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GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8923

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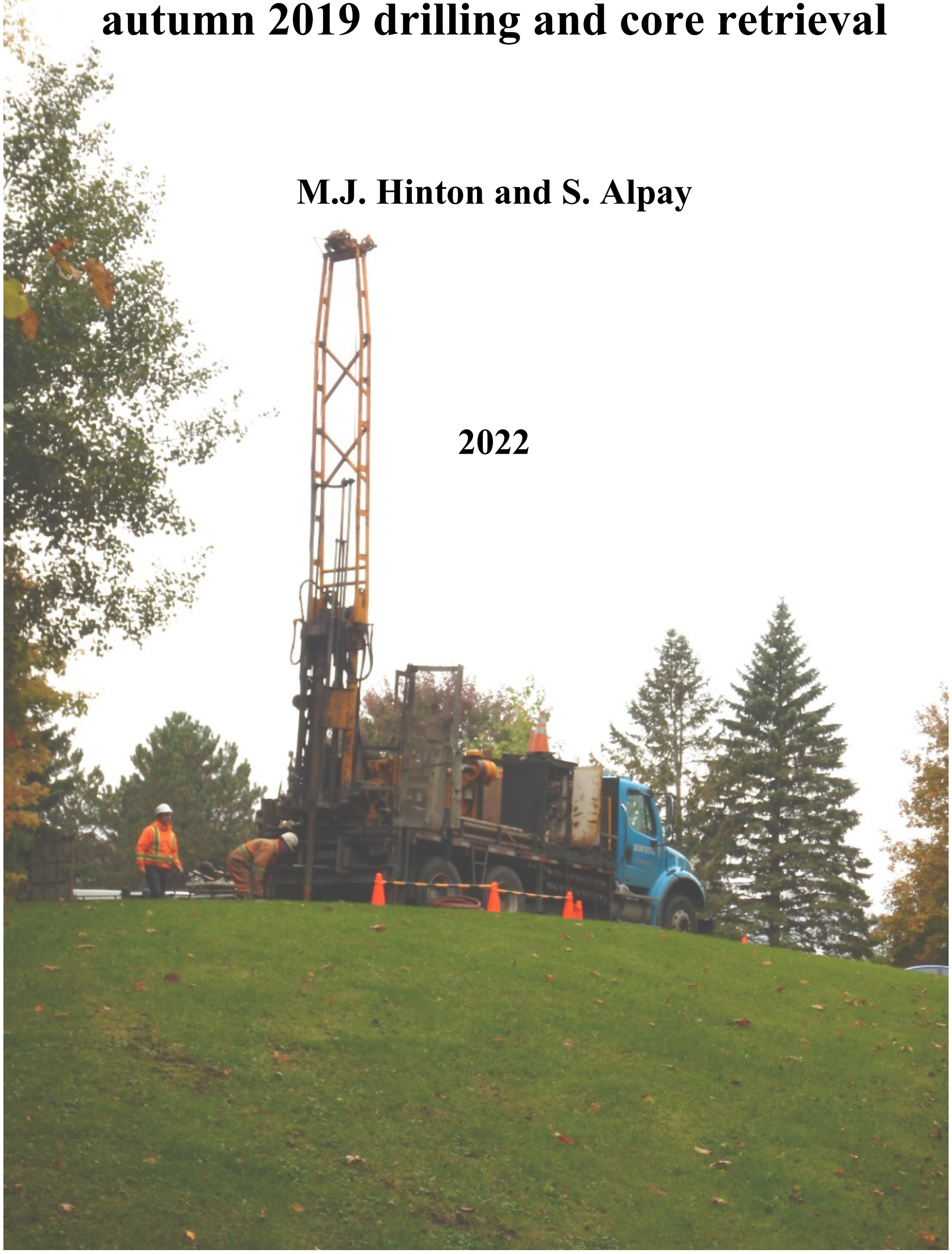
M.J. Hinton and S. Alpay

2022



Canada

ISSN 2816-7155
ISBN 978-0-660-45735-2
Catalogue No. M183-2/8923E-PDF

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Permanent link: https://doi.org/10.4095/330942

Recommended citation
Hinton, M.J. and Alpay, S., 2022. Geoscientific studies of Champlain Sea sediments, Bilberry Creek, Ottawa, Ontario: autumn 2019 drilling and core retrieval; Geological Survey of Canada, Open File 8923, 1 .zip file. https://doi.org/10.4095/330942

Cover photo: CME 75 drill rig at site BC16; Photograph by M.J. Hinton, NRCan photo 2022-320

Summary

The Rideau Valley Conservation Authority (RVCA), in collaboration with the City of Ottawa, is managing the Bilberry Creek Hazard Mapping Project to map flood risk and slope stability hazards along Bilberry Creek in Orleans, a suburb of Ottawa, Ontario. For a parallel study, the RVCA and the City of Ottawa drilled boreholes at two sites (BC16 to a depth of 48.8 m, and VC2 to 65.9 m) to provide the Geological Survey of Canada (GSC) with near-continuous core samples for geological, geochemical, geophysical, geotechnical and hydrogeological analyses. PVC casings were installed at BC16 and VC2 to allow for geophysical logging. Vibrating wire piezometers and water table wells were installed in adjacent, shallower borings to measure groundwater pressures or levels at various depths. This report documents the fieldwork and methods used to collect core samples and to install casing and piezometers at the drilling sites. Data arising from this study will provide comprehensive multidisciplinary characterizations to establish two geological reference sites within Champlain Sea deposits.

Résumé

L'Office de protection de la nature de la vallée Rideau (OPNVR), en collaboration avec la Ville d'Ottawa, gère le projet de cartographie des risques du ruisseau Bilberry pour identifier les risques d'inondation et les risques liés à la stabilité des pentes le long du ruisseau Bilberry à Orléans, en banlieue d'Ottawa, en Ontario. Pour une étude parallèle, la OPNVR et la Ville d'Ottawa ont foré des trous de forage à deux sites (BC16 à une profondeur de 48,8 m et VC2 à 65,9 m) afin de fournir à la Commission géologique du Canada (CGC) des échantillons de carottes quasi continus pour des analyses géologiques, géochimiques, géophysiques, géotechniques et hydrogéologiques. Des tubages en PVC ont été installés à BC16 et VC2 pour permettre la diagraphie géophysique. Des piézomètres à corde vibrante et des puits de nappe phréatique ont été installés dans des forages adjacents moins profonds pour permettre la mesure des pressions ou des niveaux des eaux souterraines à profondeurs différentes. Ce rapport documente le travail sur le terrain et les méthodes utilisées pour prélever des carottes et pour installer des cuvelages et des piézomètres sur les sites de forage. Les données découlant de cette étude fourniront des caractérisations multidisciplinaires complètes pour établir deux sites géologiques de référence au sein des dépôts de la mer de Champlain.

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Appendices: Field observations during drilling and coring

GSC Open File 8923 includes appendices. Field observations are recorded in a Microsoft Excel workbook (GSC Open File 8923, Appendices Field observations.xlsx) for BC16 and VC2 in two spreadsheets: Appendix A, BC16 and Appendix B, VC2.

The spreadsheets are also included as pdf files ready to print on Tabloid sized (11″×17″) paper:
GSC Open File 8923, Appendix A, BC16.pdf and GSC Open File 8923, Appendix B, VC2.pdf

Introduction

Background

The Rideau Valley Conservation Authority (RVCA), in collaboration with the City of Ottawa, is conducting the Bilberry Creek Hazard Mapping Project to identify and map flood risk and slope stability hazards along Bilberry Creek in Orleans, a suburb of Ottawa, Ontario. The RVCA contracted an engineering consulting firm to conduct geotechnical investigations of 18 sites: 16 within the eastern tributary of Bilberry Creek (BC) and 2 within the western tributary (also informally known as Voyageur Creek, VC[1]) at depths ranging from 4 to 31 m. As a component of these studies, they drilled additional deeper boreholes at two sites (BC16 and VC2) to provide the Geological Survey of Canada (GSC) with nearly continuous core samples for geological, geochemical, geotechnical and hydrogeological analyses (Figure 1). The GSC has a long legacy of Champlain Sea research and mapping (e.g. Johnston, 1917; Wagner, 1970; Gadd, 1986; Fulton, 1987; Anderson, 1988; Richard, 1990). More recently, the GSC drilled boreholes in areas of thick Champlain Sea sediments (Aylsworth and Lawrence, 2003; Medioli et al., 2012; Crow et al., 2017), conducted surficial and borehole geophysical surveys (Crow et al., 2014; Crow et al., 2017; Crow et al., 2020a; Pugin et al., 2020; Crow et al., 2021b), mapped and dated landslides (Brooks, 2019; Brooks et al., 2021), investigated earthquake shaking response (Hunter et al., 2010; Crow et al., 2011; Nastev et al., 2016; Motazedian et al., 2020), explored the role of earthquakes on landslides (Aylsworth et al., 2000; Brooks, 2013; Wang, 2020), studied eskers within the Champlain Sea basin (Cummings et al., 2011; Crow et al., 2020b; Paradis et al., 2020; Crow et al., 2021a), modeled groundwater flow and transport in Champlain Sea sediments (Hinton and Alpay, 2020) and developed 3-D stratigraphic and hydrostratigraphic models (Logan et al., 2009; Parent et al., 2021).

Objectives

The GSC began field work in autumn 2019 with research objectives to investigate: (1) the geological, hydrogeological and geochemical factors influencing the geotechnical properties of Champlain Sea muds; (2) geochemical changes arising from groundwater flow within Champlain Sea deposits; and (3) two new reference sites within Champlain Sea sediments, characterized using a comprehensive suite of geological, geotechnical, geophysical, hydrogeological, and geochemical data. The RVCA project primarily focuses on geotechnical measurements in the upper 4-31 m of Champlain Sea sediments, whereas the GSC boreholes will provide a broader scope of investigation to greater sediment depths. Hence, the GSC investigations will provide the RVCA and City of Ottawa with a comprehensive geoscience context in parallel with the Bilberry Creek Hazard Mapping Study.

The primary drilling objective was to recover continuous undisturbed core through the entire thickness of Champlain Sea sediments until refusal, when drilling could not penetrate further, at the underlying till or the bedrock surface. Cores, collected in Shelby sampling tubes, were destined for scanning by computed tomography (CT) to produce high-resolution X-ray images

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[1] It is not evident that the western tributary of Bilberry Creek drains to its original outlet near the confluence of Bilberry Creek and the Ottawa River. As a result of development, it appears to drain to the Ottawa River through a storm sewer farther west.

before extrusion and sub-sampling. A secondary objective was to case the deepest borehole at each site with 3″ PVC pipe to allow a diameter wide enough for insertion of the geophysical tools for subsequent borehole logging of Champlain Sea sediments. Finally, an additional fieldwork objective was to obtain measurements of hydraulic head at different depths.

This GSC Open File report documents the fieldwork for drilling and coring of the boreholes and provides records of the borehole completions as PVC pipe, monitoring wells or vibrating wire piezometers (VWP). This information aims to facilitate the meaningful use and interpretation of cores and groundwater heads. Detailed documentation of the cores and groundwater levels will follow in subsequent publications.

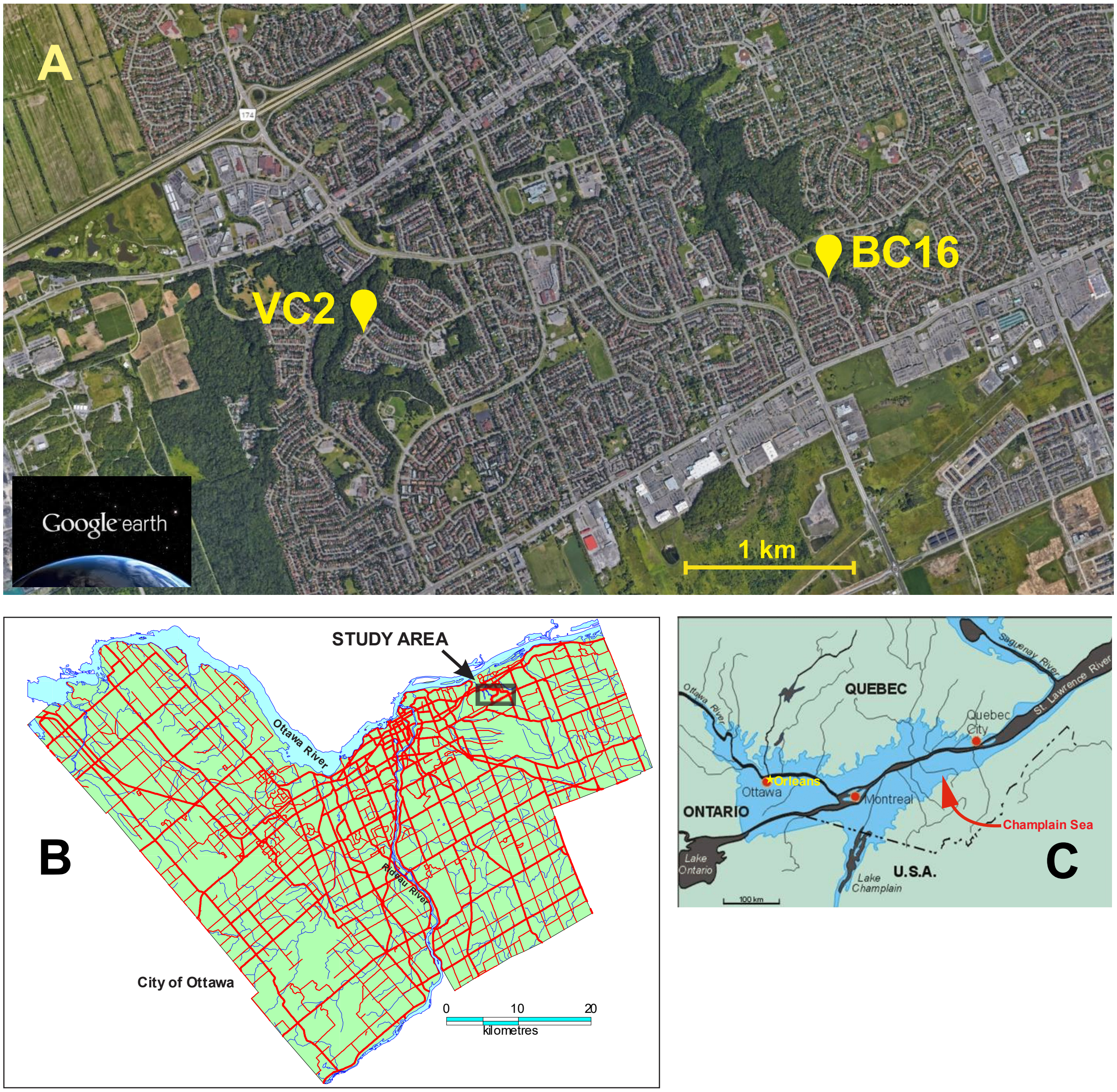

Figure 1. A) Locations of new borehole sites, BC16 and VC2, in Orleans; **B)** Location of Orleans within the boundary of the City of Ottawa (after Crow et al., 2007); **C)** Location of Orleans with respect to the extent of Champlain Sea deposits within the St. Lawrence Lowlands (after Aylsworth, 2012)

This GSC Open File is the third of a series for this research, which documents pertinent methods and results of Champlain Sea sediment studies in Bilberry Creek. The first details the methods used to preserve the core samples in Shelby tubes at the field locations (Alpay et al., 2020); the second documents geophysical field surveys to estimate the thickness of Champlain Sea sediments at the Bilberry Creek study sites by measuring the resonant frequency of ambient seismic waves (Dietiker, 2020). Additionally, Al-Mufti et al. (2022) report on the analysis and interpretation of CT scans of cores in an open-access publication.

