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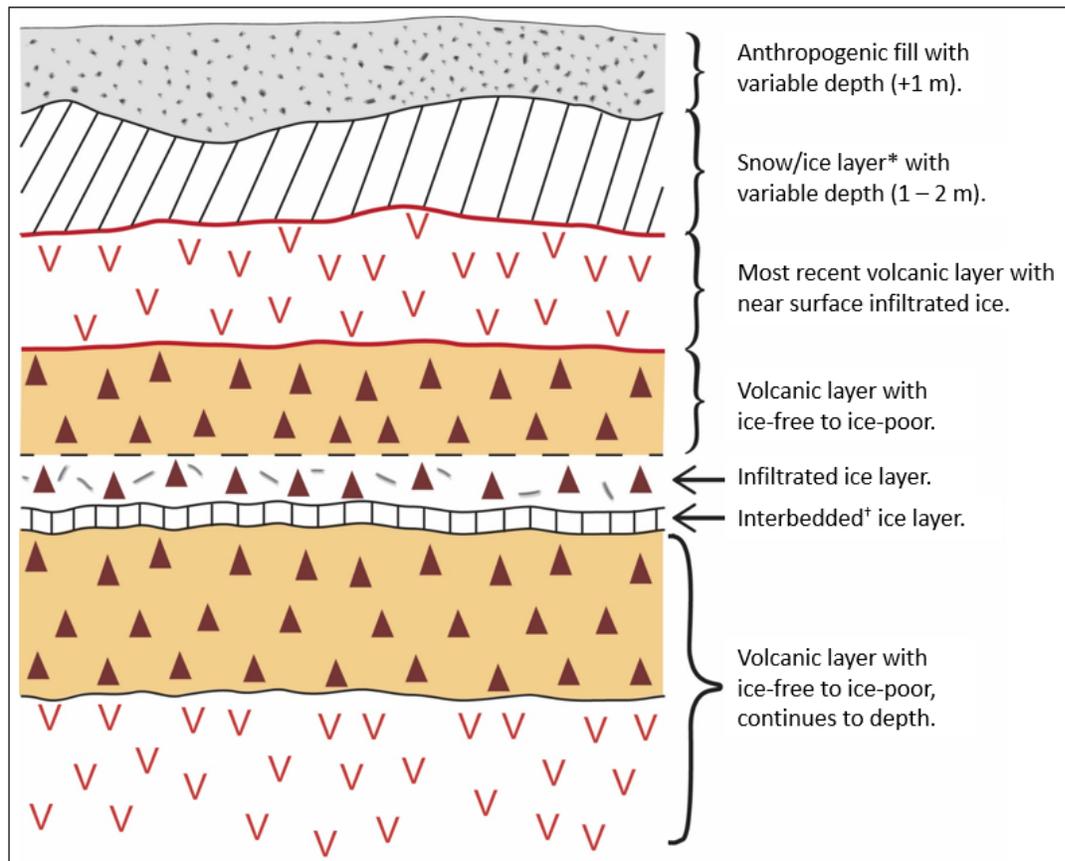


Engineering for Polar Operations, Logistics, and Research (EPOLAR)

Geotechnical and Foundation Review for the McMurdo Master Plan

Kevin Bjella, Rosa T. Affleck, and George Blaisdell

June 2018



* Prior surface snow or ice with varying depth and overlaid with fill.

† Sporadic layer of interbedded ice.

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Geotechnical and Foundation Review for the McMurdo Master Plan

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Abstract

Construction of large buildings is currently part of the major infrastructure development plan at McMurdo Station. Therefore, the overall goal of this study is to provide recommendations for selecting better-suited foundation designs for the new facilities by using existing geotechnical studies recently taken on site. Based on a detailed visual assessment of photos from the geotechnical coring conducted by a third-party consultant, we interpreted the results to indicate that ice-poor to nearly ice-free ground-ice conditions exist nearly everywhere across McMurdo Station and at a depth less than 3 m. This assessment provides foundation design options to prepare for the new development by excavating the near-surface ground-ice interval, replacing with compacted non-frost-susceptible fill material, and constructing shallow foundations with at-grade first-floor design. The benefits of the shallow foundation design include lower construction material needs, increased energy efficiency, optimized drainage and snow/ice accumulation prevention, increased seismic safety, and more appealing architecture for an austere environment.

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Preface

This study was conducted for the National Science Foundation (NSF), Office of Polar Programs (OPP), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-17-19, “McMurdo Master Plan Geotechnical/Foundation Review.” The technical monitor was Ms. Margaret Knuth, program manager, NSF-OPP, U.S. Antarctic Program; she also provided logistical guidance and technical supervision.

The work was performed by the Force Projection and Sustainment Branch (CEERD-RRH) of the Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Harley Cudney was Acting Chief, CEERD-RRH; Mr. J. D. Horne was Chief, CEERD-RR; and Ms. Janet Hardy was the program manager for EPOLAR. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

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COL Bryan S. Green was Commander of ERDC, and Dr. David W. Pittman was the Director.

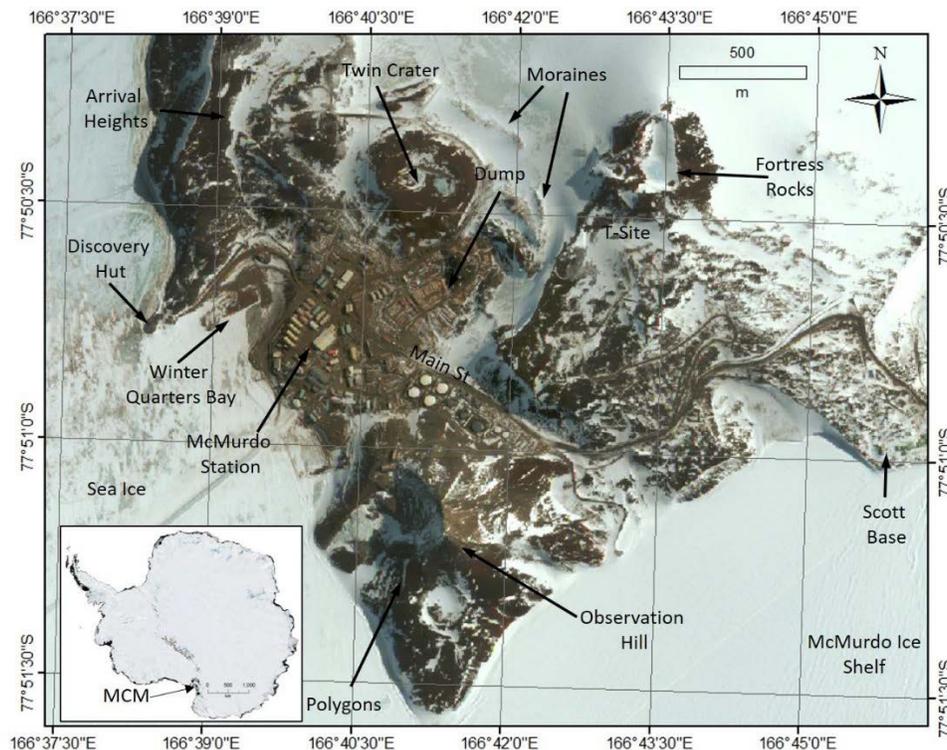
Acronyms and Abbreviations

bp	Before Present
CRREL	Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations and Logistics
ERDC	Engineer Research and Development Center
MCM	McMurdo Station
NSF	National Science Foundation
OPP	Office of Polar Programs
QA/QC	Quality Assurance / Quality Control
RQD	Rock-Quality Designation
UCS	Unconfined Compressive Strength
USAP	U.S. Antarctic Program
VEOC	Vehicle Equipment Operations Center
VMF	Vehicle Maintenance Facility

1 Introduction

The National Science Foundation (NSF), U.S. Antarctic Program (USAP), is planning for major infrastructure replacement and upgrades at McMurdo Station (MCM) (NSF 2015), which is located on a small, perennially glacier-free point of land (Hut Point Peninsula) that is part of Ross Island (Figure 1). To assist with this effort, this paper reviews geotechnical studies conducted at MCM to ascertain the foundation alternatives available for the redevelopment. The terrain in the MCM region consists of perennially frozen ground, or permafrost. The information used in this paper includes results from a U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) study (Affleck et al. 2017) and from two reports by Golder Associates (referred to as “Golder”) (Fenwick and Winkler 2016, Fenwick et al. 2017). There has been little geotechnical information within MCM other than these most recent geotechnical studies, making this review as comprehensive as possible given the available information.

Figure 1. McMurdo Station and surrounding geographic features (Affleck et al. 2017). (The background is from DigitalGlobe, Inc., satellite image WorldView-3 taken from the 6 December 2015 panchromatic band.)



1.1 Background

Permafrost is any earth material that remains at or below freezing for two or more years. All permafrost terrains contain ground ice to some degree, and this ground ice is problematic for engineered structures (Andersland and Ladanyi 1994; Eranti and Lee 2000; Freitag and McFadden 1997; Johnston 1981). Complicating the issue, ground ice is very heterogeneous across the terrain, both in type and extent, often times with the volumetric quantity varying by up to an order of magnitude within meters in the frozen stratum. Thawing of ice-rich permafrost leads to thaw consolidation and differential settlement. In these instances, improper engineering and construction can cause long-term problems that require high maintenance expenditures; and in some cases, the infrastructure fails beyond repair (Bjella 2010; Eranti and Lee 2000; Freitag and McFadden 1997).

1.1.1 Arctic permafrost

The majority of exposed permafrost in the world exists in the Arctic where substantial landmasses are present in latitudes and altitudes that can support annual average temperatures below the freezing point of water. Most of what is understood about permafrost derives from experience and studies in the northern parts of the Northern Hemisphere (Andersland and Ladanyi 1994; Eranti and Lee 2000; Freitag and McFadden 1997; Johnston 1981).

The permafrost of Arctic terrains generally consists of sediment-type materials deposited by rivers, lakes, wind (loess), and slope wash (colluvium). These are very common as surface and near surface materials, and these generally overlie bedrock with the bedrock depth depending on the location. These types of surface materials allow for water infiltration, which then becomes host to matrix ice (pore-space ice), common in Arctic permafrost (Kanevskiy et al. 2008). In the frozen state, these sediment materials often have varying degrees of ice content or moisture values (ranging from near saturation to supersaturation) resulting in a correspondingly high bearing capacity. When thawed, however, especially the fine-grained types, the material becomes oversaturated, with greatly reduced bearing strength. The surface and near surface (depth to 10 m below ground surface) are critical for infrastructure projects as these zones bear the weight of infrastructure yet are most thermally affected by infrastructure placement (Bjella 2014).

