Firn Permeability Impacts on Pressure Loss Associated with Rapid Air Movement Drilling

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Key Points

- The layered nature of firn may include high-permeability bands that impact the performance of an air-drill system.
- Borehole pressure loss is highest in firn that has bands of higher air permeability layers.
- Results indicate that the presence of higher-permeability layers near the bottom of the borehole would most directly lead to pressure loss large enough to impede drilling.

Abstract

The polar ice sheets of Greenland and Antarctica are sensitive indicators of weather and climate, and also serve as natural archives of past climate; evidence from within and below the ice is important for scientific investigations. A variety of ice drilling techniques have been used for a wide array of scientific applications, including mechanical ice coring, hot water drilling of access holes, and compressed air-drilling of holes to contain explosive charges for seismic measurements. Creating access holes using compressed air-drilling in ice has rapid rates of penetration in some locations on an ice sheet, yet the technique has failed at shallower depths in other locations. This paper investigates the interaction of the properties of the aged snow, called ‘firn’, with pressure loss associated with compressed air-drilling. Specifically, we report on numerical studies examining the impact of firn layering and firn permeability on air-drill induced pressure changes inside the borehole and in the surrounding firn. Results indicate borehole pressure loss is highest in firn that has bands of higher air permeability layers. A loss of borehole pressure would lead to decreased ice-chip air transport up through the borehole, causing degraded drill performance as ice chips clog the drill bit, stalling the drill. Numerical results show that

the presence of higher-permeability layers near the bottom of the borehole may lead to sufficient pressure loss to impede drilling. In contrast to other kinds of ice drilling, where casing the borehole near the surface is common, casing the bottom of the borehole may be necessary for rapid air movement drilling in areas where high permeability bands of layers exist at depth.

Keywords

Ice sheet, drilling, firn properties, permeability.

Introduction

The polar ice sheets of Greenland and Antarctica are sensitive indicators of weather and climate, and also serve as natural archives of past climate. In the cold, high central regions of the ice sheets where the snow seldom melts, the glacial ice is multiple kilometers thick. With annual snowfall accumulation rates on the order of centimeters, the top approximately 60-120 m of the ice sheet consists of aged porous snow called ‘firn’; at greater depths, the firn has been compacted to solid ice. A variety of ice drilling techniques are used for various scientific purposes on the ice sheets. For example mechanical ice coring is used for retrieving ice cores for climate records; hot water drills are used for creating access holes for subglacial sampling; air-drills using compressed air create holes for seismic measurements of ice sheet characteristics. Creating access holes using compressed air-drilling in ice has shown rapid rates of penetration in some locations on an ice sheet, yet the drill can stall at shallower depths in other locations. For example, air-drilling campaigns have successfully drilled to 90 m depth at sites in West Antarctica (Bolsey, R., 2009), yet the same drill has stalled at approximately 63 m at the South Pole Station in East Antarctica (Jayred, M., 2011).

Understanding the mechanism of air-drilling through any porous media, whether it is through earth or polar firn, relies on understanding forced fluid flow in a channel through the porous media. Beavers and Joseph (1967) examined free flow of a Newtonian fluid past a saturated permeable block in

order to understand boundary region interactions occurring at the open channel-porous media interface at Reynolds numbers less than 100. They found that a boundary layer exists within the porous media due to viscous shear effects. Both Berman (1953) and Granger et al. (1989) presented analytical solutions of laminar flow through a rectangular channel through porous media associated with their studies of microfiltration systems. Granger also extended the study to investigate laminar flow in a cylindrical channel. Both studies found that pressure and velocity profiles decrease along the flow direction, especially in situations where the walls have a higher permeability. For higher velocity flows, Olson and Eckert (1966) experimentally tested turbulent air flow (Re on the order of 10^4) through a porous tube in a situation involving injection of air through the porous wall for transpirational cooling. They found that most changes in flow parameters, including momentum flux, occurred within the initial entrance length of 10-12 tube diameters. With respect to drilling applications, where there is a high Re flow in an open cylindrical channel through a porous material without injection along the wall, there is a lack of published information about the effect of permeable formations on drilling efficiency, despite numerous applications including oil extraction, ground water extraction, underground storage, and scientific investigations.