Drill sites and site selection

The RVCA and their subcontractor selected accessible, spatially-distributed sites for the Bilberry Creek Hazard Mapping Study on City of Ottawa property. From these, the GSC aimed to select two sites with thick Champlain Sea sediments. Evidence from previous studies (Torrance, 1988; Medioli et al., 2012; Crow et al., 2017; Hinton and Alpay, 2020) suggest that thicker Champlain Sea sediments generally retain more of the original seawater salinity, which has been used to quantify groundwater flow and diffusion (Hinton and Alpay, 2020).

A geophysical survey of resonant frequencies (horizontal-to-vertical spectral ratios, HVSR) (Dietiker, 2020) provided depth estimates for 12 of the 16 sites (Figure 2). This survey measures the depth to the resonator or hard layer, which is the basal till or bedrock surface. This depth is conveniently synonymous with the base of sediments within the Champlain Sea basin. GSC coring sites were selected from results of this survey at two locations with the greatest estimated depth to firm ground (or sediment thickness), VC2 (72 to 80 m) and BC16 (54 to 59 m).

Field methods

Drilling and coring

Drilling and coring were conducted with a truck-mounted CME 75 drill rig (Figure 3). The borehole was advanced two feet at a time by coring undisturbed sediment with thin-walled 30-inch-long Shelby tubes ahead of (below) the drill casing (Figure 4A). After retrieving the core, the casing was advanced two feet to the next target sample depth by wash boring (Figure 4B). Wash boring used direct circulation of water as the drilling fluid while advancing the HWT size drill casing (4½″ outer diameter (OD) with tapered threads, 2.5 threads per inch) fitted with a casing shoe.

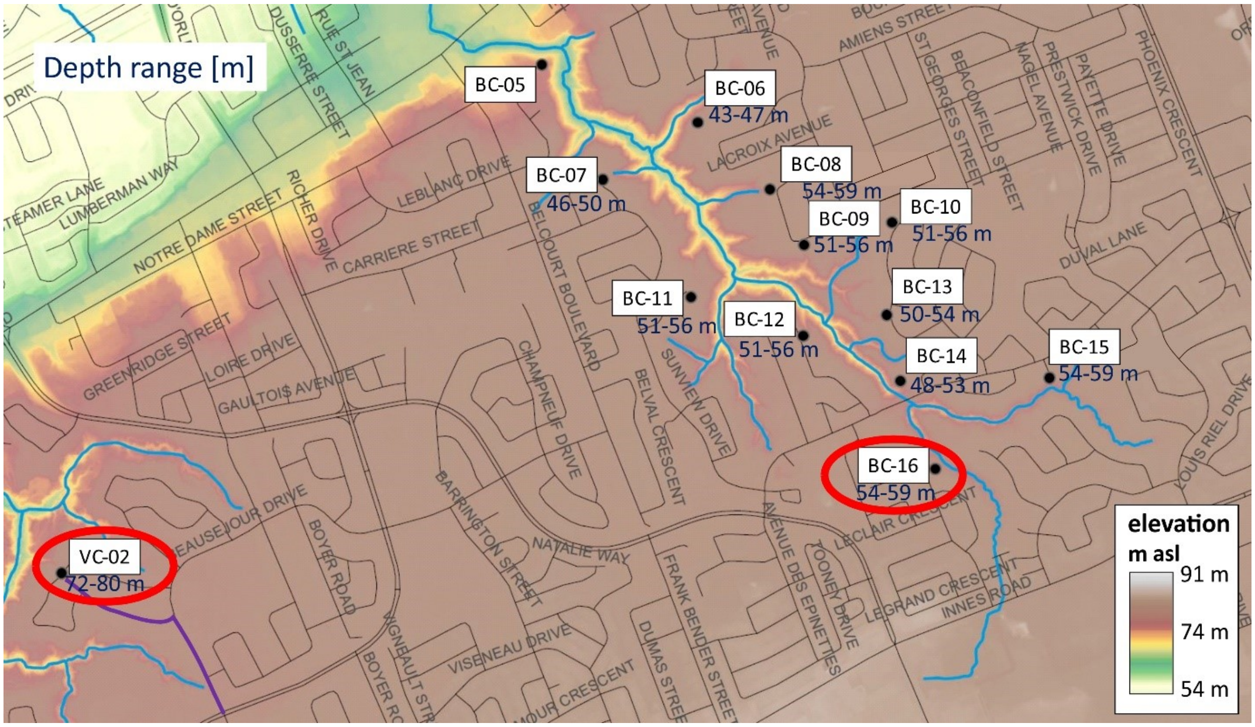

Figure 2. Estimated thickness range of Champlain Sea sediments at selected RVCA drill sites (from Dietiker, 2020); Colours in the base map represent the ground surface elevation in metres above sea level (m asl).

Ideally, this procedure would produce continuous sampling of undisturbed sediment from the ground surface to the bottom of the borehole in 2-foot intervals. In practice, the Shelby tube did not consistently penetrate the full two feet of undisturbed sediment or it may not have retained the full core, so core recovery was not entirely continuous. Incomplete core retrieval could result from many factors, such as variations in sediment properties, coring equipment, method and force used to advance and retrieve the Shelby tube, waiting time prior to core retrieval, depth of sample, water level within the borehole, obstructions, and suction on the core sample. Similarly, these factors can also influence the quality of the recovered core since the goal was to recover core that is minimally disturbed from its *in situ* condition. Consequently, no single method would guarantee the success of coring the two boreholes. Rather, the sampling method was continually adapted in consultation with the expertise of drillers and technicians in an attempt to maximize core recovery and quality, while remaining within the drilling budget. This report documents the drilling and collection of cores to share the details that can bear on subsequent analysis and interpretation.

Figure 3. CME 75 drill rig at site BC16; Photograph by M.J. Hinton, NRCan photo 2022-321

Samplers

Sediment cores were retrieved using three different sampling devices: i) piston, ii) open tube and iii) split spoon samplers. Deployment of the first two samplers was with thin-walled, steel Shelby tubes, 30″[2] (76 cm) in nominal length and 2⅞″ (7.3 cm) nominal diameter. Both piston and open tube samplers are considered suitable for recovery of relatively undisturbed cores in soft to medium stiff clays and silts (Cornforth, 2005). For the piston sampler, the Shelby tube is secured to the piston in a retracted position with the sampler's conical point extending past the bottom of the Shelby tube (Figure 5). The sampler is threaded onto A-sized drill rods and lowered down the casing to the top of the desired sampling depth interval. The conical point at the end of the Shelby tube prevents sediment from entering the tube so that the tube can be pushed through any

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[2] Since all drilling was conducted in imperial units, diameters are reported in inches and depths in feet. "Nominal" dimensions refer to the stated, standard diameter or length of rods, pipe or casing; actual sizes may differ slightly from these values.

remaining drill cuttings to the desired sampling depth (Figure 5D). The piston is then extended a full 24 inches (61 cm) using water pressure inside the drill rods to drive the Shelby tube past the conical point and into undisturbed sediment below the casing. When the piston is fully extended, water flow is diverted into the drill casing, allowing the driller to confirm deployment of the Shelby tube. The design of the piston sampler used by the driller allowed the extended Shelby tube to rotate freely from the drill rods, so that the core could not be rotated to shear the core sample from the underlying sediment. Consequently, breaking the contact of the core from the underlying sediment could only be achieved by pulling upwards on the piston corer, rather than by turning it. This action relied on both the friction of the sediment within the tube and the suction created within the sampler above the sediment to retain the sample within the Shelby tube. As a result, the piston sampler was generally more effective in shallower, softer sediments. However, some or all of the core would often be missing from the bottom of the Shelby tube when the underlying sediments were stiff and the contact harder to break.

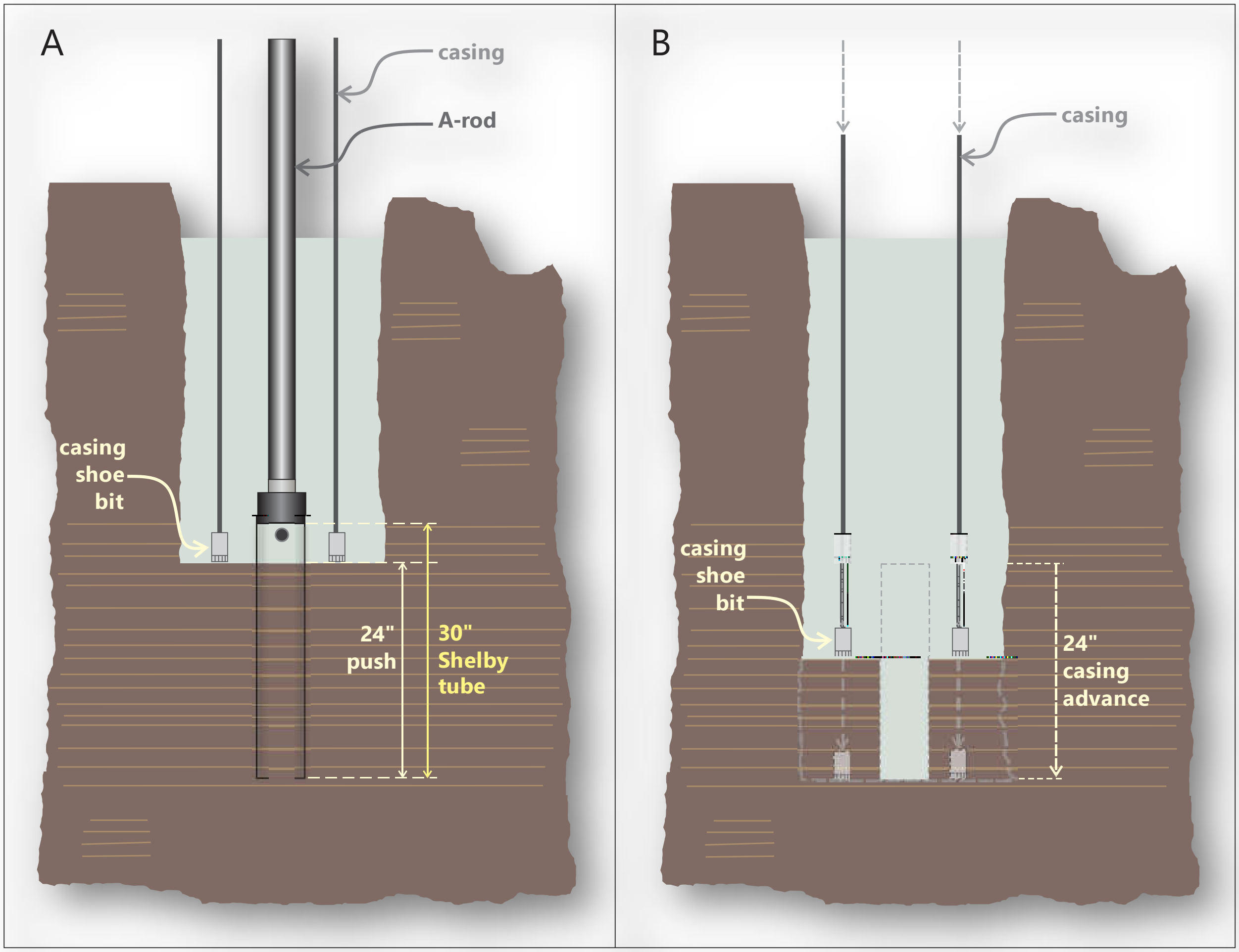

Figure 4. A) Schematic of coring below the casing with an open tube sampler; **B**) Advancing the casing prior to coring the next depth

Figure 5. Piston corer; **A**) Piston in retracted position; **B**) Moveable piston head where Shelby tube attaches; **C**) Conical point; **D**) Shelby tube attached to piston corer, ready for deployment; and **E**) Piston extended and Shelby tube removed after sampling; Photographs A-C, E by M.J. Hinton, NRCan photos 2022-322 2022-323, 2022-324, and 2022-326 respectively; Photograph D by H.L. Crow, NRCan photo 2022-325

The open tube sampler (which the drillers called the "A-rod" sampler because it attaches directly to the A-sized drill rods) consists of an adapter between the drill rods and the Shelby tube (Figures 4A and 6). The adapter contains a check valve to allow air and water to escape the Shelby tube when it is pushed into the sediment and to prevent water inside the rods to put any pressure on the core sample when is it raised within the drill casing. Its simplicity in design and operation make this a common sampler for geotechnical sampling; it is also the sampler the consultant used for the geotechnical cores in the RVCA project.