Large quantities of intrusive ice are also commonly associated with Arctic permafrost. The wet summers of the Arctic facilitate the development of these features, often referred to as massive ice. These include wedge ice and segregation ice and require surface water or active-layer ground water for creation. Wedge ice features are the result of water infilling and freezing in contraction cracks in the soil, and they can measure meters in width and depth and tens of meters in length (Bjella 2013; Freitag and McFadden 1997). Segregation ice is the result of groundwater attraction to an advancing freezing front. Segregation ice can exist in larger sheets many centimeters in thickness and many meters to tens of meters in lateral extent, but this generally occurs in only very wet environments and where deeper active layers occur.

1.1.2 Antarctic permafrost

Generally, Antarctica resides in a continuous permafrost zone, meaning the climate is cold enough that permafrost exists everywhere at the perennially ice-free margins and to great depths. Early literature described the terrain around MCM (Figure 1) and the surrounding area as having polygonal and sand-wedge features indicative of a typical permafrost landscape (Péwé 1959, 1991; Bockheim 2009). Péwé (1959) suggested that the formation of “polygons and sand wedges is similar to the origin of foliated ice wedges and polygons in the Arctic. Periodic contraction cracks in the perennially frozen ground around McMurdo Sound, cracks produced by the great change in temperature from summer to winter, are gradually filled with clean sand which filters down from above in the spring and summer.” These features are still visible in a few places, including the escarpment on Arrival Heights and Observation Hill (Klein et al. 2008).

Ross Island, to include the MCM area of Hut Point Peninsula and Winter Quarters Bay, was created by successive eruptions of volcanic material from Mt. Erebus, a currently active stratovolcano located on the island, with Strombolian (lava fountain) type eruptions. The volcanic material was flowing over, or falling upon, previous depositions, resulting in stratified layers of solidified rock. According to Mankinen et al. (1988), the eruptions took place from approximately 1.38M to 0.33M years before present (bp), which indicates that the majority of the deposition occurred during the Pleistocene, which is the most recent glacial era, recognized to have occurred from approximately 2.2M to 12K years bp. This has important implications for the understanding of the ground-ice condition of the MCM area.

In the case of MCM permafrost, the terrain is composed of repeating sequences of volcanic flowing materials placed one on top of another, essentially layers of volcanic rock and potentially ice, but not primarily loose sediments. As a mass of volcanic rock layers in either the thawed or frozen state, the material would likely provide greater bearing capacity than a loose sediment. Minor amounts of sediment may have been created at the surface or deposited by warm-season erosion and remobilization, but the extensive frozen environment of the region precludes large-scale depositional events typical of wetter environments. The dry (i.e., low precipitation and relatively short austral summer) Antarctic environment significantly limits the amount of active layer or seasonally thawed surface layer above permafrost in the summer season, restricting summer meltwater available to infiltrate within the near-surface layer. Ground ice does occur in these volcanic strata at MCM but not in the same manner as in the wet Arctic terrains, which has an entirely different cryostructure formation.

A very shallow active layer exists at MCM and is at a maximum depth of 30 cm in the undisturbed ground and 60 cm in the anthropogenic fill (Affleck et al. 2017). The lack of meltwater in the MCM area prevents large-scale development of wedge ice; however, sand wedges can be found on the Arrival Heights area of MCM (Figure 1). These features inherently have little associated massive ice (Péwé 1959, 1991).

Tabular segregation-ice features can be observed in the active-layer soils of MCM at the millimeter to centimeter scale, both in thickness and lateral extent. These mostly occur in the saturated, sandy gravel sediment that can be found around MCM in the summer season and are created by meltwater runoff or other sources. Segregation ice of any scale will generally not be found directly intruded or in voids between the volcanic rocks of the MCM area but may exist as non-conformable ice between volcanic strata.

Another distinctive feature of the terrain around MCM is significant amounts of manually placed material at various locations. Bulldozed volcanic fill material has been pushed and dumped to facilitate construction projects since the station was first constructed in 1958. Fill material refers to processed or harvested materials that are used for pads and construction projects on-site. As Affleck et al. (2017) explain, this fill material may in some cases have been placed on top of existing surface ice and snow (Figure 2). In cross section, this may appear as fill material of silt, sand, and gravel overlying a significant thickness of ice. This ice in turn would

overlie a stable volcanic strata at a much greater depth. This was discovered in a test pit excavated near the hazardous waste yard in 2016 (Affleck et al. 2017). Some of this fill has other material such as metal and wood included. Because of the very sloped terrain of the station area, many benches and terraces have been created to accommodate various infrastructure; therefore, the surface fill materials will have greatly varying depths within close distances, and they possibly can include large amounts of matrix ice, segregation ice, and buried snow and ice.

Figure 2. Examples of near-surface buried massive-ice features found at MCM. *Left*: A snow dump with fill material on top (Site 2 in Fig. 6). *Right*: Massive ice formed from a seasonal meltwater or ephemeral surface flow that pooled and froze in the area (Site 4 in Fig. 6).



1.2 Objectives

The current major infrastructure development plan at McMurdo Station involves construction of large buildings. Therefore, the overall goal of this study is to provide recommendations for selecting better-suited foundation designs for the new facilities by using existing geotechnical studies recently conducted at MCM.

1.3 Approach

To recommend better-suited foundation designs for the new facilities, we needed to provide background information on the distinction between the Arctic and Antarctic permafrost. Given the limited deep-strata geotechnical information, section 2 describes our three cryostructure morphological scenarios to understand how the ground ice was emplaced. In section 3, we discussed the background of engineering and construction characteristics relevant to MCM frozen earth. These included thaw consolidation, potential creep, foundation types, soil characteristics, drainage, and compaction considerations for constructions. In section 4, we assessed

Golder's interpretation of their results for the main boreholes where new buildings are proposed to be constructed (Fenwick and Winkler 2016; Fenwick et al. 2017). Following the same naming convention for boreholes and transect names used in Fenwick and Winkler (2016) and Fenwick et al. (2017), we provided our own assessment by using the photos in the bore logs. We related our hypothesized subsurface models into a summarized assessment (Section 5). Section 6 describes the selection of the foundation options at MCM based on our qualitative assessments of the ground-ice conditions and followed by our recommendations and explanation of our conclusions.

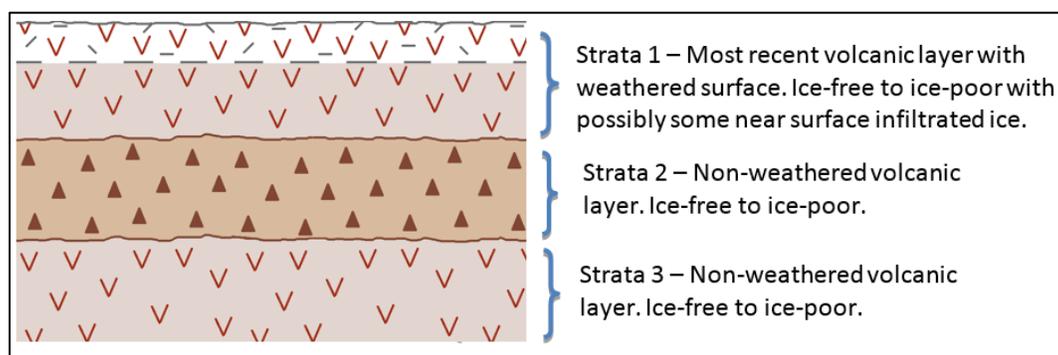
2 Models of McMurdo Permafrost

To distinguish the frozen ground conditions at MCM, we hypothesize three cryostructure morphological models to understand how the naturally occurring ground ice was emplaced; where it was emplaced; and the possible horizontal, lateral, and volumetric extent. These models allow us to determine the ground ice extent outside of the specific locations of the boreholes from Golder data (Fenwick and Winkler 2016; Fenwick et al. 2017) and to understand the potential thaw-settlement risk associated with selecting alternative foundation designs. The models include strata of ice-free, interbedded-ice, and infiltrated-ice conditions. Surface snow and ice that may have been anthropogenically buried is not illustrated in these cryostructure models and can be best envisioned as very near-surface snow and ice with some depth of fill material and possible debris.

2.1 Ice-free strata

The volcanic ejecta (lava, ash, and pyroclastic fall) was deposited in a hot state with little or no associated free water. On cooling and solidification, the ejected materials syngenetically became part of the existing permafrost. Because there was little associated free water in the material, no entrained ice (matrix ice) would have been formed within this newly frozen stratified layer. This existing stratum would be considered as ice-poor to ice-free (Figure 3). The very near surface of this stratum may contain matrix ice due to very shallow summer thawing and infiltration of meltwater.

Figure 3. Graphic illustrating the ice-free to ice-poor stratigraphy.

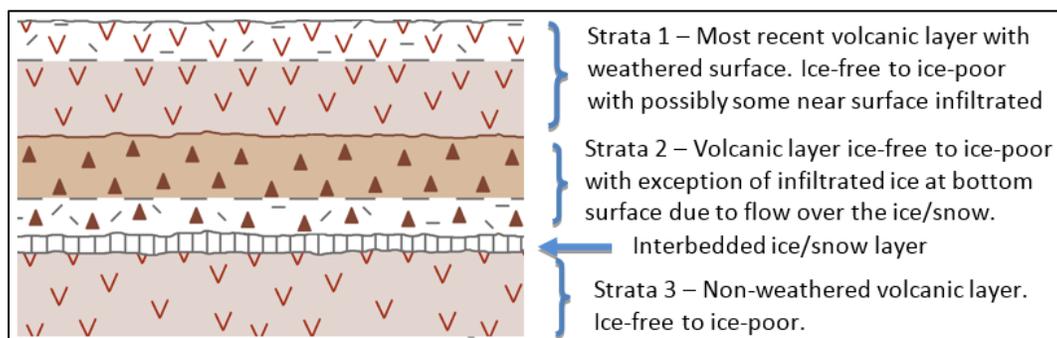


2.2 Interbedded ice

Volcanic flow may have traveled over or fell on ice and snow (Figure 4) that covered a previous volcanic deposition, resulting in an unconformable

contact with the ice and snow, creating irregular sequences of rock and ice. This interbedded ice layer may be centimeters to meters thick and may be 100% ice that overlies the rock strata (strata 3 in Figure 4). The interbedded ice layer would have then been overlaid by the subsequent volcanic deposition with high matrix ice content from the associated ice and snow melting process (i.e., the bottom of strata 2 in Figure 4). It is likely that meltwater may have been drawn from the bottom of strata 2, forming a mixture of a volcanic layer and some amount of infiltrated ice. The top or most recent deposition (strata 1 in Figure 4) would consist of weathered or fractured volcanic material with minimal ice content.