Rotary drilling technology using compressed air or other gases as the circulation fluid has long been used in the petroleum industry. In drilling through rock, air as the circulating fluid has several advantages over hydraulic drilling, including a greater drilling speed as well as a smaller likelihood of causing formation damage, which is crucial in optimizing well production in oil and gas recovery projects (Nicolson, 1953; Lyons et al., 2009). The use of compressed air-drilling for creating access holes in an ice sheet has long supported important geophysical discoveries about ice sheets and ice sheet behavior. For example, air-drilling enabled the seismic records of englacial seismic reflectivity at the bottom of the ice sheet at several sites in West Antarctica including WAIS Divide and Thwaites Glacier (Horgan et al., 2011). The Ice Drilling Design and Operations group of the U.S. Ice Drilling Program (www.icedrill.org) currently uses an air-drill, the Rapid Air Movement (RAM) drill for creating access holes in the ice sheet.

The RAM drill uses compressed air to drive rotating cutters for penetration in polar firn, and it has successfully drilled to approximately 90 meters depth at various sites across the West Antarctic Ice Sheet, but was unable to penetrate past approximately 63 meters when used at the South Pole on the East Antarctic Ice Sheet. The cause of drill failure has been unclear. No measurements of firn permeability exist at any of the drill sites where the RAM drill has been used.

For any porous material, intrinsic permeability is the material property that is proportional to the ratio of the pressure drop in the flow direction to the fluid flow rate through the material. On the polar ice sheets, regional differences in environmental conditions such as snow accumulation rate and ambient temperature play an important role in the development of the physical properties, including permeability of layered snow and firn (Albert et al. 2004; Courville et al., 2007; Horhold et al., 2009; Gregory et al., 2014). This paper presents results of numerical finite element experiments to investigate the effects of firn permeability on forced air flow through a cylindrical channel in the firn associated with a borehole air-drill system. We do not aim to model the mechanics of the RAM drill mechanical components in this study, due to a lack of any information on the firn parameters with depth at the locations where the drill has been used. Instead, the goal is to investigate the nature of pressure changes in the borehole and in the surrounding layered firn under pressure forcing conditions that would be induced by a pneumatic drill, in effort to better understand the impact that the permeability of the firn could have on rapid air-drilling.

The East Antarctic plateau generally exhibits lower accumulation rates and colder average temperatures when compared with sites in West Antarctica or on the Greenland ice sheet. The South Pole, East Antarctica, for example, has a mean annual temperature of -51°C and accumulation rate of $8\text{ cm ice-eq yr}^{-1}$ (e.g. Severinghaus et al., 2001). In contrast, the WAIS Divide site in West Antarctica and Summit, Greenland are both warmer and receive more annual snowfall, with mean annual temperatures of -31°C and -31.4°C and $22\text{ cm ice-eq yr}^{-1}$ and $23\text{ cm ice-eq yr}^{-1}$ respectively (Severinghaus et al., 2010; Schwander et al., 1993). Lower accumulation areas tend to coincide with more permeable firn compared to higher accumulation sites due to an increased snow crystal residence time at the surface; resulting in

99 prolonged exposure to temperature gradients causing snow metamorphism in near surface firn (Rick and
100 Albert, 2004, Albert et al., 2004; Courville et al., 2007, Horhold, Albert and Freitag, 2009). Near-surface
101 temperature gradients are caused by diurnal and seasonal temperature swings, with the strongest
102 gradients, due to diurnal changes, existing in the top 20 cm (e.g. Brandt and Warren, 1997). The near-
103 surface temperature gradients induce differences in vapor pressure within the snow and firn that drive firn
104 grain metamorphism. This temperature-driven metamorphism favors the growth of large crystals while
105 small crystals sublime (e.g. Colbeck, 1983), leading to larger interstitial pore spaces (Albert et al., 2004;
106 Flanner and Zender, 2006).