The sampler was lowered on drill rods until it made contact with the sediment surface. Sometimes the weight of the drill rods was sufficient to advance the Shelby tube into the sediment, particularly in soft sediment. When the weight of drill rods was insufficient, pipe wrenches and body weight were applied to advance the Shelby tube. For stiffer sediments, hydraulic pressure from the drill rig was needed to advance the Shelby tube. The greatest advantage of this sampler over the driller's piston sampler was the ability to rotate the drill rods and the Shelby tube to shear the core from the underlying sediments before retrieval, which retained more of the sample in the Shelby tube. A shortcoming of this sampler was that the Shelby tube remained open when lowered in the casing, so that any settled drill cuttings (Figure 7A) or sediments not removed by wash boring that remained in the casing (Figure 7B) could enter the tube and become part of the core sample. The presence of cuttings sometimes limited the depth of undisturbed sediment that could be sampled since the excess sediment at the top filled part of the Shelby tube. For this reason, additional time was usually required when coring with an open tube sampler to wash more sediment and cuttings from the drill casing before sampling each time the casing was advanced.

Figure 6. Temporary capping of Shelby tube following sampling with an open tube sampler; Photograph by M.J. Hinton, NRCan photo 2022-327

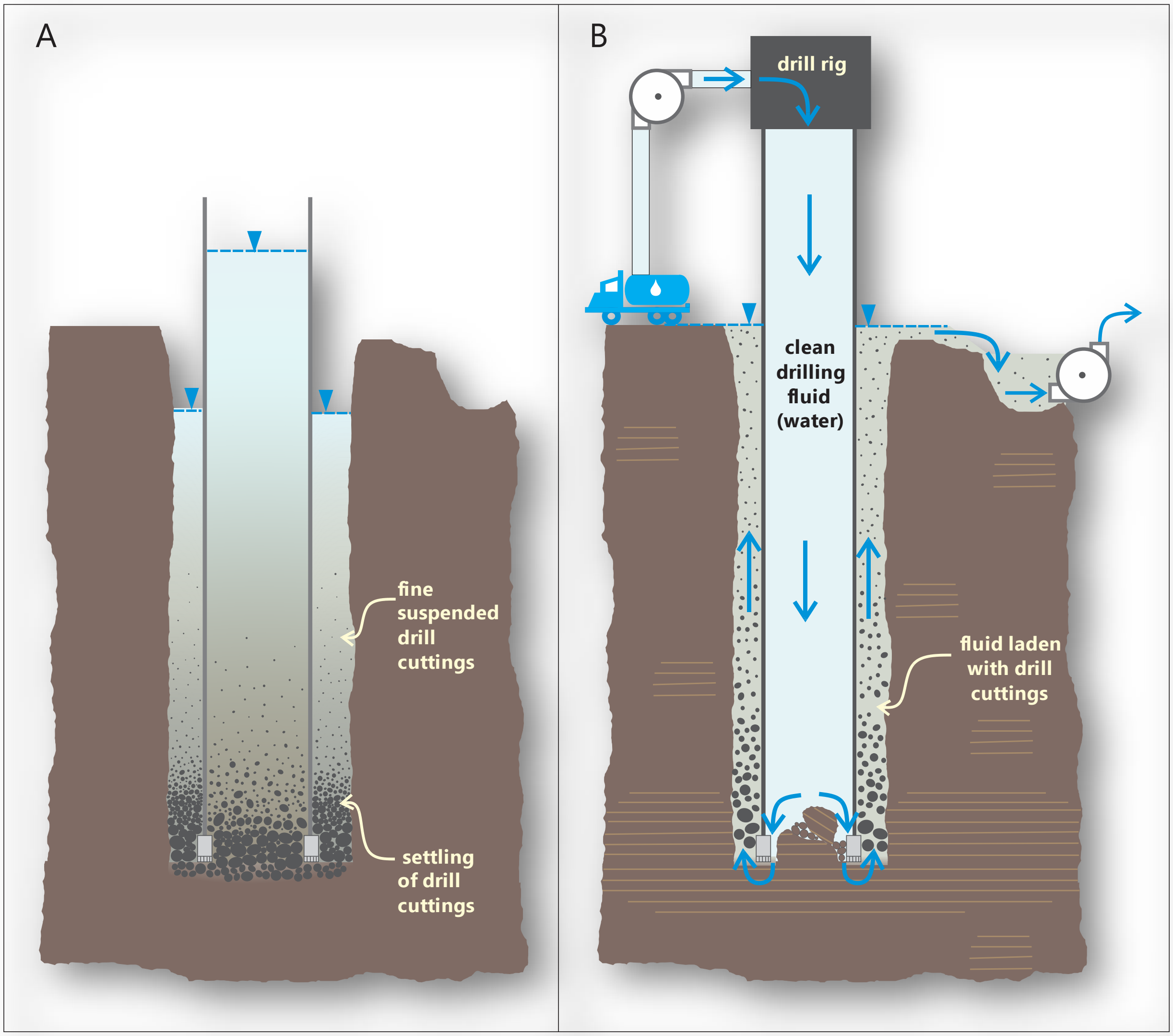

Figure 7. A) Cuttings settled inside the drill casing; and **B**) Sediment not fully removed from the drill casing, prior to coring

The split spoon sampler (Figure 8) was occasionally necessary in hard material, such as till or fill, or sand, or when the piston and open tube samplers failed to recover a sample. A thin-walled Shelby tube could not penetrate till or fill and typically cannot retain a sand sample. The split spoon sampler reliably returned sediment samples because of the core catcher at its base. However, the samples are not sealed in a Shelby tube and can be more disturbed because the core catcher drags along the side of the core, the thicker walls of the sampler displace more sediment and the standard procedure of using hammer blows to advance a split spoon (as part of a Standard Penetration Test) can alter consolidation and geotechnical properties.

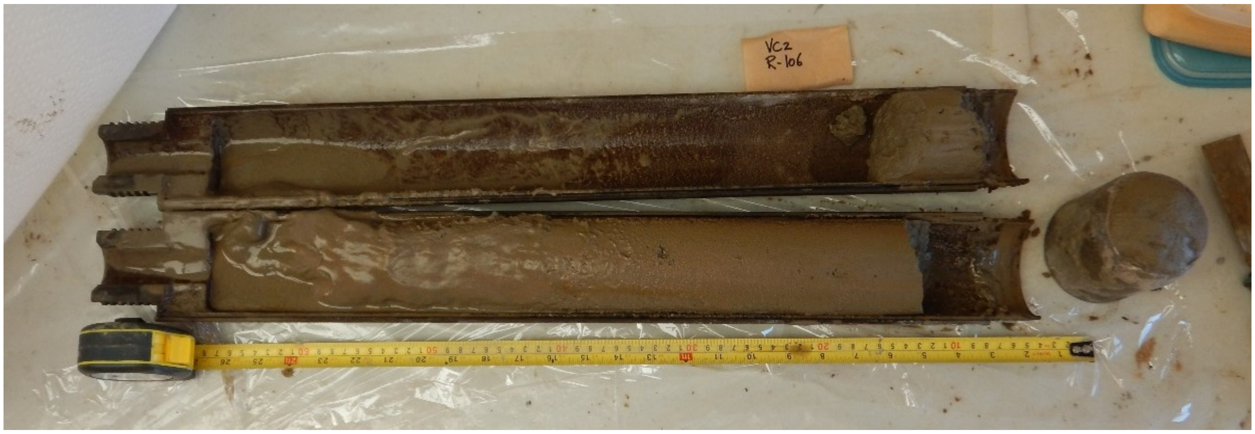

Figure 8. Split spoon sampler; Photograph by M.J. Hinton, NRCan photo 2022-328

Core handling and preservation

Cores were raised to ground surface by “tripping” or lifting the coring apparatus while sequentially unthreading the drill rods, which lengthened the time required for sampling deeper cores. Given the mast height, it was possible to remove 20 feet of drill rod at a time. At surface, a vinyl cap was temporarily placed on the bottom of the Shelby tube (Figure 6) to prevent sample loss when removing it from the sampler and for carrying it to a nearby field laboratory. The laboratory was housed within a truck (Figure 9), where on-site field measurements were possible for core length and sediment strength (using a pocket penetrometer), in addition to core sealing and preservation. The Shelby tubes were sealed with a mixture of beeswax and petroleum jelly (Figure 10) and kept cold for daily transport to refrigerated storage at the GSC following methods described by Alpay et al. (2020). Selected segments of split spoon samples were subsampled in the field and either preserved in thick plastic zippered freezer bags or, for larger segments split lengthwise, sealed with several layers of plastic wrap.

Advancing the drill casing

After retrieval and handling of each core sample, the drill casing (4½″ OD, HWT size and thread) was advanced two feet by wash boring with direct circulation of drilling fluid to remove the cuttings (Figure 4B). The drilling fluid was water, without any additives. It was circulated directly into the drill casing to return up the annulus with the drill cuttings. It was not recirculated. Return flow discharged to a small sump pit to settle out coarse sediment before the used water could be pumped into a sediment filter or dewatering bag to retain finer silt before discharging to the environment (Figure 11). The water source was municipal water trucked to the site and fed by gravity to the drill rig (Figure 12). Drill casings were in 5′ (1.524 m) lengths so the height of the casing protruding above ground surface varied from core to core. When coring, the drill casing was disconnected from the drill head and clamped at the ground surface to prevent sinking into the mud from its weight (Figure 13).

Figure 9. Core preservation field laboratory; Photographs by S. Alpay, NRCan photo 2022-329, and inset NRCan photo 2022-330

Figure 10. Cores sealed with wax mixture and packed for field transport to GSC; Photograph by M.J. Hinton, NRCan photo 2022-331

Figure 11. Preparation of drilling sump and sediment bag at site BC16; inset, sump prior to drilling; Photographs by M.J. Hinton, NRCan photo 2022-332, and inset NRCan photo 2022-333

Figure 12. Water truck at site VC2; Photograph by M.J. Hinton, NRCan photo 2022-334

Figure 13. Clamp attached to drill casing and supported by two, A-sized, drill rods; Photograph by M.J. Hinton, NRCan photo 2022-335

Borehole completions

Naming conventions

Both the GSC and the geotechnical consultant named boreholes with their own conventions for this project. The consultant's borehole numbers are identified in this report to allow cross-referencing between reports. GSC boreholes are identified as GSC-BH-*site*-*borehole number* where *site* is either BC16 or VC2 and *borehole number* is the sequential number of boreholes at each site (for GSC related drilling). Each installation within a borehole is given a separate identifier. For solid PVC casing in the deepest borehole, it is GSC-*site*. For monitoring wells and vibrating wire piezometers, it is GSC-*site*-p*X* where X is a sequential number from the shallowest to the deepest piezometers.

PVC casing

The deepest borehole at each site was completed with a 3″ (nominal diameter), flush-threaded, PVC pipe. These solid (i.e. unslotted) casings were installed to accommodate the diameter required for borehole geophysical logging (Figure 14). Before installation of the PVC casing, the borehole was flushed thoroughly with water to remove as much of the drill cuttings as possible. Bentonite grout (Baroid AQUAGUARD®), mixed in a ratio of 24 U.S. gal. of fresh water per 50 lb. sack, was pumped into the borehole using a tremie pipe to emplace the grout from the bottom up and displace the drilling fluid from the borehole. The PVC pipe was lowered into the grout, adding one threaded section at a time, and filling it with fresh water to reduce the buoyancy. When the full length of the PVC was installed, the drill casing was removed, and the borehole was topped up with grout (Figure 15). PVC (at BC16) and ABS (at VC2) surface casings protect the PVC pipe (Figure 14) and prevent public access. Medium bentonite chips (⅜″ graded, CETCO PUREGOLD® or Baroid HOLEPLUG®) sealed the upper annulus of the borehole. Quartz sand (#2, Atlantic Silica Inc.) filled the uppermost foot of the borehole and the annulus between the surface and PVC casings.

Figure 14. Geophysical logging of GSC-VC2; 3″ PVC pipe is visible inside the ABS protective casing. Photograph by M.J. Hinton; NRCan photo 2022-336

Figure 15. Filling the borehole annulus of GSC-VC2 with grout pumped through a tremie pipe after removal of the drill casing; Photograph by M.J. Hinton; NRCan photo 2022-337

Vibrating wire piezometers

Vibrating wire piezometers (VWP) were installed in shallower boreholes at each site. Details of the VWPs at each site are provided in the site description sections below. The VWP measures total pressure (combined barometric and water pressure; i.e. not vented to the atmosphere) in a buried sensor that allows for more rapid equilibration of groundwater pressure within the low permeability Champlain Sea sediments than a standpipe piezometer. The VWPs, model VW2100 manufactured by RST Instruments, were calibrated in the laboratory by RST and in the field by the GSC. Before installation, the sensor was saturated and pre-packed in filter sand (quartz sand

#2, Atlantic Sand Inc.), held in place by multiple layers of nylon and cable ties (Figure 16). The pre-packed filter ensured installation of the sensor in sand as a fail-safe, in case placement of an external filter sand in the borehole did not align with the VWP. It also provided weight to keep tension on the cable during installation. VWPs were monitored using RST DT2011 and DT2011B dataloggers that record both pressure and temperature.

Figure 16. Vibrating wire piezometer packed in filter sand prior to installation at BC16; Photograph by M.J. Hinton, NRCan photo 2022-338

Monitoring wells

A 2″ (nominal diameter), flush-threaded, PVC monitoring well with a 10′ (3.05 m) slotted screen was installed within a separate borehole at each site to measure groundwater levels at or near the water table. A separate drilling crew installed the monitoring wells using a track-mounted drill rig and 210 mm (OD) hollow stem augers. Water level was monitored in each well with Solinst Levelogger® Edge and Barologger Edge dataloggers to measure total pressure and barometric pressure, respectively. Together, the well and vibrating wire piezometers serve to monitor hydraulic heads at different depths, which provide data to measure vertical hydraulic gradients and the direction of vertical groundwater flow.

