Coring of unconsolidated permafrost deposits: methodological successes and challenges

Graham L. Gilbert
Geology Department, The University Centre in Svalbard, UNIS, Norway & Department of Earth Science, University of Bergen, Norway & Center for Permafrost, Department of Geoscience and Natural Resource Management, University of Copenhagen, Denmark
Hanne H. Christiansen
Geology Department, The University Centre in Svalbard, UNIS, Norway
Ullrich Neumann
Kolibri Geo Services, Risør, Norway

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ABSTRACT
This technical note presents three scales of drilling infrastructure for comparison. These three methods include: (1) a small hand-drill designed for retrieving cores down to ca. 5 m depth, (2) the medium-scale UNIS Permafrost Drill Rig (down to ca. 50 m depth), and (3) an industrial drill rig designed for coring to depths of greater than 1 km. All methods vary with respect to maximum drill depth, operational cost, and ease of transport throughout the landscape.

RÉSUMÉ
Cet article compare trois méthodes de forage de tailles différentes. Ces trois méthodes correspondent à: (1) une petite foreuse portative conçue pour récupérer des carottes allant jusqu'à 5 m de profondeur, (2) une foreuse de taille moyenne UNIS Permafrost Drill Rig (jusqu'à environ 50 m de profondeur) et (3) une grosse foreuse industrielle conçue pour forer à des profondeurs de plus d'un km. Les méthodes de forage varient en fonction de la profondeur maximale des forages, des coûts d'exploitation, ainsi que de la facilité de leur transport sur le terrain.

1 INTRODUCTION

Recent field investigation in the Adventdalen Valley (central Spitsbergen, Svalbard) and northeastern Greenland have focused on reconstructing Holocene permafrost and landscape development from frozen sediment cores obtained using three scales of drilling infrastructure. The applied coring techniques range from small, portable hand-drills (**Figure 1A**) to an industrial drill rig, designed for obtaining bedrock cores from depths of greater than one kilometer (**Figure 1B**). In addition, a unique drill rig, designed by Dipl.-Ing. Lutz Kurth Bohr- und Brunnenausrüstungen GmbH in collaboration with Kolibri Geo Services, was acquired in 2011. This drill rig, called the UNIS permafrost drill rig, is intermediate in scale and has obtained core down to a depth of ca. 25 m (**Figure 1C**). The rig can be transported around the landscape by snowmobiles during winter – reducing the environmental impact when retrieving shallow cores from remote Arctic regions. The combination of these three methods has allowed us to assemble knowledge regarding the physical state of permafrost with regards to ground-ice conditions and sediments from different geomorphic settings and sediment types both on Svalbard and in northeast Greenland.

These three scales of infrastructure vary significantly with respect to the quality of retrieved cores, maximum depth of drilling, operational costs, and rig mobility. The objective with all methods is to retrieve cores of sufficient quality to visually classify ground-ice (cryostructures) and sedimentological characteristics. Such cores also permit the calculation of gravimetric moisture content, excess ice content, and sediment grain size distributions. For this reason the retrieval of high-quality, frozen samples is critical. The aim of this paper is todescribe and compare the three drill methods mentioned above.

2 EQUIPMENT AND METHODS

2.1 Hand-drill (**Figure 1A**)

The hand-drill consists of a STIHL^{TM} BT 121 Earth Auger, drilling extensions, and an unflighted (smooth walled) core barrel with diamond cutting teeth. The system has been tested in temperatures as low as -20 °C. The gas-driven power head has a rotation speed of between 0 and 190 RPM, controlled using the throttle. The core barrel, ca. 50 mm in inner diameter, was designed for taking concrete samples and effectively 'melts' through frozen ground using friction generated during rotation. Because of this unfrozen mud accumulates along the core barrel and the system is prone to 'freezing-in' if rotation stops.

During drilling, the equipment is assembled at the ground surface and lowered into the drilled hole. The core barrel and drill extensions are screwed together and tightened by the induced torque during drilling. The power head is connected to the drill string using a wire-lock lynch pin. The series of power head, drill rods, and core barrel must be removed from the hole with each coring attempt. The maximum depth per drilling attempt is ca. 50 cm (the inner length of the core barrel). The core barrel is designed without a core-catching system. We rely on friction, generated between the core and the sidewalls within the barrel, to retrieve the core with each attempt. In order to safely operate the hand drill, an operating team of minimum two is recommended.