107 Measurements of firn layering and permeability exist from firn cores drilled in West Antarctica (Albert et
108 al 2000; Rick and Albert, 2004), at Summit, Greenland (Adolph and Albert, 2014), at Megadunes in East
109 Antarctica (Courville et al, 2007), and at WAIS Divide in West Antarctica (Gregory et al., 2014).

110 Unfortunately there have not been any permeability measurements made at sites where the RAM drill has
111 been used. In this paper, we use measured permeabilities to establish bounds for numerical experiments
112 to investigate the impact of discrete depths of high and low permeability anomalies on the impact of
113 borehole pressure differences and air flow in the surrounding firn. Anomalous bands of higher
114 permeability have been recorded in firn in past literature. Specifically, Rick and Albert (2004) discuss the
115 impact of accumulation rate and temperature on the development of microstructure, affecting the
116 permeability of one meter-scale thickness bands in the firn. They examine multiple scenarios of different
117 climate conditions that would explain a highly connected pore volume, leading to a high permeability
118 anomaly, seen at 12 meters depth on a firn core extracted from West Antarctica. They discovered that, at
119 the site investigated, a short term climatic event led to a short residence time that affected pore space and
120 permeability in a band of firn near 12 meters depth.

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123 Theory

124 This study investigates multidimensional air flow, forced by higher pressure at depth in a borehole, up the
125 annular region of the borehole and also laterally out from the borehole into the porous firm. The numerical
126 simulations are single-phase flow (air); multi-phase aspects of the combined air flow and ice chip
127 transport that exist with the drill system (a multiphase mixture of air and ice chips) are beyond the scope
128 of the current study. By assuming an ice chip diameter of 5 mm, we can calculate the force due to gravity
129 pulling the chip down to be about $6 \times 10^{-4} \text{N}$. This weight is much less than the force applied due to
130 dynamic pressure exerted on the surface of the ice chip as a result of air, with a density of $1.4 \frac{\text{kg}}{\text{m}^3}$ moving
131 at $0.38 \frac{\text{m}^3}{\text{s}}$ through an annular area of 0.01 m^2 , with an approximate force of 1000 N. Thus we focus on
132 single phase-air flow and resulting pressure changes in the annular cavity and in the surrounding porous
133 firm. For the single phase steady state problem, the Navier-Stokes equations describing momentum and
134 mass conservation of a compressible gas in an open (non-porous) channel are as follows (Kundu, 2012):

$$\rho(\vec{u} \cdot \nabla \vec{u}) = -\nabla p + \eta \nabla^2 \vec{u} + \left(\eta_v + \frac{1}{3} \eta \right) \nabla(\nabla \cdot \vec{u}) + \mathbf{F}$$

$$\nabla(\rho \vec{u}) = 0$$

135 Here $\vec{u}$ is fluid velocity vector (m/s), η is dynamic viscosity (Pa·s), p is pressure (Pa), η_v is the coefficient
136 of bulk viscosity, $\mathbf{F}$ is a body force matrix such as gravity and ρ is fluid density (kg/m^3). Within the
137 porous media (firm), Darcy's equation describes the flow with an added Brinkman term to account for
138 fluid viscous effects (Guta and Sundar, 2010):

$$\frac{\eta}{\kappa} \vec{u} = -\nabla p + \frac{\eta}{\varepsilon_p} \nabla^2 \vec{u} + \frac{1}{\varepsilon_p} \left(\eta_v + \frac{1}{3} \eta \right) \nabla(\nabla \cdot \vec{u}) + \mathbf{F}$$

$$\nabla(\rho \vec{u}) = 0$$

139 Where κ and ε_p are permeability and porosity of the firm respectively.

The inlet condition is established using air flow rate measurements taken during an air-drill (RAM drill) field project at the South Pole, East Antarctica. The maximum volumetric flow rate entering the borehole was recorded to be approximately $0.38 \frac{m^3}{s}$ (800 SCFM) (Benson, pers comm 2014). Dividing by the cross sectional area of $0.01 m^2$ ($0.11 ft^2$) of the annular space, the resulting Mach number is approximately 0.12 for air temperature of $-31.4^\circ C$, which is well within the regime of subsonic flow. Hence the fluid flow calculations involves incompressible flow conditions.