Site BC16

Site BC16 is located on city property in a park area along Wildflower Drive between Danniston Crescent and Midsummer Terrace, in Orleans, Ottawa. The ground surface of the park and path slopes from the drill site down towards Bilberry Creek where there is a sewer outfall (Figure 17), suggesting that some of the park area may have been excavated to install the sewer and would include some fill material for regrading. The surficial geology is mapped as offshore marine deposits (clay, silty clay and silt) of the Champlain Sea (Richard, 1982).

Figure 17. Drone aerial photograph of site BC16 showing labeled casings and the sewer outfall indicated by the arrow; Photograph by A. Grenier, NRCan photo 2022-339

Coring

Site BC16 was cored 7-22 October 2019 with the installation of the deep casing and VWP on 24 October 2019. A separate drilling crew installed the monitoring well under supervision of the geotechnical consultant on 23 October 2019. Table 1 is a compilation of daily drilling progress and Figure 18 displays daily weather data measured at the Ottawa International Airport (20 km SW). It was important to consider air temperature for appropriate core preservation without freezing (Alpay et al., 2020).

Sediments at site BC16 consist of muddy fill from surface to a depth of approximately 14′6″ (4.4 m), glaciomarine mud of the Champlain Sea from 14′6″ to 147′ (4.4-44.8 m), glaciolacustrine rhythmites from 147′ to 154′1″ (44.8-47.0 m) and till from 154′1″ to the bottom of the borehole at 160′ (47.0-48.8 m; Figure 19). Unit descriptions and contacts are based on field logs and CT scans results (Al-Mufti et al., 2022).

Shelby tubes and split spoon samples from BC16 were numbered sequentially from R-001 to R-066, with the prefix "R" to denote the run (i.e., trip down the borehole). However, there was not a sample for each run and sometimes more than one run for a given depth interval. Consequently, the sample numbers do not denote the number of runs. However, each run was recorded in the field and is summarized in a spreadsheet in Appendix A. In total, 97 runs were completed at BC16, 29 with a piston sampler, 56 with an open tube sampler and 12 with a split spoon sampler. From these attempts, 17 piston sampler cores, 39 open tube sampler cores and 11 split spoon samples were retrieved at BC16 (Figure 19). The recovery of intact core at site BC16, as a percentage of the depth from the base of the fill to the bottom of the second borehole (GSC-BH-BC16-2), was 71% (43% open tube, 16% piston and 13% split spoon; Figure 19).

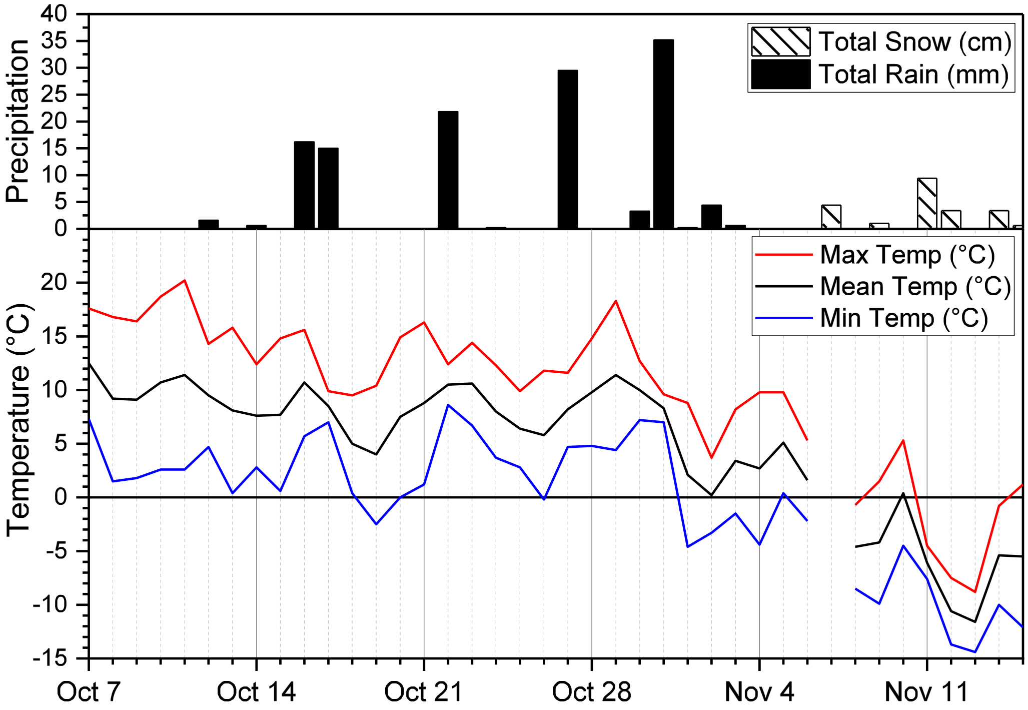

Figure 18. Daily weather data measured at the Ottawa International airport during the drilling program in 2019

Table 1. Summary of daily drilling progress

Date	Site	BH #	Core start (ft)	Core end (ft)	Casing start (ft)	Casing end (ft)	Samples from	Samples to	Notes
Mon, 07-Oct-19	BC16	1	0	20	0	18	R-001	R-008b	Start GSC-BH-BC16-1
Tue, 08-Oct-19	BC16	1	20	36	18	34	R-009	R-016	
Wed, 09-Oct-19	BC16	1	36	54	34	52	R-017	R-024	
Thu, 10-Oct-19	BC16	1	54	70	52	68	R-025	R-031	
Fri, 11-Oct-19	BC16	1	70	76	68	76	R-032	R-034	Casing sank, sediment disturbed to 95 feet
Tue, 15-Oct-19	BC16	2	60	62	0	76	R-027C		Advanced GSC-BH-BC16-2 to previous depth
Wed, 16-Oct-19	BC16	2	76	92	76	92	R-035	R-040	
Thu, 17-Oct-19	BC16	2	94	108	92	106	R-041	R-043	Casing separated
Fri, 18-Oct-19	BC16	2	108	126	106	124	R-044	R-050	
Mon, 21-Oct-19	BC16	2	126	144	124	144	R-051	R-058	
Tue, 22-Oct-19	BC16	2	144	160	144	158	R-059	R-066	
Wed, 23-Oct-19	BC16 VC2	3 1	 0	 26	0 0	27.2 24	 R-101	 R-113	Monitoring well concurrently installed in GSC-BH-BC16-3 by another drill crew. HWT casing at VC2. Start GSC-BH-VC2-1
Thu, 24-Oct-19	BC16	1,2							Installed 3" PVC in GSC-BH-BC16-2 and VWP in GSC-BH-BC16-1
Fri, 25-Oct-19	VC2	1	26	42	0	38	R-114	R-120	Replaced HWT casing with PW casing
Mon, 28-Oct-19	VC2	1	42	56	38	56	R-121	R-126b	
Tue, 29-Oct-19	VC2	1	56	76	0	74	R-127	R-136	Removed all PW casing but 20' (6.1 m), put HWT casing back in hole
Wed, 30-Oct-19	VC2	1	76	96	74	94	R-137	R-144	
Thu, 31-Oct-19	VC2	1	96	114	94	114	R-145	R-153	
Fri, 01-Nov-19	VC2	1	114	122	114	122	R-154	R-157	
Mon, 04-Nov-19	VC2	1	122	138	122	136	R-158	R-164	
Tue, 05-Nov-19	VC2	1	138	152	136	152	R-165	R-171	
Wed, 06-Nov-19	VC2	1	152	168	152	166	R-172	R-177	
Thu, 07-Nov-19	VC2	1	168	180	166	178	R-178	R-183	
Fri, 08-Nov-19	VC2	1	180	188	178	188	R-184	R-186	
Mon, 11-Nov-19	VC2	1	188	200	188	198	R-187	R-191	
Tue, 12-Nov-19	VC2	1	200	210	198	208	R-192	R-196	
Wed, 13-Nov-19	VC2	1	210	216	208	216	R-197	R-199	
Thu, 14-Nov-19	VC2	2			0	56			Installed 3" PVC in GSC-BH-VC2-1 and started drilling GSC-BH-VC2-2 for VWP
Fri, 15-Nov-19	VC2	2			56	136			Completed drilling GSC-BH-VC2-2 and installed VWP
Mon, 6-Jan-20 & Tue, 7-Jan-20	VC2 VC2	3 4			0 0	94.2 16			Installed two VWPs in GSC-BH-VC2-3 and installed a monitoring well in GSC-BH-VC2-4

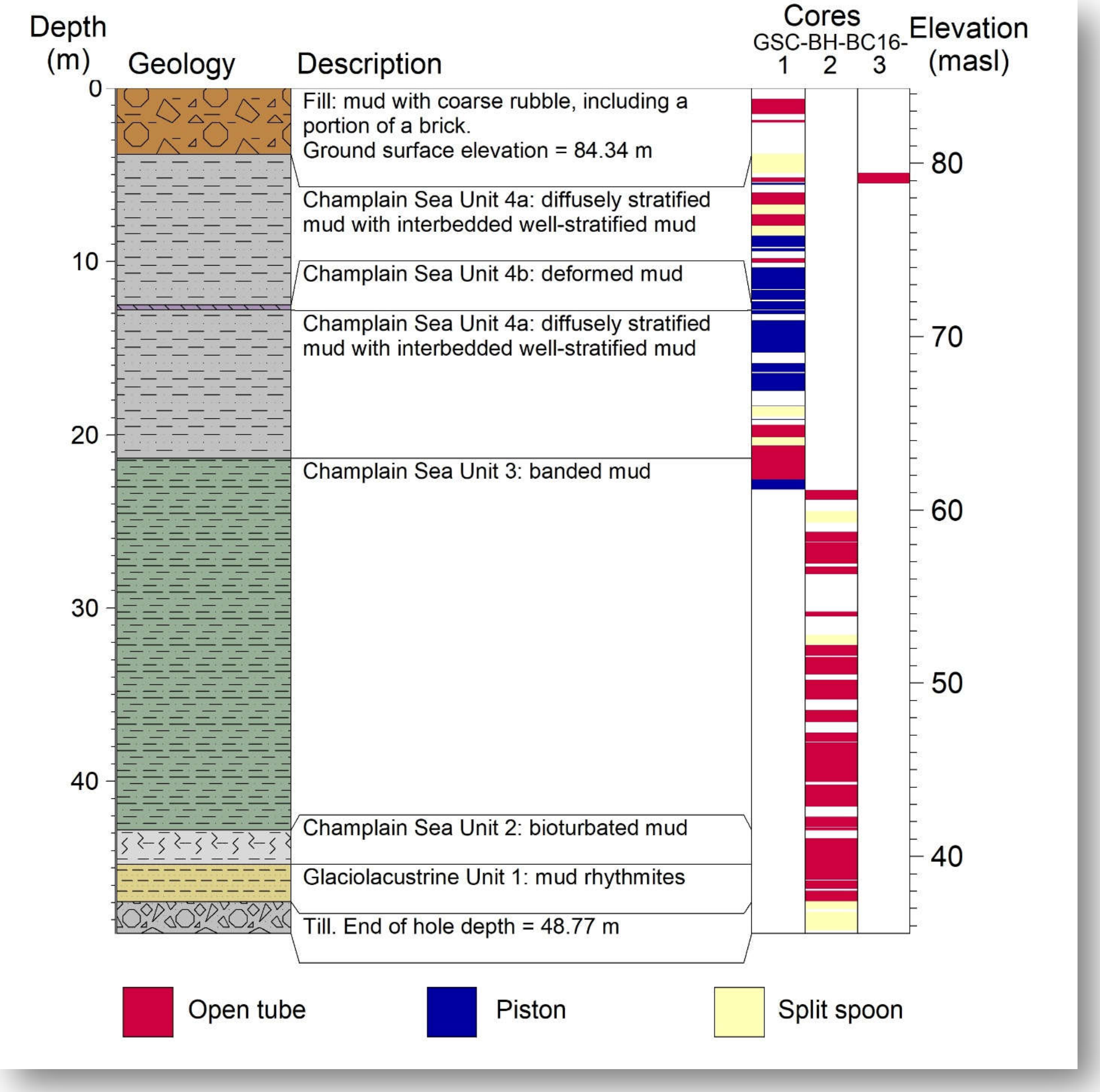

Figure 19. Simplified BC16 borehole log and coring intervals

Coring and drilling challenges

Several challenges during drilling and coring influenced core retrieval and sample quality with additional effects on productivity, time and cost.

Fill

The fill, or backfill, used to grade the slope at site BC16 consisted mostly of mud but also included construction waste such as stones and fragments of concrete and brick. The fill was not well suited for coring with Shelby tubes; several were dented, recovery was poor and recovered sediments were disturbed. The split spoon sampler penetrated and recovered the fill more effectively.

Piston sampling

The drillers used a new piston sampler for this project and, consequently, neither the drilling crew nor geotechnical contractor had experience with it. As noted above, the sampler rotated freely from the drill rods so that operator could not turn the core to shear it away from the underlying sediment and break the contact. Therefore, pulling on the drill rods and the piston sampler was the only alternative to break the core away from the underlying sediment. Successful piston core retrieval was sometimes accompanied with resistance to pulling on the sampler and a sudden release of tension. In contrast, when pulling the sampler met little resistance, the Shelby tube frequently returned to the surface empty because the target sample slid out from the bottom of the Shelby tube. When the piston sampler had little or no recovery, open tube or split spoon samplers were used occasionally to recover the remaining sediment in the target depth interval. In general, retrieval of piston samples was less successful in stiffer sediment at deeper depths. Consequently, no piston samples were attempted below a depth of 86′ (26.2 m).

Wait time before retrieval

The initial plan was to deploy the Shelby tube and retrieve the core immediately. However, initial core recovery was poor, which prompted the drillers to add a wait time for cohesion to develop between the mud and the Shelby tube wall. This approach proved to be more successful but made the coring progress slower and increased field costs. Wait times started at 30 minutes for shallow sediments but were reduced to 10 minutes in stiffer sediments.