Hand drilling is a good, though time consuming, method to retrieve samples from the top 2-5 m of sediments, depending on the sediment type and time available. Typical rates of drilling are between 0.5 and 1.0 m per hour. Since 2012, ca. 30-40 cores from 2 m to 5 m in length have been retrieved from Greenland and Svalbard using this method in both summer and winter.

Figure 1. The different drilling infrastructure. A – Hand Drilling; B – Industrial Drill Rig; C – UNIS Permafrost Drill Rig.

2.2. UNIS Permafrost Drill Rig (**Figure 1C**)

The UNIS permafrost drill rig was acquired in response to the need to evaluate the potential effects of on-going climatic changes on periglacial landforms in permafrost areas throughout Svalbard and Greenland. The rig consists of a hydraulic engine (Honda GX690), two air compressors (CompAir C14), a drill boom, and drill head.

Compressed air is used to cool the drill bit and transport cuttings to the surface. Connected in parallel, the two compressors produce 2.8 m^3 of air per minute at 7 bar. The drill can be equipped with a single core barrel (1 m length), double core barrel (1 m length), or rotary-air hammer drill. Additionally, six drill bits have been designed to meet the challenges posed by drilling in different substrates.

In general, drill bits with impregnated diamonds are used when drilling through rock and gravel, and drill bits with carbide inserts used in fine-grained sediments (**Figure 2**). The rake angle of the carbide bits have been further modified to ease drilling through ice and sediment. For mud and sand, bits with a rake angle of 0° have yielded the best results (**Figure 2A, B, E**). When ice is encountered a bit with a higher rake angle (30°) is used (**Figure 2D**). For bedrock and gravel, impregnated diamond bits are used (**Figure 2C, F**). This combination of drill bits has permitted core recovery from heterolithic substrates. In addition to coring, the drill rig can be equipped with a rotary air hammer drill. This destructive method allows us to make a hole (ca. 55 mm in diameter) and has been used to install casings for monitoring ground temperatures.

During drilling, the core barrel is attached to the drill head (drill motor) by a series of 1 m steel extensions. Following each drill attempt the entire drill string (extensions plus core barrel) must be removed from the hole in order to retrieve the core. The result of this is that the rate of drilling decreases with increasing depth. Over an interval of ca. 20 m the rate of drilling is between 0.5 and 1 m per hour.

The drill rig is mounted on a sledge which can be towed by a snowmobile. The rig has also been used during the snow-free period when it is transported using a fork lift or other transporting devices. The manufacturer states a maximum core retrieval depth of 50 m. However, investigations using coring have not exceeded 25 m to date. Recently, in April 2015, this rig was used to drill a 50 m hole to install temperature sensors for ground thermal monitoring. In this case no core was retrieved. However, this method has been used to recover cores from drill holes totalling 10 m to 25 m in length at ca. 8 sites in Svalbard and on Greenland. An operating crew of three to four is recommended when coring with two responsible for the drill operation, one in charge of core documentation and storage, and potentially one for equipment maintenance.