Boundary Conditions

The geometry of the problem is 3D axisymmetric, with boundary conditions along the two walls of the concentric cylindrical geometry of the borehole, plus boundary conditions laterally along the snow surface of the top boundary, laterally at depth below the bottom of the borehole, and vertically through the firn at large distance from the borehole. Figure 1 depicts the geometry of the problem. The inside wall of the annulus, at the drill line interface, is set to have a no-slip boundary condition. The outside wall of the annulus is along the borehole interface between the air in the borehole and the surrounding firn. At this interface, continuity of the air flow velocity field and pressure are enforced. The outer vertical edges of the computational domain for the firn, far from the borehole, as well as the lateral boundary along the snow surface at the top of the annulus and surrounding firn allow air to escape with pressure under hydrostatic conditions:

$$\rho_{firn\ matrix} = (g\rho_{firn} + g\rho_{pore\ air})z$$

Where $g\rho_{firn}$ and $g\rho_{pore\ air}$ are the weight per unit volume of the ice in the firn and air contained in pore space above depth z . All pressures in the borehole-firn system in this model are gage pressure readings, therefore the pressure boundary condition horizontally along the snow surface ($z = 0$) will be defined as zero.

The inlet air flow forcing this system is set at the bottom of the borehole, for simulating air velocity and pressure drop along the direction of flow up the annulus and also out into the surrounding firn. Pressure drop through the drill head is neglected. Bottom borehole pressure is assumed to be a combination of hydrostatic pressure, due to the weight of the air column inside the borehole, plus the pressure contribution from three air compressors that were run in parallel, rated at $0.19 \frac{m^3}{s}$ (400 SCFM), 1.28×10^6 Pa (200 psig), forcing air out of the drill line into the bottom of the borehole (Benson, pers comm 2014). The inlet pressure contribution in this model is approximately 1.03×10^6 Pa (150 psig), based on measured readings from a gage downstream of the three compressor assembly during a field campaign with the RAM drill (Benson, pers comm 2014).

Methods

The Model

The snow surface exists laterally radiating out from $r = 0$ m to $r = 10$ m, and the modeled vertical region extends from $z = 0$ m to $z = -80$ m depth in the firn (Figure 1). The open air space in the borehole extends from $r = 0.027$ m (1.05 in) to $r = 0.064$ m (2.5 in), and the bottom of the borehole is at $z = -40.5$ m. The pressure condition at the bottom of the borehole is set at $0.027 \text{ m} < r < 0.064 \text{ m}$, $z = -40.5$ m. The left-hand figure in Figure 1 shows the two-dimensional velocity vector field caused by air entering the bottom of the borehole, within the firn column, where it can be seen that the greatest magnitude of air velocity escaping into the firn is near the bottom of the borehole. At distances farther from the bottom of the borehole, the air flow slows due to viscous forces. The right-hand diagram of Figure 1 is a close-up view of the annular space and firn geometry. The multidimensional axisymmetric problem is solved by the finite element method, using COMSOL Multiphysics® software.

Permeability is prescribed as a function of depth in the model through use of a nonlinear, least-squares regression fits to existing permeability data:

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$$e^{-0.077z+3.9 \times 10^{-10} \text{ m}^2} \quad [1]$$

185 Where z is depth (m).

186 The nonlinear fit results from regression curve-fitting to firn core permeability data from Summit,
187 Greenland (Adolph and Albert, 2014), a site with generally moderate firn permeability. Note that this fit
188 does not replicate all of the variability that occurs across length scales in the firn column, but the fit is
189 useful for model investigations of the impact of the overall permeability trends on air-drill interaction
190 with the surrounding firn.