Removal of cuttings

Water was used as the drilling fluid to avoid potential contact of cores with drilling mud or additives. Water removed mud and fine sand cuttings, as observed in the return flow and sump pit (see Figure 13). In retrospect, the density, viscosity and annular velocity of water used as the drilling fluid did not appear to be sufficient to displace coarse sand, gravel, pebbles and concretions from the borehole, particularly at greater depths (Figure 20). After advancing the casing, circulation ceased and cuttings that remained in the borehole settled, so that the only effective removal of coarse cuttings from the borehole was by coring. As a result, cuttings were typically present at the base of the borehole, which both open tube and split spoon samplers would intercept at the top of the next run (Figure 7A). These are interpreted as being disturbed parts of the core by assessment of CT scans or by visual observation, if obvious. Similarly, sometimes the drilling fluid did not break up the drilled sediment within the casing and a plug of intact sediments or clumps of partially intact sediments could not be circulated out of the drill casing (Figures 7B). These incompletely drilled sediments are observed in the CT scans at the top of some cores (Figure 21).

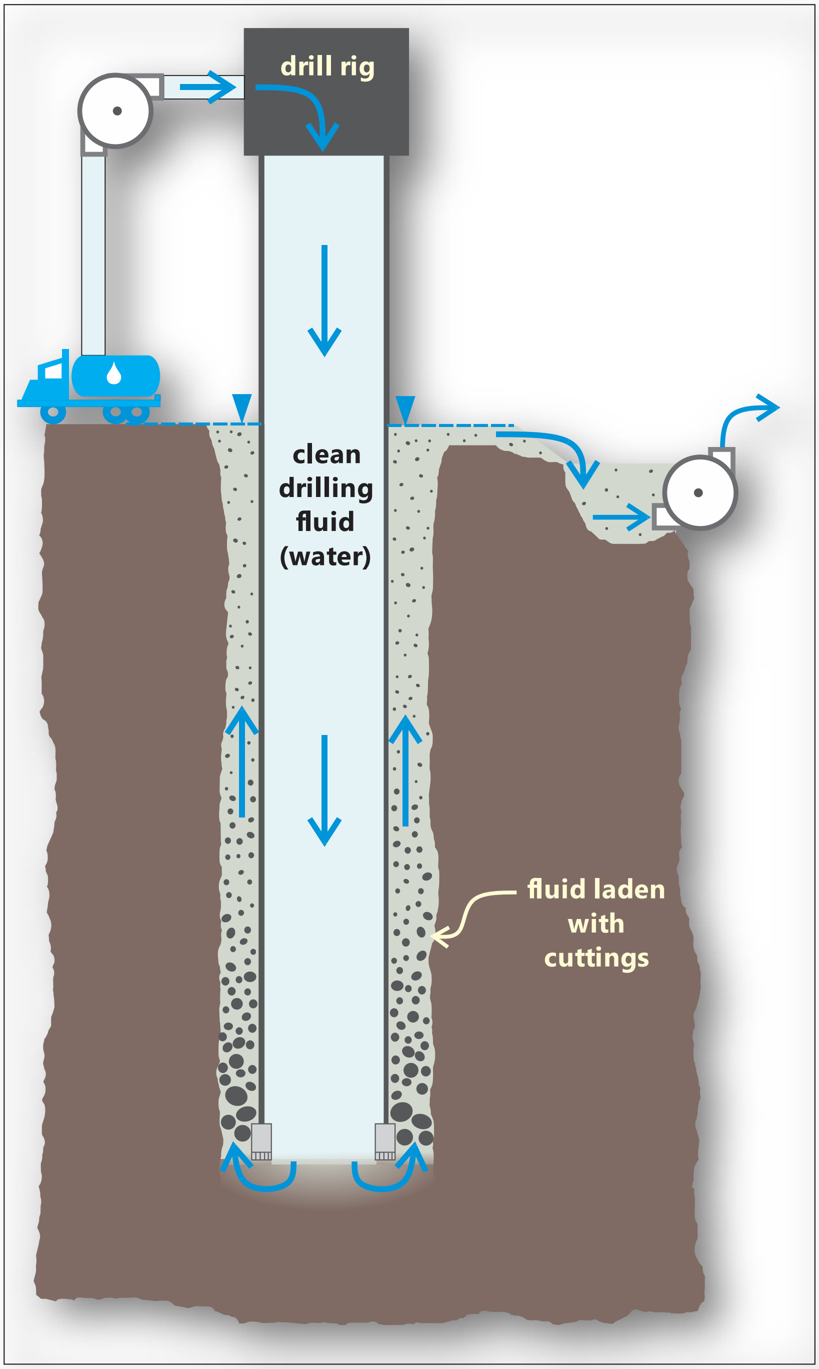

Figure 20. Incomplete removal of coarse cuttings from the borehole from the use of water as a drilling fluid

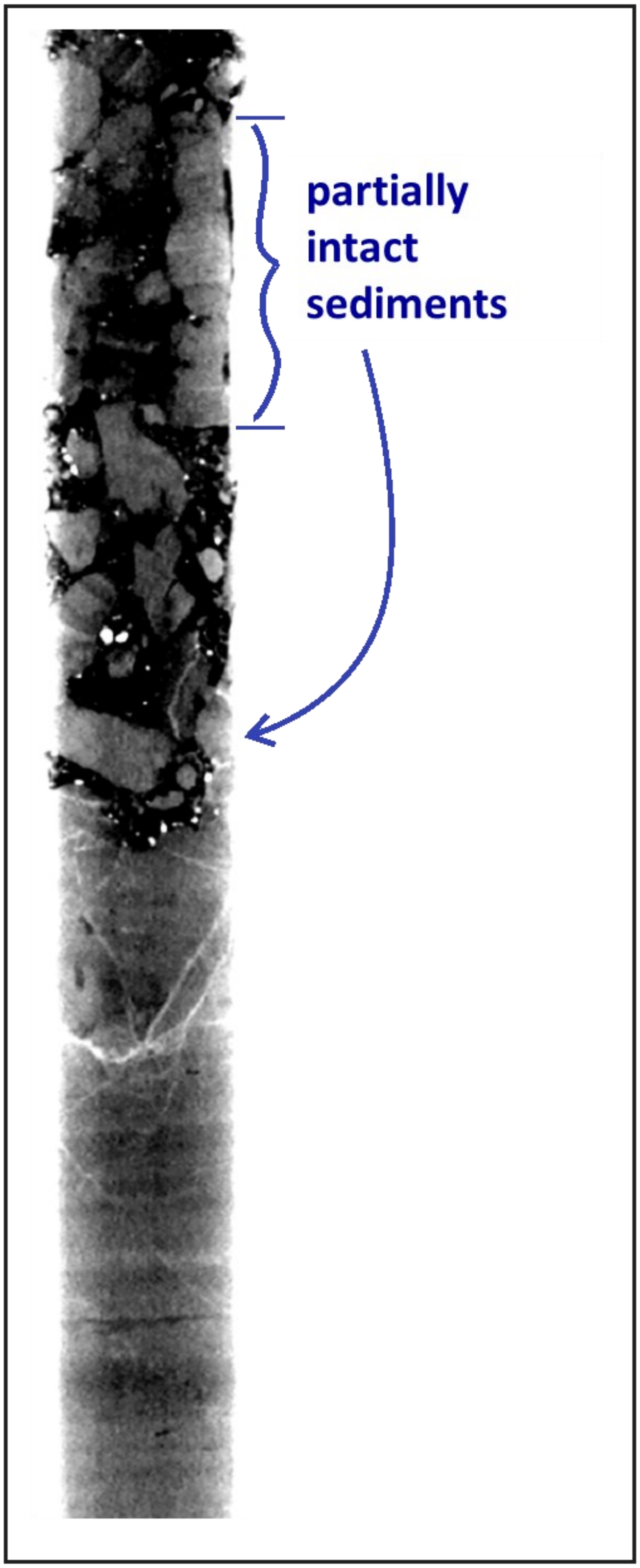

Figure 21. CT scan of disturbed sediment at top of R-045 (BC-16) with some chunks of intact layering

Concretions

Concretions from the core are smooth, rounded or flattened nodules, typically 3-6 cm long (Figure 22A and 22B) formed by chemical precipitation within Champlain Sea sediments (Gadd, 1980). The concretions occurred between approximately 40-110′ (12-33 m) at BC16. Their presence became an obstacle for coring with several dented Shelby tubes and poor or no recovery for several runs (Figure 23). The higher density of the concretions, compared to that of the sediment, make them easy to identify in CT scans (Figure 22C and 22D). Although concretions were occasionally sampled *in situ* within undisturbed core (Figure 22C and 22D), they were more commonly found in the cuttings at the top of a core (Figure 22D). As described above, it is likely that the drilling fluid viscosity and circulation were insufficient to remove the concretions, so they would settle to the bottom of the borehole when circulation stopped for coring.

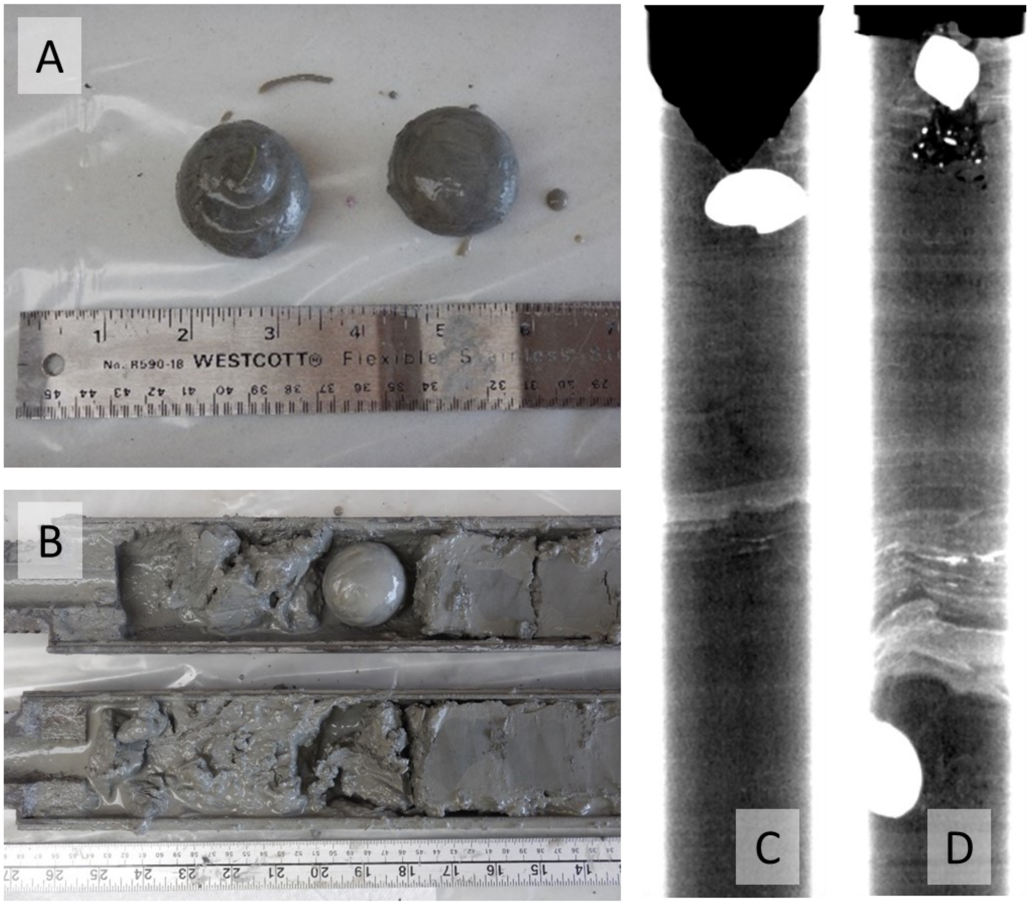

Figure 22. A) and **B**) Concretions; **C**) and **D**) concretions evident in CT scan as white spherical or ellipsoid objects, R-024 and R-039, respectively; Photographs A and B by M.J. Hinton, NRCan photo 2022-340, and NRCan photo 2022-341 respectively

Figure 23. Shelby tube dented by a concretion; Photograph by M.J. Hinton, NRCan photo 2022-342

Dropped drill casing

After collecting sample R-034 to a nominal depth of 76′ (23.2 m), the drill casing was advanced accordingly, but was not adequately secured in the casing clamps at the surface. The casing sank under its own weight. Although the drillers managed to recover the casing, it had sunk to a depth of 95′ (29.0 m) during the recovery process, thereby disturbing sediments within this interval. This first borehole (GSC-BH-BC16-1) was maintained open for subsequent installation of a vibrating wire piezometer. A new, second borehole (GSC-BH-BC16-2) was drilled approximately 1.5 m away from the first. Three attempts to resample some intervals missed in the first borehole yielded only half a Shelby tube sample (R-027C). Retrieval of all subsequent core samples was from the second borehole, with the exception of sample R-007B, collected by the geotechnical contractor using an open tube sampler from the monitoring well borehole (GSC-BH-BC16-3).

Casing separation

When the second borehole intercepted a depth of 92′, the drill casing became unthreaded at a depth of 60′. The driller kept access open to the lower casing by lowering A-rods down through the upper casing. After removing the upper 60′ of casing, a tapping tool on the A-rods allowed the removal of the lower casing. The tapping process appears to have pushed the casing down to at least 94′ and possibly to approximately 98′ because the next Shelby tube sample penetrated to 100′ from its own weight. At a sampling depth of 100′, the sampler sank to 101′9″ before it encountered any resistance. The disturbance of the sediment near the borehole during the casing recovery may have contributed to widening of the borehole annulus that could have been responsible for the appearance of backflow issues that started at a depth of 100′.