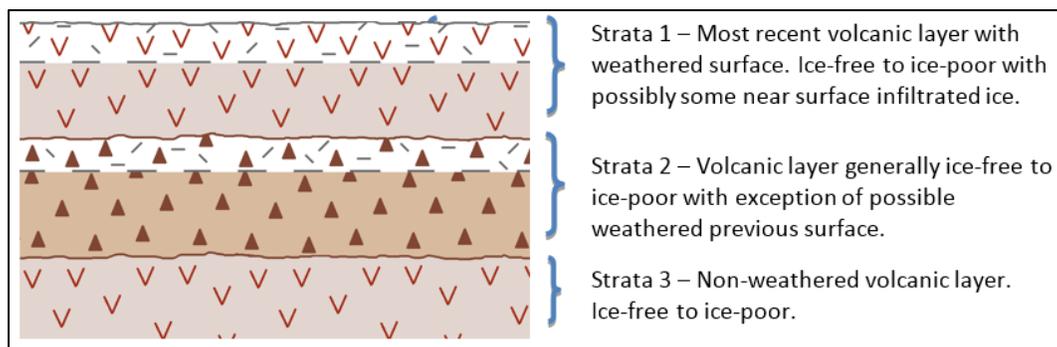
Figure 4. Graphic illustrating the interbedded ice and rock stratigraphy.



2.3 Infiltrated ice

Rock that is at and just below the surface (~10 cm to 20 cm), could be subjected to a brief summer thawing. The meltwater from surface ice and snow could infiltrate the rock through vesicles, voids, fractures, and joints (Figure 5). As the layer becomes buried by successive volcanic flow from additional volcanic events, this infiltrated water is frozen into ice as the rock strata becomes permafrost.

Figure 5. Graphic illustrating infiltrated ice stratigraphy.



3 McMurdo Frozen-Ground Considerations

An important engineering and construction characteristic of frozen earth material is the amount of consolidation that occurs upon thawing, which is primarily dependent on the volume of ground ice present. As previously mentioned, typical permafrost terrains are created by sediments deposited by water, wind, and gravity (slope degradation) in various states of water saturation. The frozen sediment is supported by, and the bearing strength is dependent on, the ice cement either within the available pore spaces (matrix ice) or by segregated ice lenses (intrusive ice). This is then characterized by a frozen volume and an associated bearing capacity. The sediment can also be characterized by a thawed volume and associated bearing capacity where thawing generally greatly decreases the bearing strength. In the simplest terms, the consolidation potential of a soil column is calculated by making measurements of the ground-ice volume and removing that calculated volume from the soil column. This provides an estimate of the changes in bulk volume, which is translated to settlement at the surface. Low ground-ice volume equates to thaw insensitivity, and the material simply exists at below freezing temperatures, and the bearing capacity is essentially the same regardless of whether the soil or rock is frozen or allowed to thaw.

3.1 Thaw consolidation

For competent rock, the behavior for thaw consolidation differs from that of cemented sediment materials, particularly where the minimal ice may exist only in fractures and joints or in the available pore space of the porous rock. In the case of the volcanic strata of the MCM area, we presume an ice-poor scenario where the vesicles, which were formed by escaping gas created in small voids in the hardening rock, are host to the pore ice. On thawing, no change in strength of the rock mass occurs because no significant consolidation or volume change occurs. Based on this, we hypothesize that in a very general case, little to no consolidation occurs when permafrost composed of volcanic rock thaws; and the in situ bearing capacity is retained. This applies for the majority of the subsurface at MCM. We characterize that the majority of the in situ permafrost that is not fill material is thaw insensitive.

A common condition in Arctic permafrost bedrock terrains is the currently or previously exposed bedrock surface that has been subjected to mechanical and chemical weathering, which creates a decomposed layer with potentially significant moisture content (Bjella 2013) from surface meltwater. Consequently, in this condition, the thaw sensitivity is very high. This scenario may have occurred in the MCM volcanic rocks to some limited extent where this decomposed layer may now be buried under the shallow active-layer material at the top of the bedrock. However, we did not see evidence of this in the boring data.

3.2 Ice creep

When ice is present, proper foundation design must also consider the viscoelastic property of ice to creep, and this is a concern when the frozen ground is very ice-rich with high matrix (pore) ice or high amounts of massive ice. Proper engineering for ice creep requires the depth and extent of the ice to be known before design. Assuming that the ice-poor ground conditions of MCM generally exist, creep may not be of a significant concern. If the alternative for the foundations is to maintain the permafrost in the frozen condition, analysis of each load-bearing location should be conducted to determine the possibility of the existence of massive ice and the extent at that particular location. Using the Golder drill data will provide a first look for analyses such as this.

3.3 Foundations on permafrost

In general, permafrost foundations can be classified into one of two modes: foundations designed to keep the permafrost frozen (passive foundation) and foundations that can be adjusted as permafrost thaws (active foundation). The main difficulty encountered with the first mode is the cost associated with structural and cooling enhancements and the long-term design criteria of an increasingly unfavorable climate (Instanes et al. 2005). The main difficulty with the second mode is how to accommodate settlement, particularly if the structure is located on very ice-rich permafrost with good potential for high differential thaw settlement. Accounting for the projected amount of thaw settlement is key to a successful design in this case, and assurance must be high that releveling enhancements and releveling techniques are sound. Structural enhancements must be braced for some differential movement and also meet current dynamic (seismic) loading requirements. However, in general, it is more costly and risky to construct a passive foundation as thermal control must be ensured and as

the required thermal decoupling ultimately can be very costly. The assessment of cost vs. risk varies, however, from project to project; and very remote locations often have quite different criteria to be accounted for.

Two types of refrigeration are generally specified with passive-mode foundations. Passive refrigeration uses no external forcing and generally refers to open air space between the structure and the ground surface or convective ducting between the at-grade floor system and the native soils. Active refrigeration takes advantage of external forcing with or without external energy expenditure, such as mechanical refrigeration systems, thermosiphons (heat pipes), and blowers. Typical construction at MCM is of the passive refrigeration type, where the structures are elevated above the ground surface, providing free airspace between the first floor and the ground surface. Many of these elevated structures consist of imported concrete slabs (footers) placed on the ground surface with attached columns as integral frame components. A few structures have been designed with a limited space below the floor and ground surface, such as Building 155 and the Vehicle Maintenance Facility (VMF), to allow for at-grade entrance of vehicles for maintenance. The warehouses, the firehouse, and maintenance facilities are constructed in a similar fashion; and these have limited air spaces with poor outdoor ambient air circulation.

Although these air spaces are not heated, higher temperatures are surely occurring at the ground surface than for similar buildings with larger space between the first floor and the ground surface, such as the high-rise buildings (i.e., Building 189) and dorms (206 through 209). These elevated structures noticeably have very limited thaw settlement, particularly the buildings with larger space between the first floor and the ground surface, while other buildings are reported with some minor settlement. Apparently, water leaking through the floor systems and pooling onto the ground underneath the building is the cause for foundation issues (L. Barna, email to author, 18 February 2018). For example, excess water from fire truck operations in the firehouse has caused minor settlement. Overtime, the water seeped through the floor cracks, pooling onto the ground underneath these buildings (i.e., firehouse and VMF). In the case of VMF, the intake vents for the passive air system had been capped, not allowing any airflow under the building.

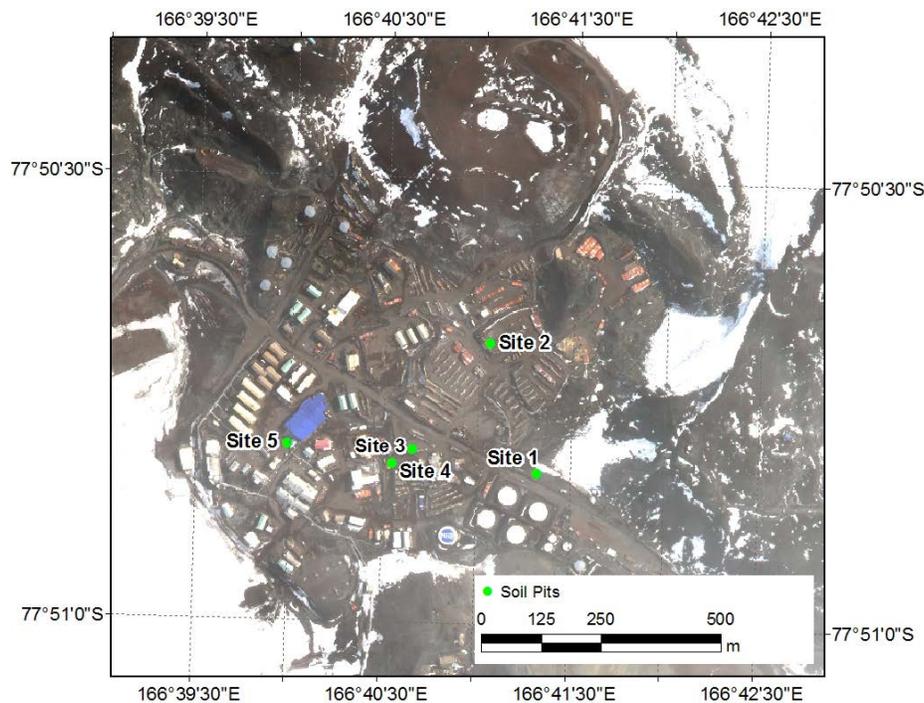
3.4 Soil index

Soil pits were excavated in five locations to characterize the near-soil sub-surface conditions (Figure 6) (Affleck et al. 2017). The pits were dug on 23 and 24 December 2015 and on 11 January 2016 by using a heavy-duty excavator (Caterpillar 336E) with the bucket for digging the materials and ripper and hydraulic hammer attachments for breaking the hard layer. Soils were generally coarse-grained soil, such as gravel and sand fragments. The gradation from ice-cemented samples of gravelly sand earth fragments (i.e., small rocks or gravel sizes less than 300 mm) are generally angular to subangular coarse-grained soil. (Angular means that the grain has sharp, pointed, and jagged corners while subangular grains are jagged but have some rounded corners). As characterized in Unified Soil Classification System types, the soil included

- well-graded gravel and well-graded gravel with silt and sands,
- poorly graded gravel and poorly graded gravel with silt and sands,
- well-graded sands and well-graded sand with silt, and
- poorly graded sands and poorly graded sand with silt.

