci, B., Stanford, K., Zagordnov, V. (n.d.). (rep.). *GISP2 Deep Ice Core Drilling*.

Goodge, J. W., & Severinghaus, J. P. (2016). *Rapid Access Ice Drill: a new tool for exploration of the deep Antarctic ice sheets and subglacial geology*. Journal of Glaciology, 62(236), 1049-1064.

Goodge, J. W., Severinghaus, J. P., Johnson, J., Tosi, D., & Bay, R. (2021). *Deep ice drilling, bedrock coring and dust logging with the Rapid Access Ice Drill (RAID) at Minna Bluff, Antarctica*. Annals of Glaciology, 1-16.

Green, J., Koci, B., & Kyne, J. (2007). *Koci drill for drilling in ice, sand and rock: drill requirements, design, performance, difficulties*. Annals of Glaciology, 47, 105-108.

Greenler, L., Benson, T., Cherwinka, J., Elcheikh, A., Feyzi, F., Karle, A., & Paulos, R. (2014). *Modeling hole size, lifetime and fuel consumption in hot-water ice drilling*. Annals of Glaciology, 55(68), 115-123.
Kolle, J. J., Theimer, K., Theimer, T., Cox, R., & Scherschel, S. R. (2008, April). *Coiled tubing jet drilling*

with a downhole pressure intensifier. In SPE/ICoTA Coiled Tubing and Well Intervention Conference and Exhibition. OnePetro.

Johnson, J., Kippenhan, M., (2017) (rep.) *DISC Drill vs. Foro 3000 Drill Analysis*. 1-24.

Kuhl, T., Gibson, C., Johnson, J., Boeckmann, G., Moravec, E., & Slawny, K. (2021). *Agile sub-ice geological (ASIG) drill development and Pirrit Hills field project*. Annals of Glaciology, 62(84), 53-66.

Lee, M. Y., Fossum, A., Costin, L. S., & Bronowski, D. (2002). *Frozen soil material testing and constitutive modeling*. Sandia Report, SAND, 524, 8-65.

Makinson, K., Anker, P. G., Garcés, J., Goodger, D. J., Polfrey, S., Rix, J., ... & Zamora, R. (2021). Development of a clean hot water drill to access Subglacial Lake CECs, West Antarctica. *Annals of Glaciology*, 1-13.

Makinson, K., Pearce, D., Hodgson, D. A., Bentley, M. J., Smith, A. M., Tranter, M., ... & Siegert, M. J. (2016*). Clean subglacial access: prospects for future deep hot-water drilling*. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 374(2059), 20140304.

Moeller, R. C., Jandura, L., Rosette, K., Robinson, M., Samuels, J., Silverman, M., ... & Biesiadecki, J. (2021). *The Sampling and Caching Subsystem (SCS) for the scientific exploration of Jezero crater by the Mars 2020 Perseverance rover*. Space Science Reviews, 217(1), 1-43.

National Aeronautics and Space Administration. (2021, September 6). *NASA's Perseverance Rover Collects First Mars Rock Sample* [Press release]. Retrieved from https://www.nasa.gov/press-release/nasa-s-perseverance-rover-collects-first-mars-rock-sample

Perras, M. A., & Diederichs, M. S. (2014). *A review of the tensile strength of rock: concepts and testing*. Geotechnical and geological engineering, 32(2), 525-546.

Priscu, J. C., Kalin, J., Winans, J., Campbell, T., Siegfried, M. R., Skidmore, M., ... & Elsworth, C. (2020). *Scientific access into Mercer Subglacial Lake: scientific objectives, drilling operations and initial observations*. Annals of Glaciology, 1-13.

Quintero, L. (2002). *An overview of surfactant applications in drilling fluids for the petroleum industry*. Journal of dispersion science and technology, 23(1-3), 393-404.

Rack, F. R. (2016). *Enabling clean access into Subglacial Lake Whillans: development and use of the WISSARD hot water drill system*. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 374(2059), 20140305.

Schwander, J., & Rufli, H. (1988). *Electromechanical drilling in dry holes to medium depths*. In Proceedings of the 3rd International Workshop on Ice Drilling Technology (pp. 10-14).