Backflow

Fresh water was circulated under pressure when the casing was advanced to clear the borehole of drill cuttings (Figure 20). When the target depth was reached and the return flow on the outside of the casing gradually became clearer, the circulation was stopped and the drill head disconnected from the casing. Occasionally, drilling water would flow back up the casing (backflow) to the surface, even when the casing was up to four feet above ground surface (Figure 24). The driller was concerned that this backflow indicated flowing artesian conditions in the borehole. However, the backflow was temporary and would decrease and stop within a minute or two. The water level would often continue to recede within the casing. Furthermore, all the backflow out of the drill casing flowed into the borehole annulus on the outside of the drill casing with no overflow to the sump, indicating that the borehole was losing fluid. This backflow was interpreted as the re-equilibration of pressure differences between the denser muddy water in the annulus with the lighter, clean water within the casing (Figure 25). This density difference and flow from the annulus to the casing would explain the pressures above the ground surface, the dropping drilling fluid level in the annulus that accommodated the overflow from the casing, and the decreasing backflow with time. One consequence of backflow is the flow of fluid laden with cuttings into the drill casing. As pressures equilibrate and backflow ceases, the cuttings can settle out within the drill casing (Figure 7A), and then are sampled by the open tube and split spoon samplers (Figure 4).

The appearance of backflow at a depth of 100′ could be related to the disturbance of the sediment near the borehole from the casing separation and recovery. The disturbance may have widened the borehole annulus which could, in turn, reduce both the velocity of the drilling mud up-hole and the ability to remove coarse sediment from the borehole. This process will be described in greater detail for site VC2.

Figure 24. Backflow from the drill casing at a borehole depth of 100′ (30.5 m) at site BC16; Photograph by M.J. Hinton, NRCan photo 2022-343

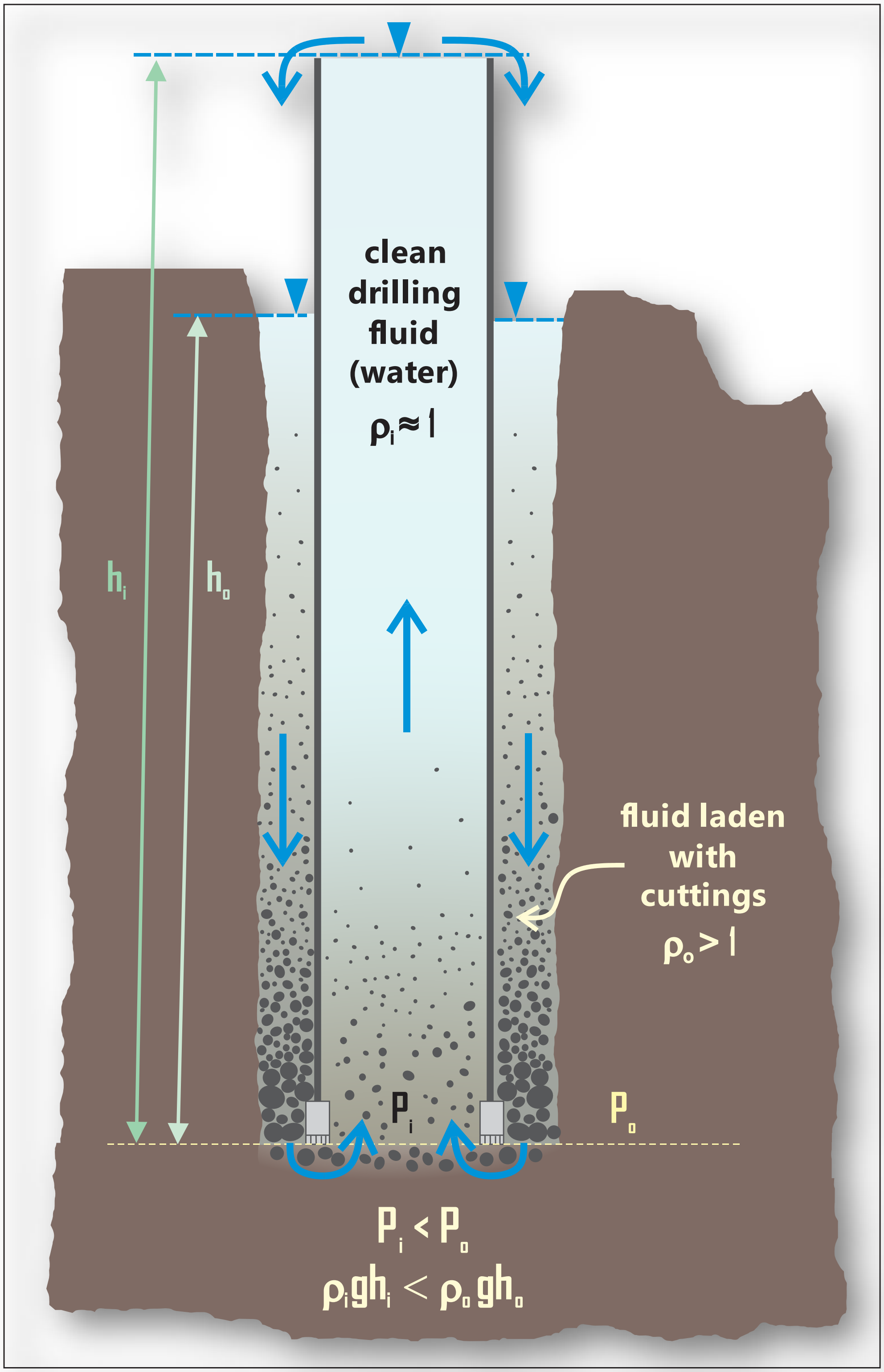

Figure 25. Backflow created by unequal pressures inside and outside the drill casing; P = pressure, ρ = density, g = gravitational acceleration and h = height of fluid; subscripts denote inside (i) and outside (o) the drill casing

PVC pipe installation

The depth of refusal at which the drill casing could not penetrate further was within the till at a nominal depth of 158′ (48.16 m), which forced the tires of the drill rig to lift off the ground. Although the original intention was to include a 3″ slotted PVC pipe at the base to make this casing a piezometer, the clearance for a tremie pipe between the PVC and drill casing was insufficient for placement of a sand filter around the slotted casing and proper grouting. Consequently, it was necessary to choose between a 2″ piezometer that would not accommodate all downhole geophysical tools and a 3″ solid pipe that would not serve as a piezometer. The priority was for borehole geophysical measurements, so the 3″ solid pipe was selected. This second borehole at BC16, GSC-BH-BC16-2, was grouted and the casing installed as previously described. The PVC pipe was initially cut close to ground surface so the drill rig could be moved back over the second borehole to the first borehole for VWP installation. The pipe was subsequently extended and a protective PVC surface casing added and sealed with bentonite chips (⅜″ graded). Filter sand (quartz sand #2) was emplaced between the PVC pipe and protective casing. The PVC casing, GSC-BC16, reaches a depth of 47.40 m below ground surface. The construction details are provided in Figure 26 and Table 2.

Vibrating wire piezometer installation and operation

The first borehole, GSC-BH-BC16-1, with the drill casing that sank and was recovered, was reoccupied on 24 October 2019. The drill casing was lowered into the borehole to a depth of 70′ (21.3 m) with only water circulation (i.e., drill casing rotation was not necessary). The casing was raised to 68′ (20.7 m); natural fill and cuttings filled the hole below this depth. Filter sand (quartz sand #2, Atlantic Sand Inc.) was emplaced in the borehole, the VWP was lowered to the target depth, more sand was emplaced around the pre-packed VWP and the drill casing was slowly raised. More sand was added to create an external sand pack from depths of 68′ to 61′9″ (20.73 to 18.82 m). The borehole was then grouted to surface using Baroid AQUAGUARD®. Table 3 lists pertinent VWP installation data, also shown in Figure 26.

The borehole was later completed at the surface with bentonite chips and a flush-mounted (i.e. ground surface) surface casing (Figure 26). The VWP was connected to an RST DT2011 datalogger on 19 November 2019. Unfortunately, the surface grading resulted in water filling the casing and flooding the datalogger. On 20 November 2020, the surface casing was excavated and reinstalled with improved surface drainage away from the casing (Figure 27).

Monitoring well installation and operation

The 2″ monitoring well was installed on 23 October 2019. The completed well included a 10′ (3.05 m) screen and an 11′ (3.4 m) sand filter pack (quartz sand #2). Bentonite chips sealed the remainder of the monitoring well. A steel surface casing was installed to protect and lock the monitoring well. Water level monitoring began on 6 December 2019 with the installation of a Solinst Levelogger® Edge and a Solinst Barologger Edge. Table 4 provides the monitoring well installation data, also shown in Figure 26.

Site BC16 layout

The completed site BC16 consists of monitoring well GSC-BC16-p1, vibrating wire piezometer GSC-BC16-p2, and a solid casing, GSC-BC16, for borehole geophysical logging (Figure 28).

Table 2. Deep borehole installations

	SI unit		
GSC installation ID		GSC-BC16	GSC-VC2
GSC borehole ID		GSC-BH-BC16-2	GSC-BH-VC2-1
consultant borehole ID		BC-16GSC	VC-02GSC
borehole, total depth	m bgs	48.77	65.89
caved sediment, depth interval	m bgs	47.40 - 48.77	none
measurement from top of protective surface casing to bottom of PVC casing, after installation)	m	48.25	66.85
protective surface casing stick up	m ags	0.85	0.95
PVC casing stick up	m ags	0.79	0.89
casing bottom - depth	m bgs	47.40	65.89
casing material		PVC schedule 40	PVC schedule 40
nominal diameter, 3-inch	cm	7.6	7.6
grout material		bentonite	bentonite
grout, depth interval	m bgs	0.00 - 47.40	0.00 - 65.89
casing - installation date		24-Oct-2019	14-Nov-2019

Note: ags = above ground surface, bgs = below ground surface

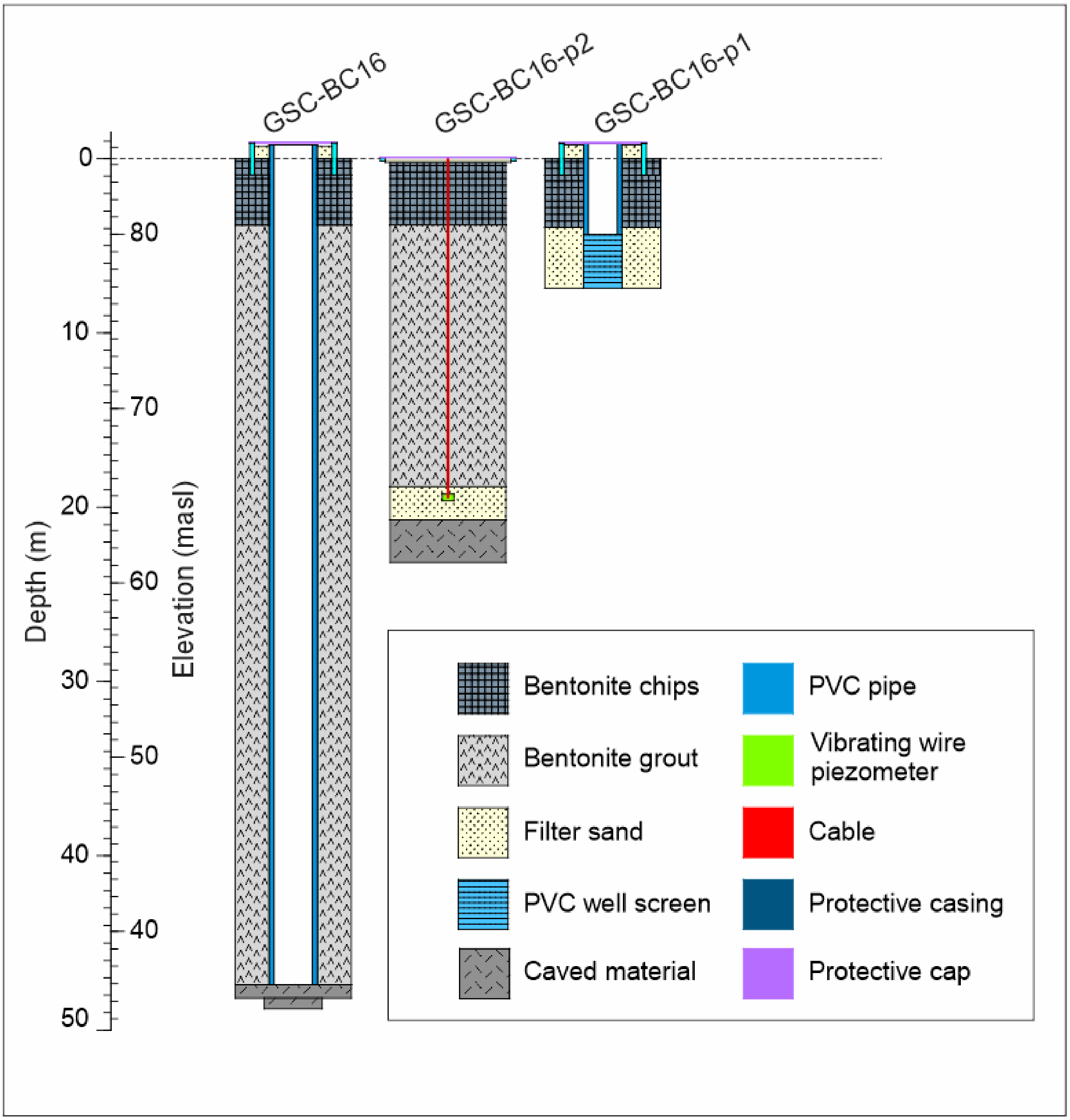

Figure 26. Borehole installations at site BC16; note that depths of the bentonite chips in GSC-BC16 and GSC-BC16-p2 are approximate.