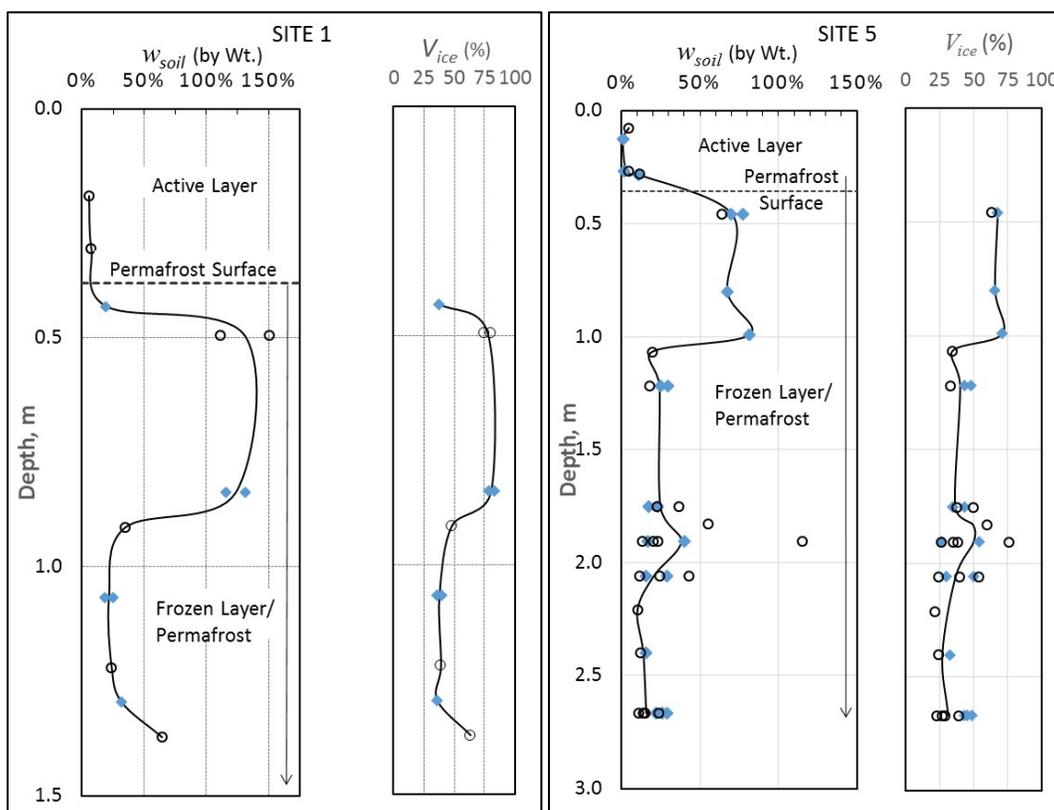
The silt contents were relatively low and ranged between 0% and 16% passing 70 μm (or a 200 sieve).

Figure 6. Map illustrating the locations of the soil pits, identified with *green circles* (Affleck et al. 2017).



The water contents from ice-cemented samples of gravelly sand earth fragments (i.e., small rocks or gravel sizes less than 300 mm) at 0.5–1.0 m deep for Site 1 ranged from 110% to 150% (Figure 8, left chart) and between 64% and 82% at Site 5 (Figure 8, right chart); these indicate significant amounts of excess ice interlayered with soil in the horizon just beneath the active layer. The lower portion of the frozen horizon, however, exhibits lower moisture content than in the upper horizons in the permafrost layer. The total volumetric ice content (V_{ice}) for Site 1 below a 1 m depth ranged from 36% to 83% while the variations at Site 5 ranged between 21% and 75% (Figure 8). Therefore, the ice accumulation and natural rock material deposition in the near surface range from ice-poor to ice-rich conditions. For more information about the soil indices of the near surface from the soil pits on site, see Affleck et al. (2017).

Figure 8. Soil moisture and ice profile of the natural (undisturbed) fill.



The soil pit at Site 5 is in the vicinity of borehole B-13 (Fenwick and Winkler 2016) (Figure 9); the characterization of ice features and soil described by Affleck et al. (2017) correlates the description in Golder's borehole, B-13. The interpretation by Golder (Fenwick and Winkler 2016) indicated that ice content is approximately between 60% and 70% from 0.5 m

to 2.1 m below the ground surface. The quantitative volumetric ice content (V_{ice}) for Site 5 showed a maximum of 76% (Figure 8, right graph) and a maximum saturation of 130% (Affleck et al. 2017). Also, hydrocarbons were observed at this location when samples were taken at 2.70 m below the ground surface.

Figure 9. Photographs of the reddish fill on the top and gray fractured rock with ice lenses at Site 5 (*left*) and cores from B-13 (*right*) (Fenwick and Winkler 2016).



3.5 Drainage

For foundations and supporting infrastructure in low-lying areas, ice can form from the freezing of successive flows of water over the top of previously formed ice (Affleck et al. 2012, 2014). Also, the freezing of surface snowmelt water around footings can cause shifting of the foundation due to expansion as the ice forms. Problematic ice buildup is common in passive-refrigeration-type foundations underneath the buildings when the terrain slopes toward and underneath the buildings, such as at the Crary Lab, power plant, and water plant buildings. This is more problematic if the area surrounding the buildings is restricted with utilities and tight spaces, creating ice buildup near the buildings and limiting snowmelt drainage (i.e., positive drainage), which are common at MCM. Positive drainage allows snowmelt to flow away from the buildings. Therefore, designs should ensure that the layout and grading of the ground around the buildings prevent the collection and ponding of meltwater and ice buildup around the building footings and foundations.

Erosion is a critical issue for loosely compacted soils and aggregates (Rollings and Rollings 1996), particularly when soil fines are eroded by water

flow, creating voids and undermining the soil structure. Similarly, excess snowmelt will potentially degrade the permafrost through thermoerosion, especially with extended and warm summers. At MCM, excess snowmelt in the summer months has created soil erosion on the permeable thawed layer, forming ephemeral rills or gullies due to soil-particle displacement on slope pads (Affleck et al. 2012, 2014). The permeability of the gravelly sand samples from MCM ranged from 0.07 to 0.11 cm per second (Affleck et al. 2012). With these permeability values, the soil is classified as a good drainage material for sandy gravel soil (Holtz and Kovacs 1981). Thus, drainage control is critical as snowmelt can potentially alter the thermal regime and affect any foundation structures. Appropriate design of the overall surface snowmelt management is recommended to ensure proper drainage. Most importantly, design and landscaping should incorporate positive surface gradients that drain snowmelt away from any engineered structures (i.e., foundations and structural walls).

3.6 Compaction

Depending on the foundation alternative chosen, building engineered structures potentially requires excavation of ice-rich soil; and soil will be replaced with non-frost-susceptible and ice-free fill materials. Fill material with high ice content is not advisable to use in practice because proper compaction of ice-rich soil is difficult to achieve (Andersland and Ladanyi 2013). However, if ice-rich soil were excavated and thawed, soils with the proper soil distribution could be satisfactorily compacted at near-freezing temperatures in the summer months. Considering that the summer season at MCM is very brief, it is likely that earthwork and construction may need to be performed with precaution in subfreezing temperatures. The frozen density of compacted materials should be equal to the required maximum unfrozen density with specific moisture content. Because the summer season is short, earthwork at MCM has previously been completed successfully in the winter months under freezing temperatures. For example, the compaction of fill materials for the construction of the wind turbine foundations at the T-site commenced under freezing temperatures of -18°C and -20°C and attained thorough quality assurance and quality control (Oswell et al. 2010). Thus, compacting soils in freezing conditions must be balanced with other design requirements.

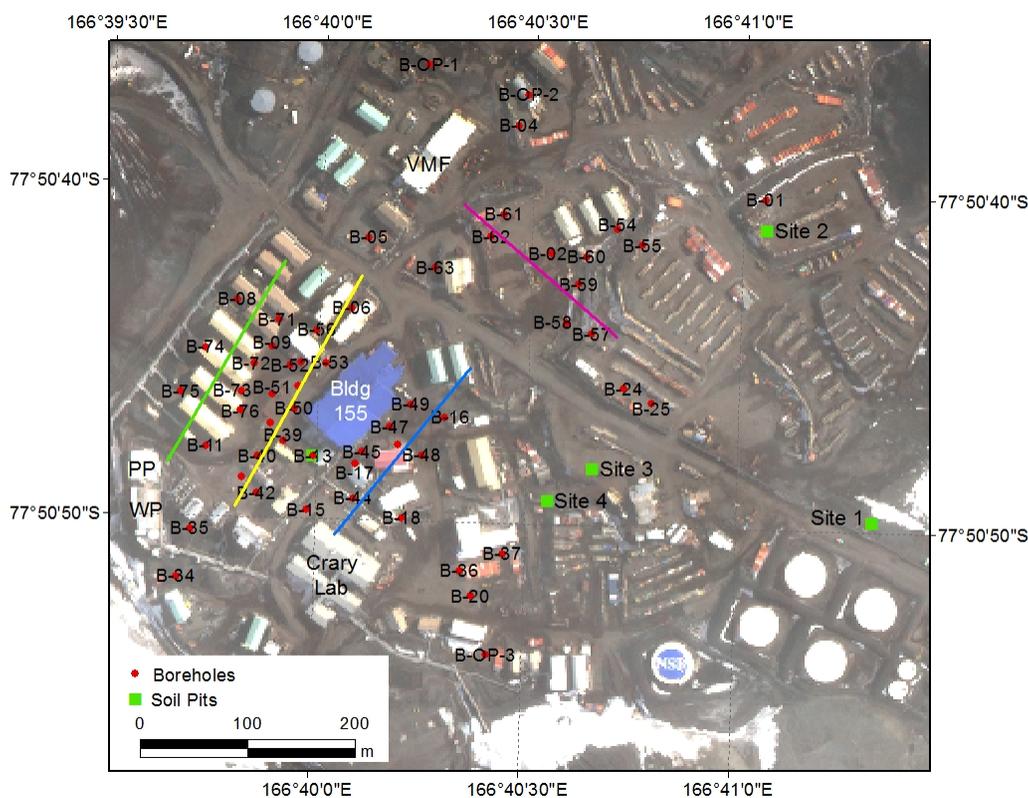
4 Coring Assessment

Golder's Phase I (Fenwick and Winkler 2016) and Phase II (Fenwick et al. 2017) geotechnical investigation produced core samples for examination, and the drilling was conducted with chilled air to maintain frozen cores during the process. Figure 10 provides a map of the borehole locations. The objectives of Golder's coring were to create a comprehensive understanding of the ground conditions beneath the proposed structures and to have better information about the ice distribution of site. Cores were logged as each was pulled from the hole, providing qualitative information on the ice condition at that particular location. The cores were not permitted to experience any thawing once at the surface, and photos of the cores depict the actual condition as the core was retrieved from the core barrel. Any significant ice encountered during drilling would have been shown within the core run; therefore, breaks in the core integrity are not interpreted to be an indicator that ice existed at those locations. Overall, the Rock-Quality Designation (RQD) as reported in the bore logs was high (>75%), especially for the basalt layer. The RQD is an estimate of the degree of fracture in a rock mass; a high-quality rock has an RQD of more than 75% where low quality rocks would have less than 50% RQD. Golder conducted unconfined compressive strength (UCS) tests on selected basalt and scoria to understand overall rock strength with results between 40 MPa and 80 MPa (Fenwick and Winkler 2016; Fenwick et al. 2017); however, their report excluded mention of whether the UCS tests were conducted on frozen or thawed samples.