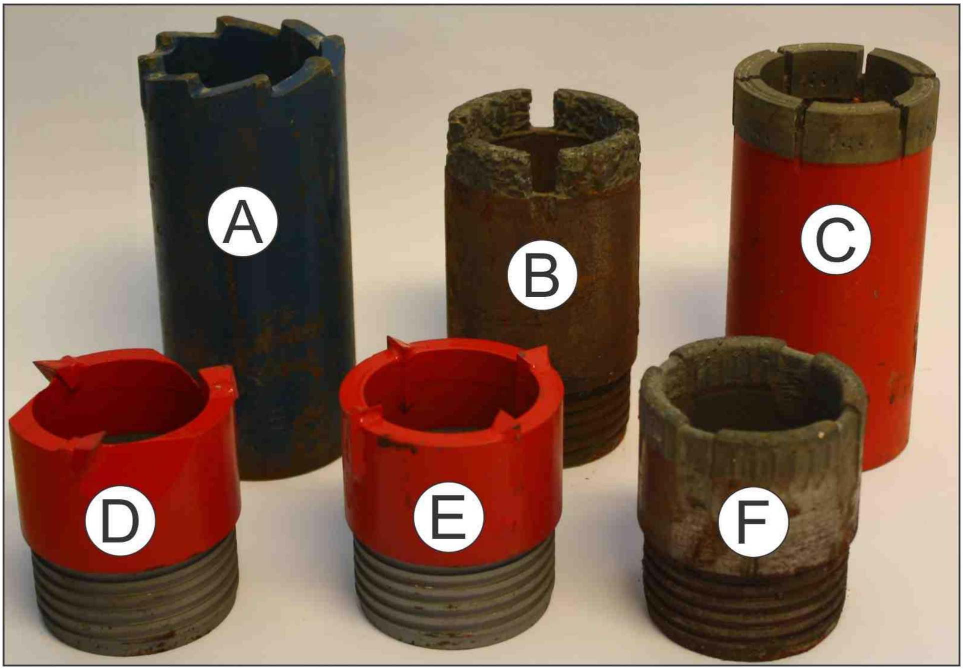

Figure 2. Drill bits used with the UNIS Permafrost Drill Rig. All bits have an inner diameter of 43 mm and are designed to rotate clockwise in a downwards direction. A – Eight hexagonal carbide inserts with rake angle of 0°. B – Impregnated carbide fragments in the crown. C – Impregnated diamond bit. D – Ice bit – three carbide inserts with rake angle of 30°. E – Four carbide inserts with a rake angle of 0°. F – Impregnated diamond bit.

2.2 Industrial Drill Rig (**Figure 1B**)

In September 2012 an industrial rig was used to drill a 60 m well in ice-bonded Quaternary deposits at the UNIS CO_2 Laboratory's well park in the Adventdalen valley bottom (Braathen et al. 2012, Gilbert 2014). This operation utilized a Boart Longyear™ HQ-3 wireline triple core barrel system. This system used water as a cooling and transport fluid. The triple-core barrel system limited the exposure of the core material to the drilling fluid by encasing the sample within a plastic tube during drilling (**Figure 3A**). The inner diameter of the core was 63.5 mm and sections were retrieved in 1.5 m lengths (**Figure 3B**). Drilling was expedited by the wireline system which allowed for core retrieval without removing the drill string. As a result, 60 m was cored in less than 20 hours (ca. 3 m per hour). During operation, the drill was run by two teams of two professional drillers, each working in 12 hour shifts. This process resulted in a retrieval rate of ca. 80 %; 48.1 m of the possible 60 m of sediment was recovered. Unrecovered intervals were distributed across the length of the core, and ranged in thickness from a few centimetres to 1.5 m.

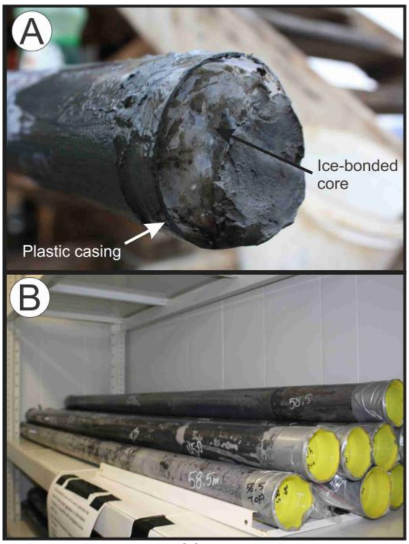

Figure 3. A – Recovery of frozen sediment core encased within the plastic sheathing. B – 1.5 m lengths of frozen cores in storage.

3 TECHNICAL COMMENTS AND CORE QUALITY

A qualitative evaluation of each drilling method in relation to the substrate composition is provided in **Figure 4**. All methods perform well in ice-rich material and fine-grained sediments (i.e. sand and mud). This observation consistent with those reported using other types of drills for permafrost coring (e.g. Brockett and Lawson 1985, Dickinson et al. 1999, Calmels et al. 2005, Saito and Yoshikawa 2009). The effectiveness of coring in these deposits is attributed to the presence of ice and grain size. Ice, acting as cement between individual grains and organic material, prevents core fragmentation during drill operation. Fine-grained sediments are additionally less susceptible to mechanical disintegration than coarser deposits. Both the hand drill and UNIS Permafrost Drill Rig are ineffective when coring in coarser material. This is attributed to the amount of energy generated while cutting through rock fragments, which effectively melts the ice contained in the core resulting in the retrieval of disturbed samples. The distinction between frozen cores from fine-grained deposits and fragmented cores from coarse-grained sediments is illustrated in **Figure 5**.