Figure 27. Improved surface drainage for the vibrating wire piezometer, GSC-BC16-p2, installed within the flush mount casing, left; The casing for borehole geophysical logging, GSC-BC16, is on the right. Photograph by S. Alpay, NRCan photo 2022-344

Table 3. Vibrating wire piezometer completions

	SI unit				
GSC piezometer ID		GSC-BC16-p2	GSC-VC2-p2	GSC-VC2-p3	GSC-VC2-p4
GSC borehole ID		GSC-BH-BC16-1	GSC-BH-VC2-3	GSC-BH-VC2-3	GSC-BH-VC2-2
consultant borehole ID		BC-16VWP	VC-02V/S	VC-02V/S	VC-02-VWP
borehole, total depth	m bgs	23.16	28.70	28.70	41.61
caved sediment, depth interval	m bgs	20.73 - 23.16	28.40 - 28.70	28.40 - 28.70	none
VWP installation depth	m bgs	19.44	13.47	28.01	41.20
filter pack material		quartz sand #2	quartz sand #2	quartz sand #2	quartz sand #2
filter pack, depth interval	m bgs	18.82 - 20.73	13.10 - 13.95	27.55 - 28.40	40.77 - 41.61
grout, depth interval	m bgs	0.00 - 18.82	0.00 - 13.10	13.95 - 27.55	0.00 - 40.77
grout material		bentonite	bentonite	bentonite	bentonite
ground surface completion		8" flush-mount casing	12" flush-mount casing	12" flush-mount casing	12" flush-mount casing
vibrating wire piezometer - model		VW2100-0.175	VW2100-0.35	VW2100-0.35	VW2100-0.7
vibrating wire piezometer - serial number		VW56559	VW16969	VW16968	VW16971
vibrating wire piezometer - pressure range	MPa	0.175	0.35	0.35	0.7
vibrating wire piezometer - installation date		24-Oct-2019	07-Jan-2020	07-Jan-2020	15-Nov-2019

Note: bgs = below ground surface, VWP = vibrating wire piezometer

Table 4. Monitoring well completions

	SI unit		
GSC piezometer ID		GSC-BC16-p1	GSC-VC2-p1
GSC borehole ID		GSC-BH-BC16-3	GSC-BH-VC2-4
consultant borehole ID		BC-16MW	VC-02MW
casing, total length (MP to bottom, after installation)	m	8.29	6.10
MP stick up	m ags	0.87	1.17
casing bottom - depth	m bgs	7.42	4.93
casing material		PVC, schedule 40	PVC, schedule 40
nominal diameter, 2-inch	cm	5.1	5.1
slotted casing, depth interval	m bgs	4.37 - 7.42	1.88 - 4.93
filter pack material		quartz sand #2	quartz sand #2
filter pack, depth interval	m bgs	3.96 - 7.42	1.52 - 4.93
grout material		bentonite	bentonite
grout, depth interval	m bgs	0.00 - 3.96	0.30 - 1.52
protective surface casing material		6" diameter steel casing	6" diameter steel casing
protective surface casing, stick up	m ags	0.94	1.24
piezometer - installation date		23-Oct-2019	07-Jan-2020

Notes: ags = above ground surface, bgs = below ground surface, MP = Measuring Point (top of PVC).

Figure 28. BC16 site layout; photograph by M.J. Hinton, NRCan photo 2022-345

Site VC2

Site VC2 is located on city property along Country Walk Drive, opposite Des Sapins Gardens, in Orleans, Ottawa. The property is at the head of a ravine branching off the western tributary of Bilberry Creek (i.e., Voyageur Creek; Figure 29) in an area where the surficial geology is mapped as estuarine and deltaic sandy sediment of the Champlain Sea (Richard, 1982).

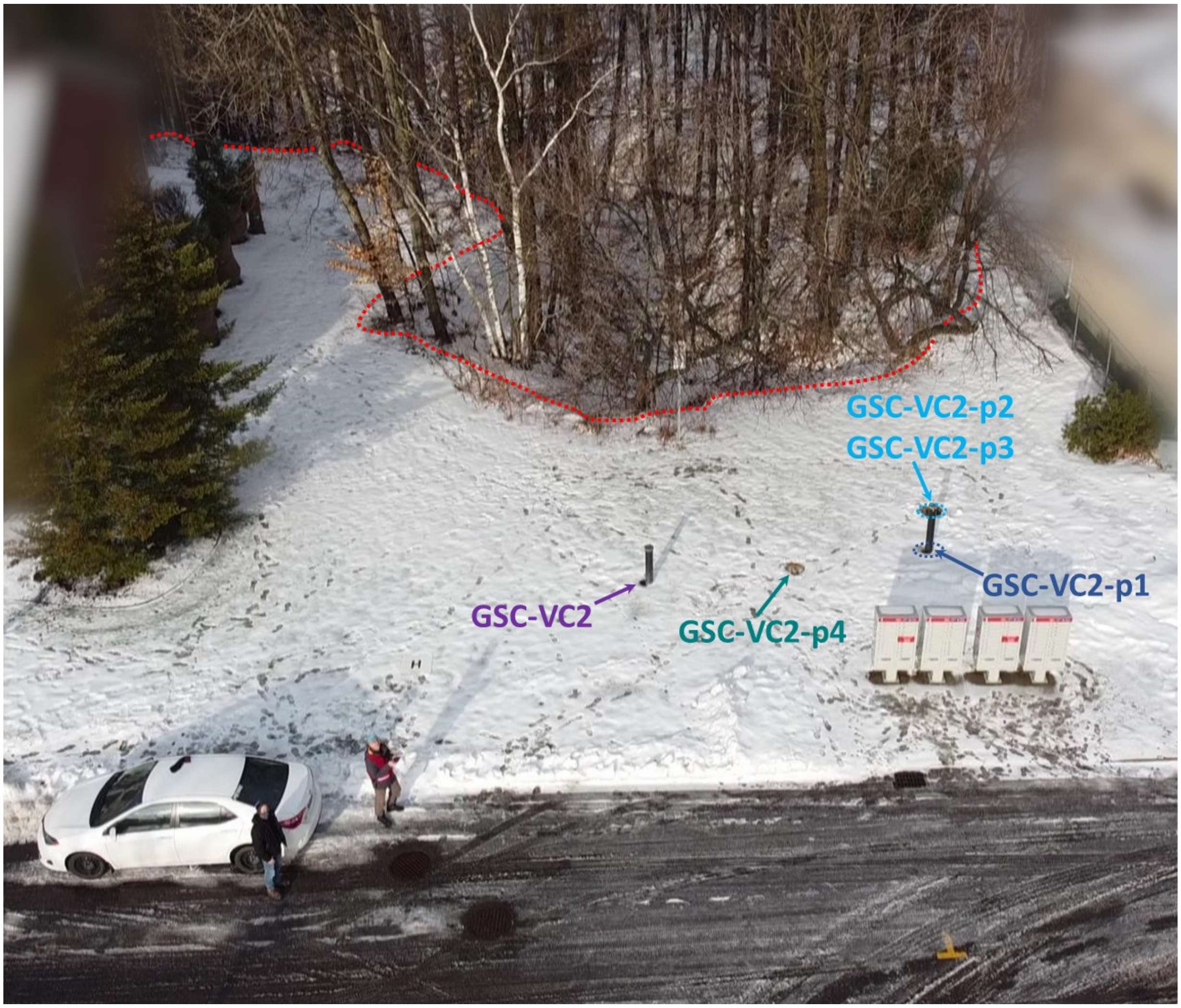

Figure 29. Drone aerial photograph of site VC2; dashed red line indicates the edge of the ravine. Photograph by A. Grenier, NRCan photo 2022-346

Coring

Site VC2 was cored from 23 October to 13 November 2019, with the installation of the deep casing on 14 November 2019. A second borehole was drilled 14-15 November 2019 to install a VWP. Two more VWPs were installed in a borehole used for geotechnical sample collection and shear vane testing 6-7 January 2020. The crew also installed the monitoring well in a separate borehole, 7 January 2020. Table 1 is a compilation of daily drilling progress. Daily weather data measured at the Ottawa International Airport (20 km SW) are reported in Figure 18. Temperatures dropped below 0°C, which required attention to prevent freezing of water in drilling equipment and sediment cores.

Sediments at site VC2 consist of silty sand described as fill from the surface to a depth of 10′ (3.0 m), silty sand from 10′ to 14′ (3.0-4.3 m) depth and muddy Champlain Sea sediments from 14′ to the end of the borehole at 216′ (4.3-65.9 m; Figure 30). Unit contacts are based on field logs and CT scan results (Al-Mufti et al., 2022).

Shelby tubes and split spoon samples from VC2 were numbered sequentially from R-101 to R-199 (see spreadsheet in Appendix). In total, 113 runs were completed at VC2, 13 with a piston sampler, 89 with an open tube sampler and 11 with a split spoon sampler. From these runs, 10 piston sampler cores, 80 open tube sampler cores and 9 split spoon samples were retrieved. Intact core recovery at VC2 accounts for 74% of the depth between the fill and the end of the borehole (65% open tube, 5% piston and 4% split spoon).

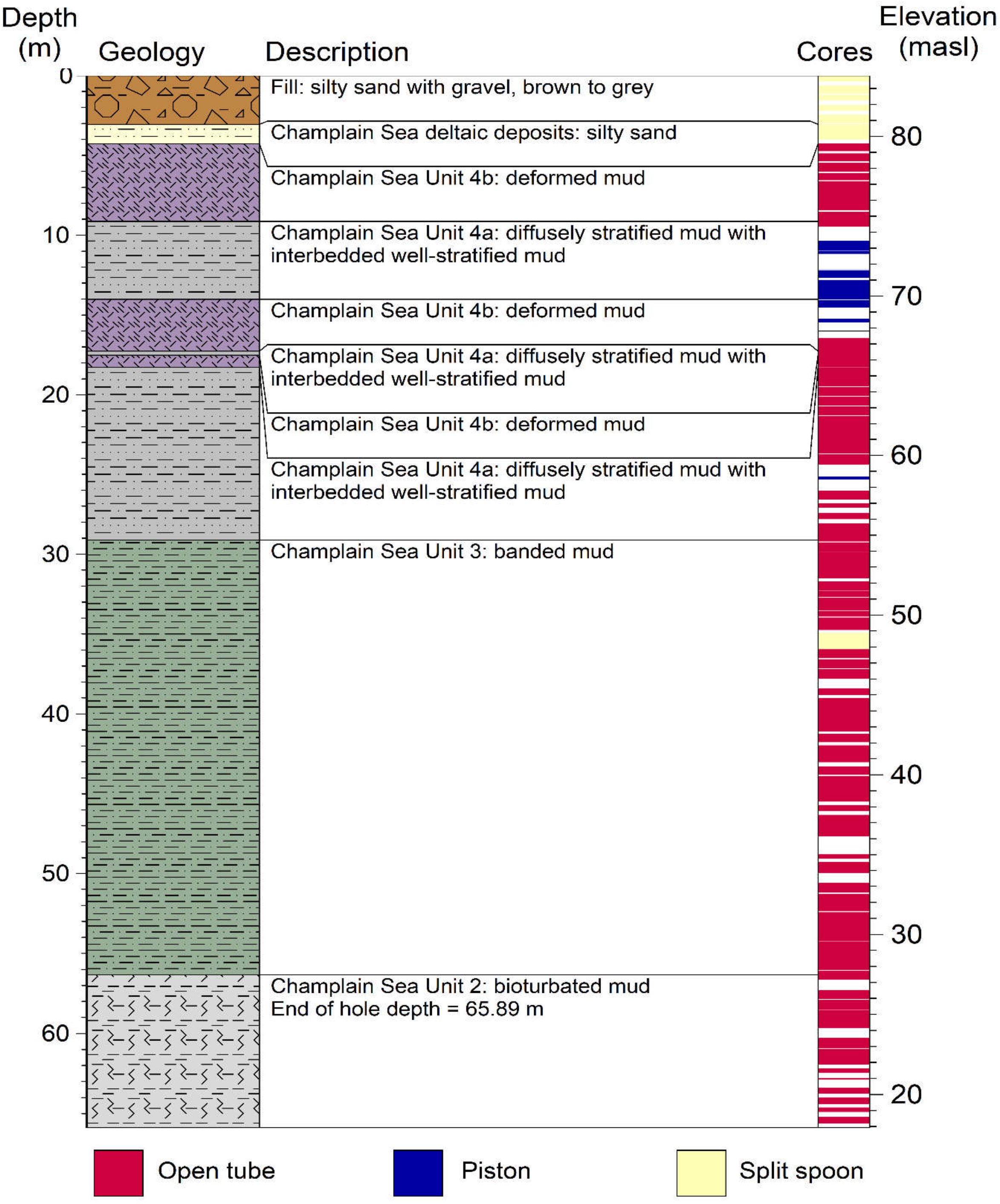

Figure 30. VC2 borehole log and coring intervals

Drilling and coring challenges

Casing size

Larger-sized, PW drill casing (5½″ OD with straight threads, 4 threads per inch) was used at the VC2 borehole to allow installation of a 3″ PVC pipe as a piezometer with a screen and filter sand because the larger inner diameter (5″) could allow sufficient space for the 3″ PVC pipe and a tremie pipe for filter sand emplacement. The PW casing was not available when borehole VC2 was started, so HWT casing was used on the first day of drilling to a depth of 26′ (7.9 m). PW casing replaced the HWT casing, but the larger diameter of the PW casing created greater difficulty in removing sediment and drill cuttings from the drill casing (Figure 7B). The increased time to clean out the casing and the thicker remaining sediment to be penetrated by the open tube sampler made continued use of the PW casing problematic. At a depth of 56′ (17.1 m), the HWT drill casing was re-introduced to drill the remainder of the borehole. Most of the PW casing was removed, leaving only 20′ (6.1 m) in the borehole for support. This decision improved the efficiency of cleaning out of sediment from the drill casing (Figure 7) and increased core recovery while reducing the time to advance casing. However, the larger annulus of a portion of the borehole from the use of PW casing ultimately reduced the effectiveness of drill cutting removal.

Backflow and drilling fluid circulation

Backflow up the drill casing after it was disconnected from the drill head was observed firstly at VC2 at a depth of 120′ (36.6 m). It was observed again at 164′ (50.0 m; Figure 31A) and became more frequent at greater depth. As in BC16, the backflow was temporary. It flowed out of the drill casing (i.e., into the borehole annulus outside the drill casing) and did not overflow to the sump. As similarly interpreted at BC16, this backflow was likely the re-equilibration of pressure differences outside and inside the casing (Figure 25). At 176′ (53.6 m) and at some deeper intervals, the backflow was greater (Figure 31B) and sometimes eventually became turbid. However, the backflow always decreased or stopped within about three minutes. At 216′ (65.9 m), the backflow lasted approximately ten minutes, was more turbid and foamed, which, according to the driller’s experience, suggested possible interception of sandy layers. The increasing concern about potential flowing artesian conditions in more permeable sediments led to the decision to stop drilling and complete the casing installation at 216′ (65.9 m).