During the Phase I drilling (Fenwick and Winkler 2016), 27 boreholes were drilled over the entire MCM master plan area with 24 of the boreholes drilled to a 3 m depth. These depths are considered relatively shallow in the context of a permafrost geotechnical investigation when considering that a heated vertical infrastructure can have a thermal influence to a 15 m depth or greater. During the Phase II drilling, an additional 47 boreholes were drilled (Figure 10), greatly increasing the borehole density per proposed structure footprint and correspondingly increasing the knowledge of volcanic deposition and the ground-ice situation. In Golder's Phase II report (Fenwick et al. 2017), two-dimensional cross-section fence diagrams were constructed to connect lines of boreholes, illustrating the general nature of the conditions under each proposed major structure.

In the following discussion, we first present the previously logged Golder information (Fenwick and Winkler 2016; Fenwick et al. 2017) and their interpretation of the results. We followed the same naming convention for boreholes and transect names used in Fenwick and Winkler (2016) and Fenwick et al. (2017). We then follow up with our notations and recommendations and explanation of our conclusions.

Figure 10. Map of boreholes from Fenwick et al. (2017). The *green, yellow, blue, and magenta lines* are projected transects of the proposed buildings for lodging, western core facility, eastern core facility, and Vehicle Equipment Operations Center, respectively.

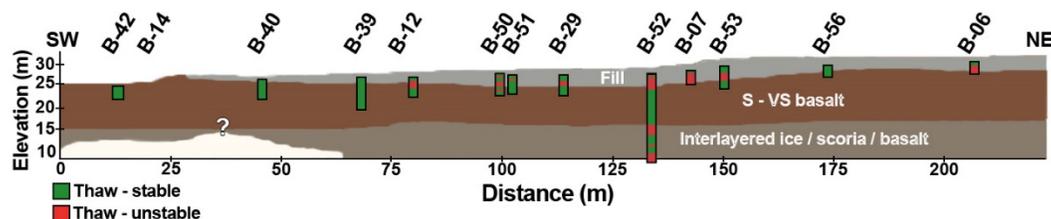


4.1 Western core facility

The cores extracted along the western transect consisted of 13 boreholes, starting with borehole number B-42 to the southwest and ending at borehole number B-06 to the northeast (identified as a yellow line in Figure 10). This transect is plotted in two dimensions in Figure 11. The stratigraphy contains an unstable fill layer (gravel, snow, and ice) with the greatest thickness at B-53 at 3.7 m; and this overlies a strong to very strong stable basalt layer of relatively continuous thickness and a maximum depth of 11 m. This basalt layer overlies interlayered scoria and basalt, which ex-

tends to an unknown depth. Boreholes B-14 and B-52 depict unstable conditions below the unstable fill zone. A more detailed description of the site is available in the June 2017 Golder report (Fenwick et al. 2017).

Figure 11. Two-dimensional geological cross section of the western core facility.



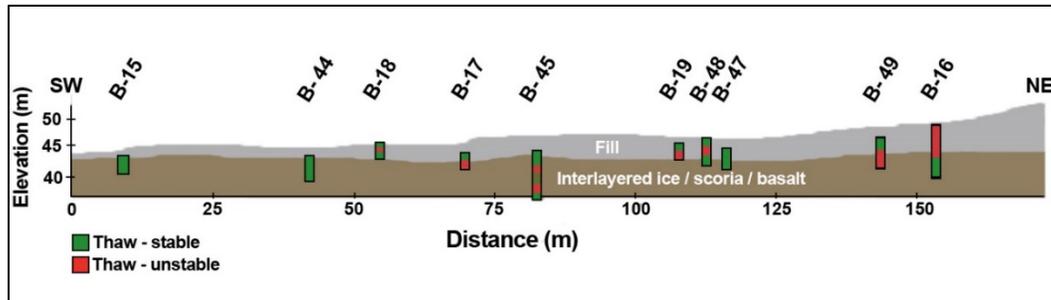
- Golder Phase II interpretation in Fenwick et al. (2017)—“The stratigraphy at this location comprises potentially thaw-unstable fill and ice overlying strong to very strong basalt. Given the thick accumulation of ice/buried snow and fill encountered in this area, remedial ground works (i.e., removal of fill) will likely be required for this area and foundations should extend to the thaw-stable basalt.”
- Our interpretation—We concur with the removal of the entire unstable fill thickness, the depth depending on the final foundation selection. Our analysis did not find ice of any major significance, indicating this will provide adequate founding strata. Specifically in B-52, the only test hole drilled into the lower scoria/basalt strata, we do not agree with the interpretation of the lower scoria/basalt strata as unstable. In this test boring, we found no indication of unstable quantities of matrix ice or intrusive ice.

4.2 Eastern core facility

The cores extracted along the eastern transect consisted of 10 boreholes starting at B-15 to the southwest and ending at B-16 to the northeast (identified as a blue line in Figure 10). Figure 12 plots this in two dimensions. The stratigraphy consists of an unstable fill layer (gravel, snow, ice, and landfill material) with a thickness of 3 m to 4.2 m. The strong to very strong basalt layer below the fill layer is inferred to be deeper at this side of the core facility location. The fill layer is depicted to overlie the interlayered scoria and basalt, which extend to an unknown depth and are depicted as unstable. Boreholes B-17, B-45, B-49, and B-16 depict unstable conditions in the geological cross section. B-16 contains fill and ice lenses

to a maximum depth of 5.7 m. A more detailed description of the site is available in the June 2017 Golder report (Fenwick et al. 2017).

Figure 12. Two-dimensional geological cross section of the eastern core facility.



- Golder Phase II interpretation in Fenwick et al. (2017)—“As with the western part of the core facility the thick accumulation of ice/buried snow and fill encountered in the area should be removed; however, the native ground cannot be relied on to be thaw-stable or be laterally consistent; therefore, consideration will need to be made to maintaining a constant temperature at subgrade level.”
- Our interpretation—We concur on the fill zone instability. Removal of the entire fill thickness may be required, depending on the foundation selection. However, we do not agree with assessment of absolute unstable material at depth. The following are detailed observations of the previously logged thaw-unstable materials noted below the fill zone:
 - B-17—We note ice-rich conditions with intervals of interbedded ice and clear ice down to a 2.2 m depth.
 - B-45—We note no visible indications of ice.
 - B-49—We note segregation ice and approximately 2.0 cm of clear interbedded ice down to a depth of 2.0 m; beyond that depth, there is no visible matrix or intrusive ice (Figure 13).
 - B-16—We note interbedded ice, 1.0 cm to 2.0 cm in thickness, at 3.2 m, 4.4 m, and 4.7 m depths.
 - The quantities of ice mentioned previously will not be detrimental to the structure if allowed to thaw, provided proper provisions are incorporated. No evidence exists to suggest that great quantities of ice, interbedded or otherwise, exist at this site.

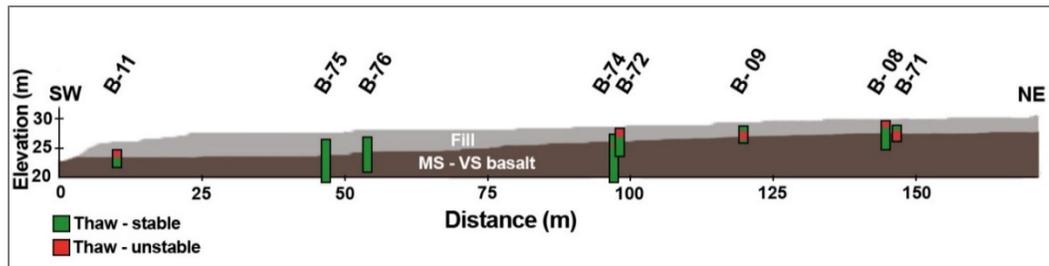
Figure 13. Core B-49 at the interval 3.0 m to 6.0 m. Competent and intact rock is shown in this photo with relatively ice-free conditions. Minor amounts of infiltration ice are noted at 5.3 m; however, this is not significant for thaw settlement. The bore log for this hole noted unstable conditions from 2.7 m to 6.0 m and also noted this interval as “strong.”



4.3 Lodging

This collection of eight boreholes starts at borehole B-11 to the southwest and ends at borehole B-71 to the northeast (identified as a green line in Figure 10). These cores are plotted in two dimensions in Figure 14. The stratigraphy consists of an unstable fill layer (gravel, snow, ice, and landfill material of wire and wood) with a thickness of 2.85 m to 3.6 m to the west of the current lodging structures and to a depth of 0.9 m and 1.6 m to the east of the current lodging structures. These thicknesses depict a fill section that is thicker to the west, created to level the site due to a westerly slope leading down to Winter Quarters Bay. The strong to very strong basalt layer below the fill layer is inferred to be deeper at this side of the core facility location. A more detailed description of the site is available in the June 2017 Golder report (Fenwick et al. 2017).

Figure 14. Two-dimensional geological cross section of the lodging area.



- Golder Phase II interpretation in Fenwick et al. (2017)—“As with the Western Core Facility the thick accumulation of ice/buried snow and fill encountered in the area should be removed and foundations should extend into the weak, thaw-stable, moderately weather basalt described above.”
- Our interpretation—We note the ice in B-11, B-72, B-09, and B-71 is primarily located in the unstable fill zone, consistent with the icy fill zone discovered at borehole B-16. We concur that these fill zones are unstable layers and that removing the entire fill thickness may be required, depending on the foundation selection. We also agree with the assessment that thaw-stable basalt exists at deeper depths. We do not see excess ice in these cores below the fill zone, primarily logged to be in the unstable fill zone. We infer that the stratum below the fill zone is very competent rock with no indications of unstable ice quantities.