Siegert, M., Kennicutt M. (2018) *Governance of the exploration of subglacial Antarctica.* Frontiers in Environmental Science, 103.

Stoxreiter, T., Martin, A., Teza, D., & Galler, R. (2018). *Hard rock cutting with high pressure jets in various ambient pressure regimes*. International Journal of Rock Mechanics and Mining Sciences, *108*, 179-188.

Talalay, P. G. (2011). *Review on Subglacial Till and Bedrock Drilling* (pp. 1-50). Technical Report PRC 01-2011, 2011: 1-50.

Talalay, P. G. (2013). *Subglacial till and bedrock drilling*. Cold Regions Science and Technology, 86, 142-166.

Talalay, P., Li, X., Fan, X., Yang, Y., Li, Y., Wang, T., ... & Zhao, G. (2019). *Experimental investigation of water freezing and estimating refreezing time in ice boreholes*. Cold Regions Science and Technology, 166, 102822.

Talalay, P. G., & Hong, J. (2021). *Perspectives for development of ice drilling technology: continuation of the discussion*. Annals of Glaciology, 62(84), 143-156.

Talalay, P., Li, X., Zhang, N., Fan, X., Sun, Y., Cao, P., ... & Li, Y. (2021). *Antarctic subglacial drilling rig: Part II. Ice and Bedrock Electromechanical Drill (IBED)*. Annals of Glaciology, 62(84), 12-22.

Timoney, R., Worrall, K., Firstbrook, D., Harkness, P., Rix, J., Ashurst, D., ... & Bentley, M. J. (2020). *A low resource subglacial bedrock sampler: The percussive rapid access isotope drill (P-RAID)*. Cold Regions Science and Technology, 177, 103113.

Tulaczyk, S., Mikucki, J. A., Siegfried, M. R., Priscu, J. C., Barcheck, C. G., Beem, L. H., ... & Schwartz, S. Y. (2014). *WISSARD at Subglacial Lake Whillans, West Antarctica: scientific operations and initial observations*. Annals of Glaciology, *55*(65), 51-58.

Wang, J., Cao, P., Liu, C., & Talalay, P. G. (2015). Comparison and analysis of subglacial bedrock core drilling technology in Polar Regions. Polar Science, 9(2), 208-220.

Williamson & Associates (n.d.). Specification Sheet ROCS Multi-Core, Rev 1.0. Retrieved from https://static1.squarespace.com/static/5c42607ee17ba3da21bb4f2b/t/6054f13eaccfd25d182cfba8/1616179523963/WaTech-ROCS+Spec+Sheet-r1.0.pdf

Xu, Z., Reed, C. B., Parker, R., & Graves, R. (2004, October*). Laser spallation of rocks for oil well drilling. In International Congress on Applications of Lasers & Electro-Optics* (Vol. 2004, No. 1, p. 1803). Laser Institute of America.

Acronyms

ASIG: Agile Sub-Ice Geological (Drill)

AT: Anti-Torque

BAS: British Antarctic Survey

BEAMISH: BEd Access, Monitoring and Ice Sheet History

BID: Blue Ice Drill

CHWD: Clean Hot Water Drill

CRREL: Cold Regions Research and Engineering Laboratory

DISC: Deep Ice Sheet Coring (Drill)

EHWD: Enhanced Hot Water Drill

HWD: Hot Water Drill

IBED: Ice and Bedrock Electromechanical Drill

IDP: U.S. Ice Drilling Program

P-RAID: Percussive Rapid Access Isotope Drill

PICO: Polar Ice Coring Office

RAID: Rapid Access Ice Drill

RAM: Rapid Air Movement (Drill)

ROCS: Remotely Operated Core Sampler

SAE: Subglacial Aquatic Environments

SCAR: Scientific Committee on Antarctic Research

SLCECs: Subglacial Lake Centro de Estudios Científicos

SLLID: Sediment Laden Lake Ice Drill

UV: Ultraviolet

WISSARD: Whillans Ice Sheet Subglacial Access Research Drilling