191 **Numerical Experiments**

192 Firn is a naturally-deposited layered, inhomogeneous medium, with individual snow precipitation events
193 forming layers that are distinguished by microstructural differences that affect the permeability. The
194 points plotted in Figure 2 show measured firn permeability as a function of depth (Adolph and Albert,
195 2014) from Summit, Greenland. The continuous, smooth curve in bold through the points is the line
196 produced by regression curve fitting to the data; the equation for the fit is given in Eq. 1. In addition,
197 boxes are drawn in solid lines at eight different depths along the curve in Figure 2 that illustrate a
198 difference of approximately one standard deviation from the mean value over that meter of firn (each box
199 is shown as one meter in thickness). For use in numerical experiments, the boxes indicated by the solid
200 lines impose a hypothesized anomalous permeability band, or group of adjacent layers which have a
201 distinctly higher permeability than mean value of the curve fit at that depth. These boxes have been
202 chosen so that the permeability of the hypothetical one-meter band would fall within the spread of the
203 measured data near that depth. For the boxes, the eight different depths are listed in Table 1, along with
204 the mean and one standard deviation of permeability for each depth range.

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Table 1 One standard deviation from mean permeability at given depth

Trial	Depth of Hypothesized permeability anomaly (m)	Mean permeability from the curve fit ($\times 10^{-10} \text{ m}^2$)	One Standard Deviation from Mean Value of permeability ($\pm$) ($\times 10^{-10} \text{ m}^2$)
1	5 – 6	41.1	20.3
2	10 – 11	27.0	7.5
3	15 – 16	15.9	3.8
4	20 – 21	9.8	2.1
5	25 – 26	9.0	3.1
6	30 – 31	4.4	1.6
7	35 – 36	3.7	1.5
8	40 – 41	2.2	0.9

207

Numerical Study 1

209 In order to evaluate the effect of permeability on air pressure within the borehole and also in the firn
210 surrounding the borehole, the model was first run at steady state with borehole depth held at 40.5 meters;
211 the firn thickness was held at 80 meters (approximate distance to lock in-depth at Summit, Greenland
212 (Faïn et al., 2009)), and the boundary condition on pressure at the bottom of the borehole was prescribed
213 to be $1.28 \times 10^6 \text{ Pa}$, in accordance with measurements from the drill operation as described above. In all
214 numerical experiments, the pressure profiles from the bottom of the borehole up to the surface along the
215 center of the annular cavity, as well as at one meter distance from borehole in the firn, will be plotted. In
216 the first numerical study, the model was run for three numerical experiments, one with firn permeability
217 following the exponential decay trend of the permeability site, seen in Figure 2, and two numerical
218 experiments that vary the permeability in only the section of firn extending from 40 – 41 meters depth.
219 The altered permeability was raised in one experiment and lowered in the other, in magnitude equal to
220 one standard deviation from the mean. Thus the hypothesized band of higher or lower permeability is still

within the range of measured permeability in that depth range. Results from these experiments are graphed in Figure 3. Figures 3a and 3c show permeability of modeled firm as a function of depth in each experiment. Figures 3b and 3d shows pressure calculated at a one meter radial distance from the annulus. A region of higher permeability firm surrounding the bottom of the borehole leads to an increase in pressure in the firm at the one meter radial distance from the borehole, as more air is able enter the porous matrix as compared to the other two cases (no-anomaly and low-permeability anomaly). Figure 3e shows the pressure along a line at the center of the annular cavity, running from 35m depth down to the bottom of the borehole at 40.5m depth. The existence of a high permeability anomaly inside the firm (dotted line) causes the most loss of pressure inside the borehole when compared to the no-anomaly and low-permeability anomaly experiments (solid and dashed lines respectively). The pressure decreases from the bottom of the borehole to the top, as expected.