4.4 Boreholes B-34 and B-35

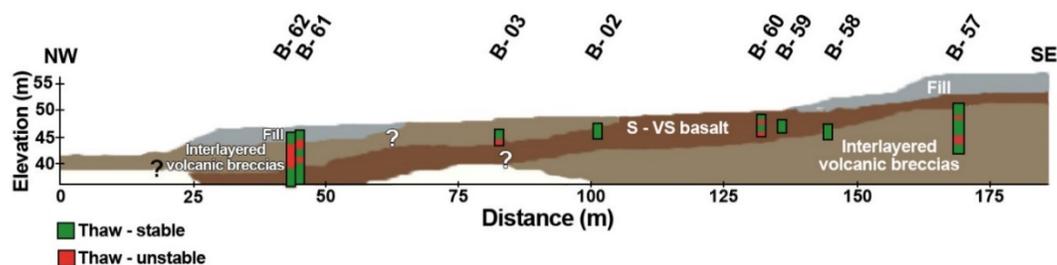
Two boreholes, B-34 and B-35 (Figure 10), were drilled to ascertain the conditions for the proposed utility corridor. Other than a thin layer of fill and weathered rock found at depths of 0.45 m and 0.65 m, strong basalt existed to the bottom of the holes at 5.0 m and 4.5 m, respectively.

- Golder Phase II interpretation in Fenwick et al. (2017)—“Both of these boreholes encountered a thin layer of fill and weathered rock underlain by strong to very strong basalt at 0.45 m and 0.65 m. The basalt was encountered through full depth of the investigations to 5.0 m and 4.5 m, respectively, for B-34 and B-35.”
- Our interpretation—We concur with Golder’s translation. We note that this location is relatively ice-free and will be suitable for nearly any type of structure. The thin section of unstable surface materials must be removed.

4.5 Vehicle Equipment Operations Center (VEOC)

The cores extracted along the VEOC transect consisted of 10 boreholes that begin with B-62 to the northwest and end with B-55 to the southeast (identified as a magenta line in Figure 10). Figure 15 plots it in two dimensions.

Figure 15. Two-dimensional geological cross section of the VEOC.



- Golder Phase II interpretation in Fenwick et al. (2017)—“Similar to the eastern core facility the thick accumulation of the ice/buried snow and fill encountered in this area should be removed; however, the native ground cannot be relied on to be thaw-stable or be laterally consistent; therefore, consideration will need to be made to maintaining a constant frozen temperature at subgrade level, as discussed in Section 7.4. The continuous basalt layer can be relied upon for bearing the foundations provided current temperature is maintained.”
- Our interpretation—Very competent basalt rock conditions exist just below the predominantly moderately stable fill zone. The mapped strata below the basalt is predominantly stable, with little excess ice exhibited in most of the boreholes. The lower section of B-55 exhibits excess ice from 5.6 m to 10.0 m; however, the thaw stability is unknown due to the lack of lab testing. The following are detailed observations of the previously logged thaw-unstable materials noted below the fill zone:
 - B-62—We note interbedded ice at 1.7 m to 1.8 m and at 2.0 m. We noted infiltration ice at 3.5 m where the red scoria changes to gray strata, and infiltration ice is noted from 6.7 m to 6.9 m. We identified these adjacent rock as thaw-stable zones.
 - B-61—In general, unstable conditions were logged by Golder from the surface down to 3.5 m. We note large portions of poor core recovery in this interval, with 2.0 cm thick visible ice at 2.25 m and weak but intact rock conditions down to 3.0 m. We note strong, ice-

- poor intact rock conditions exist to the bottom of the hole, with a 2.0 cm thickness interbedded ice layer identified at 8.7 m.
- B-60—In general, Golder logged unstable conditions from the surface down to 3.6 m with two short intervals of stable conditions, also with corresponding strong rock strength. We did not identify unstable ice conditions in the interval from 0.6 m to 1.7 m. We noted interbedded and very minor matrix ice in the interval from 2.3 m to 3.7 m. We note that this ice is not in unstable quantities; however, Golder logged this as unstable. Overall, Golder logged the rock as intact and moderately strong in this interval.
 - B-58—In general, Golder logged conditions as strong from 0.5 m down to the bottom of the hole at 3 m. We noted 2.0 cm thick interbedded ice at 0.6 m, 0.75 m, 1 m, and again at 1.4 m. We also note the vesicles are ice-free through this interval. We noted that these fracture/joint are bounded with ice. At 2.0 m down to 3 m, the core becomes very intact and competent and is logged by Golder as massive, nearly ice-free basalt.
 - B-57—In general, moderately stable fill material conditions were logged from the surface down to 1.9 m, and we concur with this assessment. This cemented coarse-grained sediment material does not appear to have excess matrix or intrusive ice. We noted interbedded and infiltration ice starting at 2.2 m and extending to 2.3 m. Golder logged stable, ice-free conditions, with moderately strong to strong rock conditions from 3.0 m to 6.0 m. Golder logged unstable conditions from 6.0 m to 7.0 m; and we do not concur with this conclusion, noting no matrix or intrusive ice in this layer with the exception of 2.0 cm thick clear ice at 7.4 m. We noted that the core is nearly 100% intact from 7.1 m to the bottom of the hole.

4.6 Boreholes B-20, B36 and B-37

Three boreholes, B-20, B-36, and B-37, were drilled in this area west of Crary Lab (Figure 10) to investigate for a proposed addition to the existing structure. The unstable fill section exists to depths of 1.65 m and 3.5 m.

- Golder Phase II interpretation in Fenwick et al. (2017)—“These boreholes contained fill to depths of 1.65 m and 3.5 m overlying strong to very strong basalt to a maximum depth of 10.0 m.”
- Our interpretation—In B-20, we noted 10.0 cm of interbedded ice at 2.8 m with intact rock to the bottom of the hole at 3.0 m. In B-36 and B-37, below the moderate to stable fill near the surface, we noted ice-

poor to ice-free conditions extending to the bottom of the holes at 10.0 m and 5.6 m, respectively.

4.7 Boreholes B-01, B-04, B-OP-1, and B-OP-2

A borehole, B-01, was drilled to investigate a proposed location for two water tanks. This borehole encountered ice nearly the entire thickness, down to 3.6 m. This area will require the ice to be removed if heated infrastructure is to be placed here.

Borehole B-04 was generally ice-free; however, very poor RQD was encountered on this core run with nearly the entire core composed of gravel-sized scoria. B-OP-1 and B-OP-2, however, consisted of ice-free or ice-poor intact rock to the bottom of the hole at 9.0 m and 4.0 m, respectively.

- Golder Phase II interpretation in Fenwick et al. (2017)—“The borehole at B-01 comprised ice for full depth.” They indicated that removal of thick ice accumulations and replacement with compacted granular aggregate are required if buildings are placed at this location. “The boreholes at B-04 comprised dry unbounded gravel (scoria) for the full depth of the borehole.” Strong basalts were encountered at B-OP-1 and B-OP-2.
- Our interpretation—We concur with the following:
 - The area where B-01 is located will require the ice to be removed if heated infrastructure is to be placed at this location.
 - The general location of boreholes B-04, B-OP-1, and B-OP-2 has favorable conditions for conventional construction. Removal of surface materials to a depth of competent rock will provide the limited provision needed for potential thaw settlement.

4.8 Borehole B-05

One borehole, B-05, consisted of interbedded and infiltrated ice, generally from the surface to the bottom of the hole at 3.0 m. Ice can be seen in all the vesicles and void spaces. It is unknown if thawing of the ice in this rock matrix will result in thaw settlement.

- Golder Phase II interpretation in Fenwick et al. (2017)—“The upper 0.7 m of the borehole comprises of well bonded fill underlain by vesicular basalt fragments in an ice matrix to the final borehole depth of 3.0 m below ground level.”
- Our interpretation—Ground ice exists nearly entirely through B-05. Unheated infrastructure can be placed at this location, or passive refrigeration can be used to prevent heat conduction to the underlying soils. Thermally coupled infrastructure contemplated for this area will require further investigation to determine thaw-consolidation potential and the depth to ice-free rock strata.

4.9 Boreholes B-24 and B-25

In B-24, interbedded and infiltration ice exists from the ground surface down to approximately 1.5 m; and ice is visible in the vesicles and void spaces of the volcanic rock. At 1.5 m, the core becomes more intact, and the vesicles are not filled with ice down to the bottom of the hole at 3.0 m. In B-25, unstable fill material is evident from the surface down to approximately 2.0 m. Interbedded ice begins at 1.2 m in multiple layers, becoming more consistent ice at 1.4 m and down to 2.0 m. The rock is more intact with no visible ice down to the bottom of the hole at 3.0 m.

- Golder Phase II interpretation in Fenwick et al. (2017)—“Bedrock was encountered in B-24 and B-25 at 1.0 m and 2.8 m below ground level with fill and ice above it.”
- Our interpretation—Unstable fill and surface material exists to 1.5 m and 2.0 m. Removal of the entire fill thickness may be required, depending on the foundation selected. Below this depth, intact competent and ice-poor to ice-free rock exists.

5 Discussion and Summary

Ice content and potential thaw settlement of permafrost must be evaluated before designing foundations of any type of structure (Andersland and Ladanyi 1994; Eranti and Lee 2000; Freitag and McFadden 1997; Johnston 1981). Ice content is determined by thawing a frozen soil/rock sample in an oven, and the moisture (ice) content is calculated by weight. Thaw settlement is determined by conducting thaw-consolidation tests (stress vs. strain) where a constant stress is imparted on a frozen sample, which is allowed to thaw; and the amount of strain is measured over time. Thaw settlement information is crucial in determining which foundation mode (passive or active) and type (shallow or deep) will be used. In the case of moderate to severe thaw-settlement potential (a frozen ground that is thaw sensitive), designs must incorporate structural provisions to prevent damage and to provide for releveling as required. Ice-content information determines ice creep potential when the ground is maintained in the frozen condition (passive mode).

As mentioned previously, when the coring samples are strong, intact rock, as is the case with most of the volcanic basalt and scoria of the MCM area, the predominant ice occupies vesicles, joints, and fractures, and is not separating individual soil particles as would be the case with a frozen sediment. On thawing, little volumetric change may occur to the rock with limited potential settlement. This scenario would predicate an active foundation mode with good potential for a shallow foundation type and slab-on-grade floor systems. This interpretation does not apply to areas with ice-rich fill material or where the fill material overlies snow and ice that was previously at the surface prior to the fill event.