Unlike the aforementioned methods, the Industrial Drill Rig with the triple-core barrel system was effective across the entire spectrum of deposits encountered in the valley bottom sediments. The Adventdalen deposits range from compact, glacial diamicton (**Figure 6A**) to glaciomarine silts (**Figure 6B**) to sands deposited during delta progradation (**Figure 6C**; Gilbert 2014). The origin of the unretrieved intervals remains is tentatively attributed to two factors. The effects of mechanical abrasion were observed in some core sections, particularly those consisting of relatively well sorted sands and gravel. Here the absence of a mud-rich matrix left sediment grains susceptible to disintegration by the pressurized water, which was used as a drilling fluid. Alternatively, Lecomte et al. (2014) provided evidence for unfrozen pockets (cryopegs) in the valley bottom sediments. Given the influence of marine conditions during deposition the sediment pore water is likely rich in solute. Ground temperature in Adventdalen is on the order of -5 °C (Christiansen et al., 2010), and deposits may contain a significant amount of unfrozen water. However, all retrieved samples appeared well frozen at an ambient laboratory temperature of 6 °C.

4 CONCLUSION

The difficulty with retrieving satisfactory cores from frozen coarse-grained deposits using portable drill rigs remains a limiting factor when attempting to characterize permafrost deposits in mountainous landscapes such as Svalbard and northeast Greenland. The high-operational costs and limited mobility of the Industrial Drill Rig will likely limit the wide-spread use of the triple core barrel system, when coring in permafrost environments. However, the success of this method is in part attributed to the use of water as a drilling fluid. The UNIS Permafrost Drill Rig is also designed to operate with water as a drilling fluid. Future investigations of coarse-grained deposits may have a greater success if this medium is used instead. Hand drilling remains the most reliable and cost-effective method of retrieving short cores from the top 5 m of deposits.

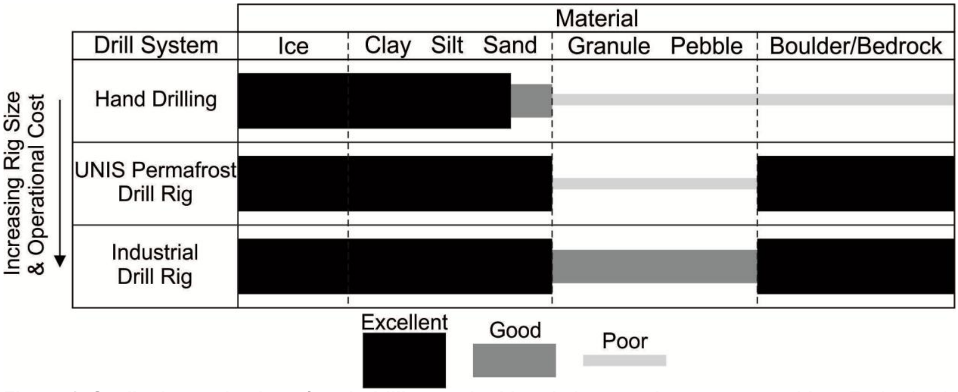

Figure 4. Qualitative evaluation of each drilling method in relation to substrate composition. Evaluation is based on the perceived quality of retrieved cores following laboratory investigation. 'Excellent' – intact cores with little or no evidence of disturbance. 'Good' – mostly intact cores with minimal to moderate disturbance. 'Poor' – complete disturbance with limited retrieval of material (no intact cores with samples thawed during drilling).

Figure 5. Differentiation between frozen and unfrozen, fragmented core retrieved using the UNIS Permafrost Drill Rig. Upwards direction is towards the left of the image.

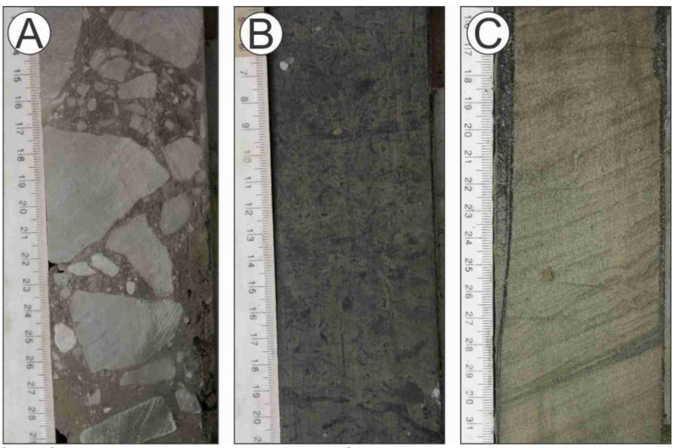

Figure 6. Samples from frozen deposits in Adventdalen, Svalbard obtained with the industry Drill rig. A – glacial diamicton; B – bioturbated marine muds; C – Sand-rich deltaic deposits. Scale in cm.

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