Numerical Study 2

The second numerical study investigates the impact of the depth of the permeability anomaly on the resulting pressure profiles and pressure loss over the entire borehole. The borehole depth was again fixed at 40.5 meters and the depth of the permeability anomaly for each trial is given in Table 1. The simulated permeability of the anomaly was adjusted in the model to be one standard deviation higher than the average of the measured values located at each depth for which the simulated anomaly was placed. The average of the permeability measurements around the depth of the anomaly, and the simulated permeability of the anomaly is also presented in Table 1. The results, plotted in Figure 4, indicate that the location of a simulated permeability anomaly on an air-drilling system does have an effect on the pressure gradient within the firm surrounding the borehole. Figure 4a shows the calculated pressure in the firm at a one-meter radial distance from the borehole. Two of the eight trials are shown, one (solid line) where the permeability anomaly is placed at depth 35-36 m, and another (dotted line) where the permeability anomaly is placed at depth 40-41m. The Figure 4b shows the results of vertically-integrating the pressure profiles (two examples are given in Figure 4a) for all eight trials, where the x axis indicates depth of the

top of the permeability anomaly. The total pressure, from air entering the firn porous matrix along the borehole, is calculated to be highest when the permeability anomaly is located at the bottom of the borehole (between 40-41m), where air is first entering the annular space. Figure 4c shows the radial pressure difference as a function of depth for each trial. The radial differential pressure, taken from center of the annulus to a lateral distance of one meter in the firn at that depth, is greater when the anomaly is located at the bottom of the borehole than in cases where it is closer to the snow surface, in spite of the fact that the permeability of the firn increases in the direction toward the surface. By Darcy's law, for a given permeability, the larger differential pressure gradient will drive a higher volumetric flow rate of air into the firn. The potential largest loss of air is thus at the bottom of the borehole where the largest differential pressure exists between the borehole and the surrounding firn. Above this depth, the pressure inside the borehole decreases, leading to a lower differential pressure at any given depth between the borehole and the surrounding firn. The lowered borehole pressure leads to less air loss into the firn, in spite of the fact that the permeability is higher in the anomalous bands closer to the surface.

Discussion

The two numerical studies described above examined the pressure effects that arise from a one-meter thick simulated permeability anomaly in the firn. Because the hypothesized one-meter thick permeability anomaly in the modeled firn is within the variance of measured permeability found within a one meter region, these simulations are not out of the realm of possibility of occurrence even under normal conditions of firn structure.

Pressure conditions in the borehole are important to air drill performance. We have shown that the pressure profile within the annulus and firn is sensitive to firn permeability, which can vary considerably under natural climate conditions between different geographical sites. Within the last two decades, microcomputed tomography (μ CT) has become integrated into polar research to improve understanding of microstructural changes that happen within the snowpack and firn in the polar regions (Flin et al.,

2003; Schneeblei and Sokratov, 2004; Freitag et al., 2004; Lomonaco et al., 2011; Gregory et al., 2014). Gregory et al. (2014) have shown that porosity is a poor indication of permeability because it does not account for the tortuosity and connectivity of the pore structure. Therefore, without direct measurements of permeability with depth, it is difficult to apply our model to another site with different site characteristics to determine pressure effects within the borehole. However by integrating the permeability during each of the eight trials examined in Numerical Study 2 above, where the higher permeability anomaly was moved to various depths, and comparing that integrated permeability with differential pressure inside the borehole, we demonstrated that the way the permeability changes with depth is critical when considering pressure effects within the borehole. Figure 5 shows a plot of the depth of the anomalous band during each of the eight experiments against the corresponding differential pressure within the borehole during each experiment (grey dots) as well as against the corresponding integrated permeability of the firm column (black dots). Since the anomaly increases the permeability of the firm at some location, all eight trials show an increase in integrated permeability as compared to the trial where no anomaly exists as would be expected (at point zero on the x-axis). The integrated permeability is marginally higher when the anomaly exists in the top ten meters. This result is expected, as the anomaly is raising the permeability where firm typically is the most permeable (refer to Figure 2). The differential pressure remains near a constant value, except in the case when the permeability anomaly is located near the bottom of the borehole. In that case the immediate loss of mass lowers the bottom hole pressure, and hence the differential pressure between the bottom and top of the borehole. This differential pressure is critical for proper drilling as it is the main driving force behind chip removal from the bottom of the borehole. Loss of differential pressure can result in clogging of the drill bit, leading to inability for the drill to continue to operate. It is evident that the impact of air loss from the borehole to the firm, affecting differential pressure within the borehole, is most sensitive to permeability anomalies at the bottom of the borehole, where compressed air first enters the annular space. Thus, in contrast to usual assumptions about borehole casings, casing near the bottom of the borehole could have a bigger impact on air-drill performance than casing near the top.