Golder's interpretation included percentages of ice within the cores and sometimes also the type of ice. However, this was conducted in the manner typical for descriptions for frozen sediments, which, as mentioned previously, upon thawing a frozen sediment disaggregates and is destabilized by losing its ice cement and increasing the water content in the pore spaces. In the case of a sediment, reporting overall ice content for a core interval provides valuable information to understand how the interval will behave and how much settlement will occur due to volume loss because, as a sediment, the entire interval loses structure upon thawing. This is not the case with competent, intact rock where reporting overall ice content for a core interval, ice that resides in vesicles, joints, and fractures, only reports how

much water will be generated upon thawing as no disaggregation and no change in structure will occur. Therefore, reporting of ice percentages and relating this to the overall stability of the intact rock core interval are not relevant. Based on this ambiguous usage of ice content, the bore logs report a determination if a particular section or unit of the core is thaw-stable or thaw unstable. Bore log nomenclature in the Golder report (Fenwick et al. 2017) was defined as follows:

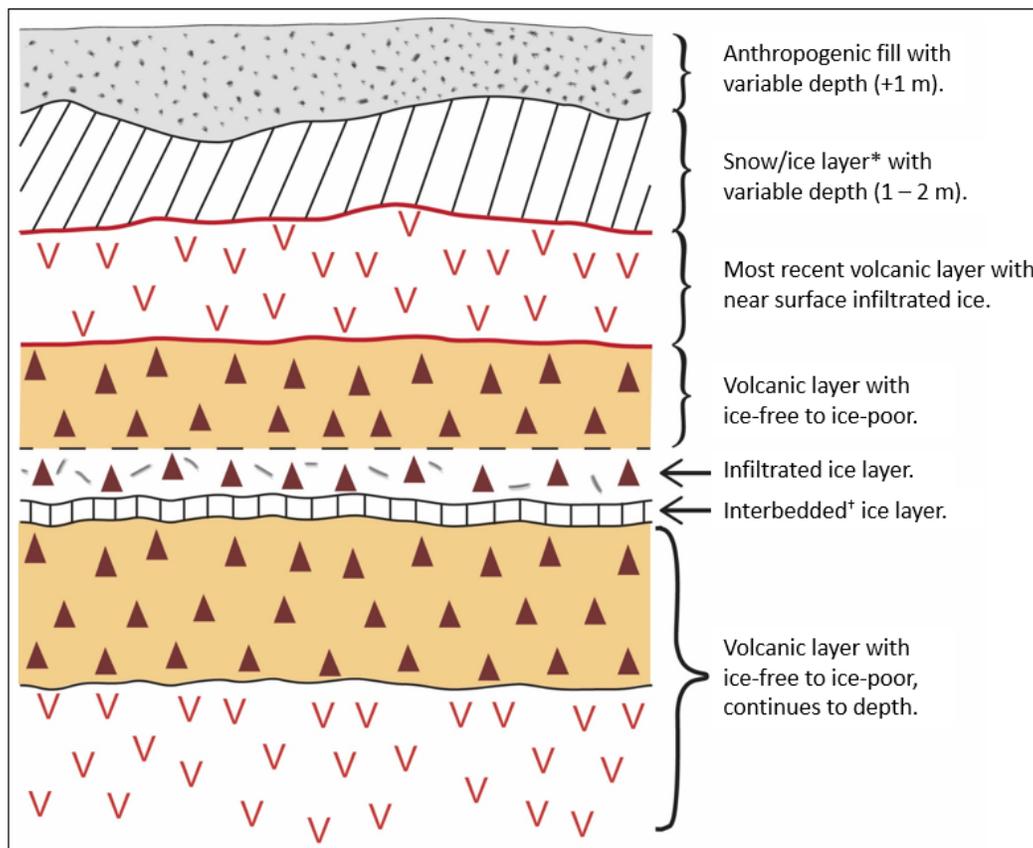
- *Thaw-Stable*—Frozen soils do not on thawing show loss of strength below normal, long-time thawed values nor produce detrimental settlement.
- *Thaw-Unstable*—Frozen soils show on thawing significant loss of strength below normal, long-time thawed values and/or significant settlement as a direct result of the melting of the excess ice in the soil.

These definitions as noted in the bore logs appear to provide the requisite evaluative indices to determine foundation mode and type. However, the lack of quantitative geotechnical data (or laboratory testing) from the core samples to properly describe and to accurately qualify these definitions for intact rock is inaccurate. For example, we noticed that where excess ice (clear ice) existed in the core run, generally at the centimeter thickness scale, a thaw-unstable assessment was generally logged in the boring logs; and we believe this is appropriate for that small interval of clear ice. However, we also noted that often a thaw-unstable assessment extended much beyond the obvious icy sections by many tens of centimeters; and it was seldom obvious how these longer sections were determined to be thaw unstable. The cores in these areas were most often devoid of any visible ice, either in the matrix or as infiltrated ice.

After we conducted our careful visual analysis on all of the core runs, we compared our analysis to the descriptions in the bore logs and also related each core run to nearby core runs for continuity determination. It is our opinion that the overall thaw instability described in Golder's report was drastically overestimated in nearly every borehole. In many cases where a determination was made in Golder's report that a particular zone or core interval was thaw unstable, our interpretation of the ice content and the consequences was directly opposite that indicated.

Based on our hypothesized subsurface models described in section 2, Figure 16 represents the generalized cross section of the three cryostructure.

Figure 16. General representation of the anthropogenic and geological cross section.



* Prior surface snow or ice with varying depth and overlaid with fill.

† Sporadic layer of interbedded ice.

Our assessment is summarized as follows:

- Ice-rich, unstable surface and fill materials to a 3 m depth—
 - Approximately 93% of the boreholes have ice-rich conditions existing within 3 m of the surface. The ice types consisted of interbedded, matrix, and infiltrated. The material in this zone primarily consisted of either fill or naturally occurring surface sediments and is often accompanied by moderate thicknesses (>2 cm) to very thick clear ice and sometimes building debris. The rock in this interval most often was 25% or lower in RQD values with accompanying poor core recovery.
 - An unstable fill layer of gravel, snow, and ice found near the surface and measured from the soil pits contained volumetric ice content between 21% and 83%. The profile of the naturally placed, ice-cemented layer contains a coarse-stratified material, which is composed of a conglomeration of fractured basaltic boulders, rocks,

gravelly sand, and ice. In other soil pits, ice deposits of either naturally or man-made formation exist.

- Interbedded and infiltrated ice—sporadic interbedded and infiltrated ice occurred at depths greater than 3.0 m but only in 11% of the boreholes drilled deeper than 3 m. In nearly all cases, these ice layers were no greater than 2 cm in thickness and were never correlated to a nearby drill hole, suggesting these icy layers are localized to less than tens of meters.
- Volcanic layer, ice-poor to ice-free strata with stable intact and strong rock below a 3 m depth—
 - An estimated 97% of the boreholes have moderate to very strong, intact, and stable (ice-poor to ice-free) volcanic rock encountered at depths greater than 3 m. The RQD for this interval generally was logged at 50% or greater and had good core recovery. In some of the holes, intact and stable rock was much shallower than 3 m; however, one borehole, B-55 at the VEOC, had ice down to 10 m.
 - Generally speaking, ice-poor to ice-free, intact, strong, and stable conditions will be encountered at depths greater than 3 m across the station.

6 Foundation Selections

We reviewed and selected foundation options for MCM based on our qualitative assessments of the ground-ice conditions by conducting a visual analysis of high-resolution core photos from Golder reports. The following subsections discuss the three most appropriate foundation options based on ground conditions, general geotechnical considerations, and integrating energy and maintenance efficiency requirements.

6.1 Option 1—Over-excavation

Because competent ice-poor or ice-free bedrock exists at a relatively shallow depth below ice-rich fill and sediments, an extremely viable method is to over-excavate these ice-rich soils down to the bedrock and to replace them with compacted ice-free granular fill. The site would be backfilled to the appropriate elevation, allowing for slab-on-grade floor systems to be installed without fear of thaw degradation. This option provides high protection against the uncertainty of climate change as the structure site will be prepared with ice-free conditions for long-term structural integrity. This option provides the ability to construct a conventional floor system, keeping the structure at grade level and preventing snow drifting and icing under the structure. Additionally, it provides the most efficient energy design and allows for buried water and sewer connections. An at-grade structure such as this is the most seismically robust design of all the alternatives and will be sufficient for all structures and uses.

At MCM, most of the excavations of ice-cemented materials have been accomplished using a heavy-duty excavator (Caterpillar 336E) with the bucket for digging the materials and ripper and hydraulic hammer attachments for breaking the hardest layers (Figure 17). An additional heavy excavator (>30 ton) equipped with a ripper shank and frost tooth (Figure 18) is potentially needed given the extent of the site excavation and earthwork. An on-site quality-control expert will be required to ensure that ice-rich, thaw-unstable material has been removed, competent ice-poor to ice-free rock is exposed, and excessive excavation in stable material does not occur. The quality control should be conducted with an on-site thaw-consolidation device (Figures 19 and 20), where a freshly excavated sample is loaded onto the apparatus, a load is placed on the sample, and heat is applied. Rapid testing for thaw stability can be conducted in this manner to quickly identify zones that may appear ice-rich but are in fact thaw-stable.

This foundation option would require the greatest amount of processed select fill material, and blasting may be required to obtain proper grade elevation in some locations.

Figure 17. Available heavy-duty excavator at McMurdo Station (Caterpillar 336E) with the bucket for digging the materials and ripper and hydraulic hammer attachment.



Figure 18. A 35-ton excavator ripping ice-poor frozen sedimentary bedrock with frost-tooth-equipped ripper shank (*inset*).



Figure 19. An on-site thaw-consolidation apparatus. The sample is loaded on the lower platen, and the upper platen (load) is being lowered for testing.



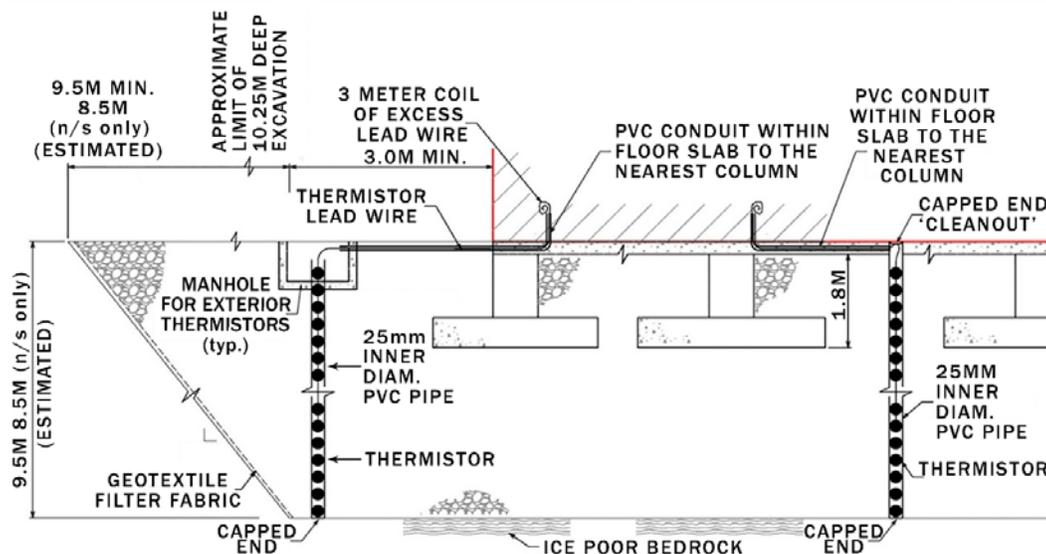
Figure 20. A loaded sample being heated with a gas burner nozzle.