296 **Conclusion**

297 This study demonstrates that the firn permeability-depth profile has significant impact on air loss from the
298 borehole of an air-drill system. Air loss through the interconnected porous space of the firn results in a
299 decrease in pressure inside the borehole as well as an increase in pressure in the surrounding firn at a
300 given depth. Pressure loss effects due to firn permeability were found to be most sensitive near the bottom
301 of the borehole, where compressed air of highest pressure first enters the annular space. The immediate
302 loss of bottom hole pressure directly leads to a loss in total differential pressure inside the borehole. This
303 differential pressure is essential for proper chip ejection as it is what helps drive air with the loose snow
304 and ice chips up to the surface. In contrast to previous assumptions that a remedy to air-drill failure might
305 be to case the top of the borehole, these results indicate that a potential solution to mitigate the loss of
306 differential pressure is to case the near bottom of the borehole, at depths near the drill head, to prevent air
307 flow and pressure loss to the surrounding firn where the highest radial differential pressure exists.

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List of Figures

Figure 1 (Left) Vector plot of velocity field when air enters the bottom of the borehole. Velocity magnitude is indicated by the length of the arrows. (Right) Diagram of the borehole, with the annular space, depth and radial direction labeled accordingly. Air exits the drill, enters the annular space, and then travels up the annulus or escapes out into the firm through the porous matrix. (Single Column Figure)

Figure 2 Permeability data measured from a Summit, Greenland firn core (Albert and Adolph, 2014) with curve fit and selected areas for numerical experiments indicated by the solid line. (Single Column Figure)

Figure 3 Effect of a high, low and no permeability anomaly **3a,c**) Full firn permeability profile with depth with **c**) focusing on depths surrounding the permeability anomaly location used for these experiments (dotted – high permeability, dashed – low permeability). **3b,d**) show resulting pressure plots with depth at one meter away from the borehole, inside the firn. **d**) focusing on depths surrounding the permeability anomaly location used for these experiments (dotted – high permeability, dashed – low permeability). **3e**) Pressure up the center of the annular space of the borehole from 35m to 40.5m. (1.5 Column Figure)

Figure 4 Effect of the depth of a high permeability anomaly. **4a**) shows total pressure profile with depth for two of the eight experiments moving a one meter thick band of higher permeability to different depths indicated by the legend (solid line - band exists at 35m - 36m and dashed line - band exists from 40m - 41m). **4b**) graphs of integrated area under each of the eight trials' (refer to Table 1) pressure curve. **4c**) Radial differential pressure from center of the annular space out to one meter within the firn matrix.

405 Depth of the top of the permeability anomaly, for which the radial differential pressure was calculated, is
406 indicated by x-axis. (Single Column Figure)

407

408 **Figure 5** Integrated firm permeability (black dots) and differential pressure (grey dots) in the borehole
409 calculated from all eight experiments where a one meter thick high permeability anomaly exists at a
410 particular depth. Depth of the top of the anomaly is indicated along the x-axis. (Single Column Figure)

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413 Figure 1

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415 Figure 2

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417 Figure 3

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