This foundation type would be very similar to that of any large temperate location structure using shallow foundation elements. Prefabricated concrete footers would be leveled at the site, backfilled at or just below floor grade where steel columns are attached (Figure 21). Because these are placed over frozen ground that now will experience above freezing temperatures to approximately 15 m or more due to the heated structures, contingency must be included to allow for minor releveling as needed. This can be accomplished by ensuring that all vertical steel columns are readily accessible and configured for ease of vertical jacking. Installation of a two-

section column, where the lower section is disconnected from the upper section near the floor level, will provide the ease in releveling. Predrilled holes in both sections of the column will allow for quick attachment of jacking buttresses as needed, and jacking at the floor level will occur against the concrete column. Thermistor strings should be installed to the bedrock level and further into the bedrock if possible. The locations for temperature strings should be at the perimeter of the foundation and internally to the structure. This allows for quick monitoring of foundation temperatures should questions arise about the foundation performance.

Figure 21. Example of a generalized design for a slab-on-grade floor system with concrete footer and columns with removal of all ice-rich rock.



6.2 Option 2—Concrete footer-and-column foundation

In this option, excavation of thaw-unstable material takes place at each column location across the structure site. Select fill is placed and compacted to bear a concrete footing, and a concrete column is erected on the footing and extends some distance above the final surface grade (Figure 21). A subfloor space exists between the surface soils and the lowest floor; and this space is unheated, is enclosed with vented skirting with a high ventilation modulus around the perimeter of the structure, and also prevents snow from drifting and ice from migrating under the facility. This provides a continuously frozen embedment for the footer and the bottom of the column. This option requires the least amount of excavation to construct, and we recommend that the native material within the footprint below the footers be excavated to a depth equal to the largest dimension of the footers to ensure removal of close-proximity excess ice, preventing ice

creep. For example, on a 1 m × 1 m footer, the native material under the footer would be over-excavated by 1 m. This type of foundation does not prevent future effects of climate change; therefore, conservative thermal mitigation measures will be important. Releveling mechanisms should be in place with this foundation to ensure that minor changes in the subsurface can be accommodated with as little effort as possible. Thermistor strings must be installed with this foundation type to verify that progressive thawing is not approaching the fill–native soils interface.

6.3 Option 3—Piles

Drilled piles would be installed with steel pipes or H-beams sufficiently into the competent bedrock to ensure minimal creep or settlement. An earth drill capable of auguring the appropriate sized holes would be required, such as a foundation drill. These end bearing piles would be back-filled with select material to provide lateral stability, and a vented and skirted air space would be incorporated to prevent minimal thawing of the near-surface, thaw-unstable soils. If ice-poor or ice-free bedrock is not attainable, the piles can be installed as adfreeze piles that obtain bearing capacity from the frozen slurry between the pile and subgrade; however, this should not be an issue at MCM. A pile foundation option also requires the least amount of excavation to construct. Founding on competent rock will ensure that issues with climate warming do not pose issues for the future.

6.4 Recommendation

Table 1 elementally compares the foundation options for design conditions and construction considerations by using color-coded ratings of risks and requirements. This list holistically generalizes the elements, including the overall costs, ground conditions, logistics, heavy-equipment availability, fill material availability, seismic considerations, climate warming risks, and USAP prime contractor familiarity. Although the list may not be exhaustive, most of these elements are unique to MCM construction because of its remoteness.

Table 1. Comparative assessment of various foundation options. *Green* = most acceptable of the options, *orange* = moderately acceptable, and *red* = least acceptable.

Elements	Options		
	Over-excavation (shallow footer)	Concrete Footer-and-Column Foundation	Piles
Costs	Potentially high due to needs for large quantities of fill	Moderate excavation and fill material needs	Low to moderate—lower excavation and fill material costs, higher structural costs
Ground conditions	All icy conditions to be removed, requires good quality assurance / quality control (QA/QC)	Partial removal of icy conditions	Extension of piles below the icy interval must occur, requires good QA/QC
Fill material availability	Potentially large quantities required	Moderate quantities required	Minimal quantities required
Logistics	Potentially many pieces of heavy equipment to ensure that excavation and processing is timely	A few pieces of heavy equipment needed for excavation and processing	Large “foundation” drill required for pile borings but lower equipment needs for excavation and fill processing
Heavy-equipment availability	Large amounts of blasting, removal, fill processing, and placement required	Moderate amounts of removal, fill processing, and placement required	Minor amounts of removal, fill processing and placement required
Climate-warming risks	Risk eliminated—site prepared for perpetuity	Significant risks—requires adequate and thorough considerations of climate factors to ensure proper design	Risk minimal—properly installed piles will extend below thaw-sensitive zone
Seismic considerations	Minimal impact—foundation nestled on the ground (i.e., slab-on-grade floor systems) provides ultimate stability	Moderate impact—partially buried shallow foundation provides minimized lateral stability unless strengthened	Potentially high impact—higher costs will be required to ensure lateral stability
Energy efficiency	High energy efficiency by coupling the floor of the structure to the ground surface and providing protected utility connections	Low energy efficiency by requiring the bottom of the structure be exposed to ambient air temperatures, meaning that often the floor of the bottom story will be cold compared to the floors of upper stories.	Low energy efficiency by requiring the bottom of the structure be exposed to ambient air temperatures, meaning that often the floor of the bottom story will be cold compared to the floors of upper stories
Drainage	Lowest risk— foundation nestled on the ground (i.e., slab-on-grade floor systems) greatly minimizes understructure drainage and snow/ice problems	Moderate risk—proper drainage and prevention of snow drifting and ice development must be ensured	Potentially high risk—proper drainage and prevention of snow drifting and ice development must be ensured
USAP prime contractor familiarity	High familiarity—over-excavation allows for traditional foundation design and construction; ice removal QA/QC will need to be ensured	Moderate familiarity—surface foundations currently at MCM are similar; remaining icy conditions must remain frozen	Low familiarity—piles foundations are very common; however, ensuring placement below icy interval will require good QA/QC

6.4.1 Over-excavation

This option provides the best overall long-term design application (Table 1). This design option removes for perpetuity all potential climate effects (e.g., potential thaw settlement of permafrost). It minimizes drainage and understructure snow and ice problems, gaining the highest energy efficiency. In addition, this design option has the lowest structure material requirements and seismic strengthening requirements. The one drawback is the high earthwork requirement. Ground-ice removal QA/QC must be stringent.

6.4.2 Concrete footer-and-column foundation

This option most closely mimics traditional MCM construction but requires maintaining proper conditions to ensure that icy ground remains frozen. Understructure drainage and snow and ice issues have proven to be a problem with these types of foundations, considering the sloping topography of the site. Earthwork requirements are somewhat significant but not as major as over-excavation. This design option has low energy efficiency, and structure material costs will be significant because of strengthening requirements for seismic considerations.

6.4.3 Piles

This option provides the least earthwork requirement but requires proper conditions to ensure that icy ground remains frozen. As with the previous option, understructure drainage and snow and ice issues have proven to be a problem with these types of foundations, considering the sloping topography of the site. This option requires adequate foundation drill size to install the pile and to drill into the volcanic materials at MCM. Stringent QA/QC will be required to verify that piles extend to the proper design depth below the icy interval. Likewise, this design option has low energy efficiency; and structure material costs will be significant with strengthening requirements to accommodate for seismic design.

7 Conclusion

This comprehensive assessment reviewed borehole information and photos from two drilling campaigns conducted by Golder and a CRREL geotechnical assessment at MCM. However, some of Golder's assessments of the boreholes were different from our own assessment. Our analysis of subsurface conditions suggests that a different and more efficient building foundation type can be used than is currently the norm, despite the permanently frozen ground condition. We interpret the drill results to suggest that an ice-poor to nearly ice-free ground-ice condition exists nearly everywhere across MCM at a depth no greater than 3 m, with a high probability of much shallower depths across MCM. This provides the opportunity to prepare for the new development by removing the near-surface ground-ice interval and replacing it with compacted non-frost-susceptible fill material processed on-site. This will allow for the placement of a shallow foundation that will facilitate an at-grade first floor design. Placing infrastructure at the surface as opposed to elevating on footer and column or on piling allows for benefits in lower construction material needs, increased energy efficiency, optimized positive drainage and snow and ice accumulation prevention, increased seismic safety, and more appealing architecture for an austere environment.

We recommend that additional subsurface investigations be conducted with boreholes and test pits to further define the ice-poor vs. ice-rich subsurface boundary believed to exist across MCM. This information must include moisture contents and thaw-consolidation testing. If only limited exploration is to be conducted, we recommend a minimum of two deep corings (>15 m depth) at each structure site, to include moisture content and thaw-consolidation testing.

The existing fill material that would be removed for these new structures is potentially reusable if adequate provision is made to screen the material for debris and large rock and to ensure that the material is ice-free. Staged construction might allow for the use of a heated temporary type structure for placement of the fill material to allow for thawing and draining. However, existing hydrocarbon-contaminated fill materials need to be examined in foundation design because of possible chemical incompatibility with building materials and potential leaching or migration during construction or excavation of soil.

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14. ABSTRACT

Construction of large buildings is currently part of the major infrastructure development plan at McMurdo Station. Therefore, the overall goal of this study is to provide recommendations for selecting better-suited foundation designs for the new facilities by using existing geotechnical studies recently taken on site. Based on a detailed visual assessment of photos from the geotechnical coring conducted by a third-party consultant, we interpreted the results to indicate that ice-poor to nearly ice-free ground-ice conditions exist nearly everywhere across McMurdo Station and at a depth less than 3 m. This assessment provides foundation design options to prepare for the new development by excavating the near-surface ground-ice interval, replacing with compacted non-frost-susceptible fill material, and constructing shallow foundations with at-grade first-floor design. The benefits of the shallow foundation design include lower construction material needs, increased energy efficiency, optimized drainage and snow/ice accumulation prevention, increased seismic safety, and more appealing architecture for an austere environment.

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