On three occasions, it was difficult to re-establish drilling fluid circulation during resumption of drilling in the morning. These occurred at depths of 138′, 188′ and 200′ (42.1, 57.3, and 61.0 m respectively). These difficulties likely resulted from the settling of cuttings overnight or over the weekend, which effectively cut off circulation within the borehole until the cuttings could be re-suspended (Figure 7A).

In retrospect, the observations of increasing backflow with depth and difficulty in re-establishing circulation were consistent with increasing difficulty to clean out drill cuttings at greater depths using water as the drilling fluid. The wider diameter of the upper 56′ (17.1 m) of the borehole, when using the PW casing, would have reduced up-hole drilling fluid velocity and decreased transport of coarse drill cuttings out of the borehole (Figure 32). The greater challenge in removing coarse sediment from the VC2 borehole would have resulted in an increasing density of drilling fluid in the annulus outside the casing and, consequently, greater backflow that took longer to equilibrate. It is likely that the use of bentonite-based drilling mud, as the drilling fluid instead of fresh water, would have improved sediment removal from the hole. Drilling mud is not commonly used in geotechnical coring within the Champlain Sea sediments because depths of the boreholes are generally shallower and the muddy sediment cuttings provide some viscosity to the water as drilling fluid.

Figure 31. **A**) Backflow at a borehole depth of 164′ (50.0 m) at site VC2; and **B**) backflow at a borehole depth of 206′ (62.8 m); photographs by M.J. Hinton, NRCan photo 2022-347 and 2022-348 respectively

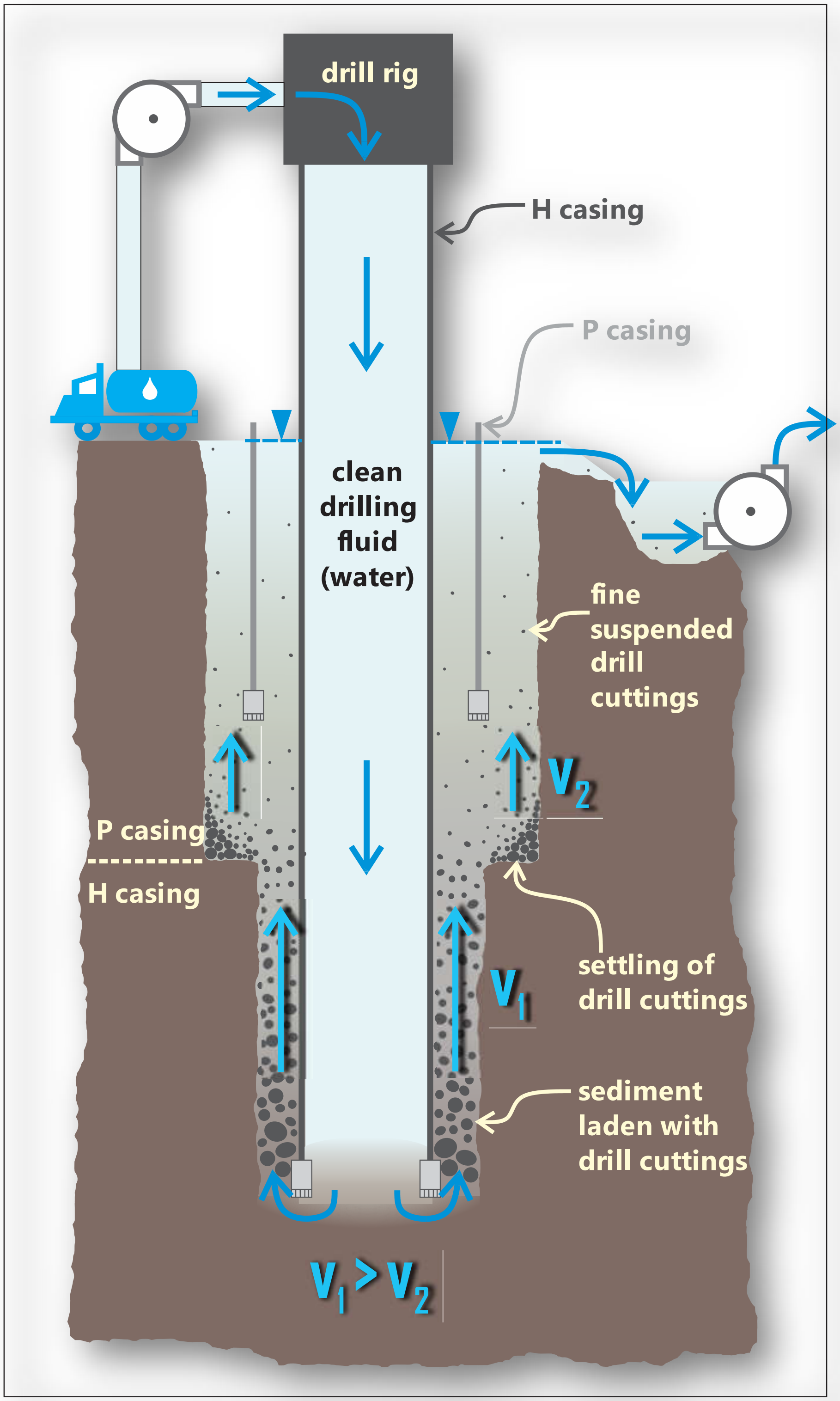

Figure 32. The use of larger diameter (P-sized) drill casing created a barrier to the removal of coarse cuttings because it decreased drilling fluid velocity up-hole (from V_1 to V_2).

PVC pipe installation

As was the case for BC16, the return to HWT-sized drill casing required the decision between a solid 3″ PVC pipe and a 2″ slotted PVC piezometer. A solid 3″ PVC pipe suitable for borehole geophysical measurements was installed in the deep borehole on 24 November 2019. The borehole was completed with bentonite grout (Baroid AQUAGUARD®), similarly to BC16. It was necessary to use 70′ (21.3 m) of drilling rods (A-sized), in addition to the drillers' combined body weights, to submerge the water-filled PVC pipe into the grout. The top of the borehole was sealed with thirty-five 50-lb (22.7 kg) sacks of ⅜″ graded bentonite chips (Baroid HOLEPLUG®). The large quantity of bentonite chips added to the borehole indicates that a significant amount of them sank into the grout (Figure 33). A 6-foot-long, 6-inch diameter black ABS pipe was installed as a protective surface casing above ground, along with one additional bag of HOLEPLUG® and five 25-kg sacks of quartz sand. The PVC pipe was completed to a depth of 65.89 m below ground surface (Table 2, Figure 33).

Vibrating wire piezometers installation and operation

With the installation of a solid PVC casing in the deep borehole, a separate, shallower borehole was necessary for a VWP installation. This borehole was drilled 14-15 November 2019 with a casing advancer (a removable tricone bit to drill sediments in front of the casing shoe) to reach the target depth of 136′ (41.45 m) more rapidly. The borehole was thoroughly washed with water before emplacing approximately 0.35 m of filter sand (quartz sand #2, Atlantic Sand Inc.) at the base. The pre-packed VWP was lowered into position and additional filter sand added for a total filter sand pack of approximately 1.1 m. The next steps were to grout the borehole to surface, using Baroid AQUAGUARD®, and install a 12″-diameter flush-mount surface casing. By 19 November 2019, the grout level had dropped to 2.6 m. That day, a datalogger was connected to begin monitoring the VWP, along with a Solinst Barologger Edge to monitor barometric pressure. Subsequently, the drillers filled in the borehole with bentonite chips and filter sand at the ground surface.

Borehole VC-02S/V (GSC borehole ID: GSC-BH-VC2-3) was drilled to a depth of 94′2″ on 6-7 January 2020 (Table 3 and Figure 33) for RVCA's geotechnical core sampling and testing. Upon completion, this borehole provided the opportunity to deploy two more VWPs. Each pre-packed VWP was emplaced within filter sand in the borehole. Bentonite chips were used to seal the borehole between and above the VWPs. The borehole was completed with a 12″ diameter flush-mount surface casing. Dataloggers began monitoring these VWP sensors on 23 October 2020. Details of the VWP installations are listed in Table 3 and shown in Figure 33.

Monitoring well installation and operation

The 2″ monitoring well was installed to a depth of 16′ (4.9 m) on 7 January 2020. The completed well included a 10′ (3.05 m) screen and an 11′ (3.4 m) sand filter pack (quartz sand #2; Table 4, Figure 33). Bentonite chips sealed the well up to 1′ (0.3 m) depth. A steel surface casing filled with filter sand served to protect and lock the monitoring well in place. Water level monitoring began on 27 October 2020 with the installation of a Solinst Levelogger® Edge; the Solinst Barologger Edge was moved to the monitoring well.

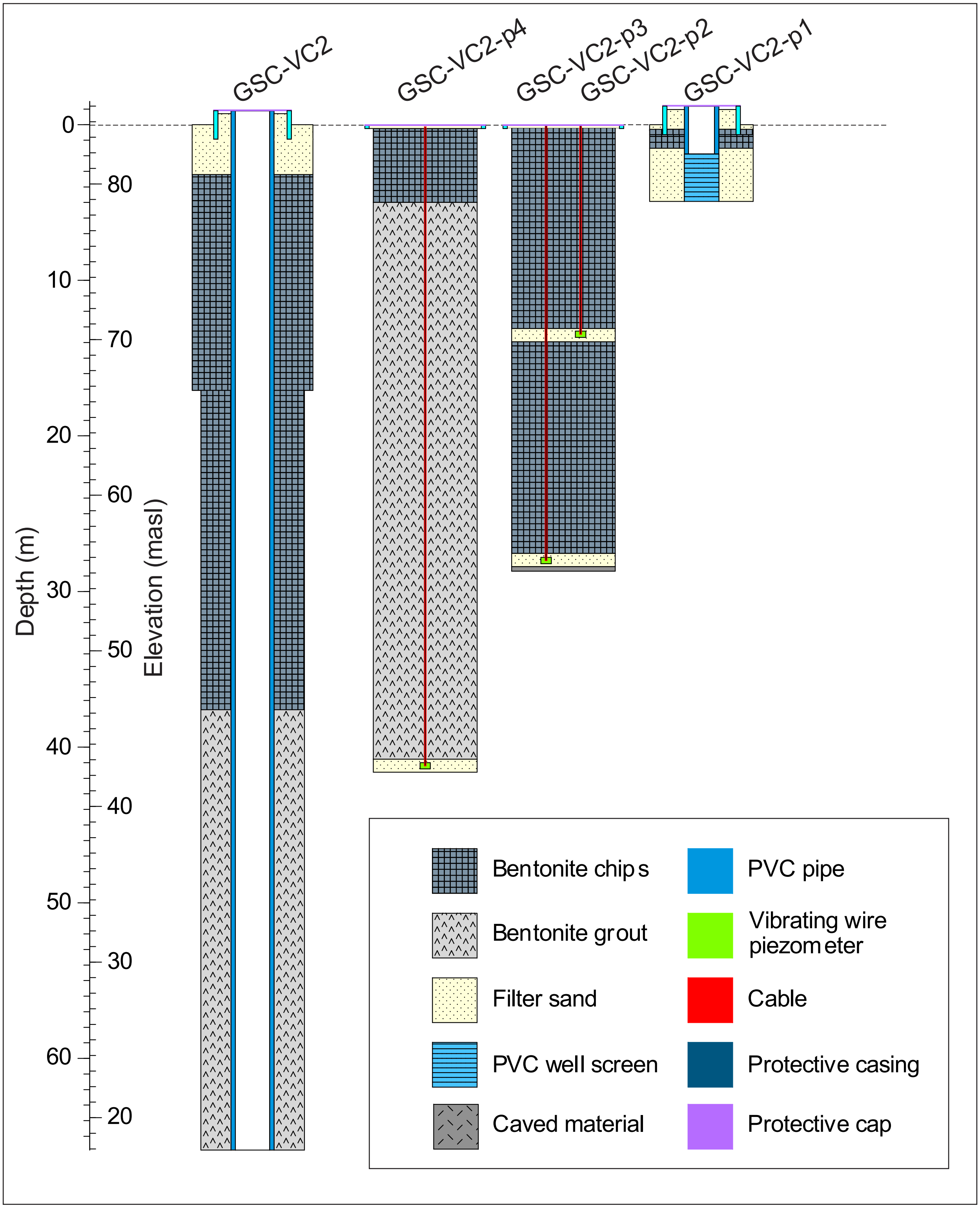

Figure 33. Borehole installations at site VC2; note that depths of the bentonite chips in GSC-VC2 and GSC-VC2-p4 are approximate.

Site VC2 layout

The completed site at VC2 consists of monitoring well GSC-VC2-p1, vibrating wire piezometers GSC-VC2-p2 and GSC-VC2-p3 inside one flush-mount surface casing, vibrating wire piezometer GSC-VC2-p4 in another, and a solid PVC casing, GSC-VC2, for borehole geophysical logging (Figure 34).

Figure 34. VC2 site layout; photograph by M.J. Hinton, NRCan photo 2022-349

GPS site survey

The locations and elevations of all installations were identified on 27 October 2020 using a Global Positioning System (GPS) survey at each site (Table 5). The surveys were completed using two Hemisphere® S321 GNSS receivers/antennas in a base station and rover Real Time Kinematic (RTK) configuration. Each survey established the position of the base station by continuously collecting GPS data over a period of 3 hours and 50 minutes at BC16 and 2 hours 8 minutes at VC2. The rover measured the relative location of each surveyed site (corrected to the base of the shaft) while receiving RTK positions via a UHF radio link from the base station (Figure 35). The GPS data were post-processed using the Canadian Spatial Reference System Precise Point System (CSRS-PPP) by the Canadian Geodetic Survey (NRCan), available online. Offset corrections of the base station position were applied to the rover GPS data. Horizontal and vertical errors of the base station are estimated to be approximately 1 and 2-3 cm, respectively. Casing heights above ground surface (stick-ups) were measured with a measuring tape.

Table 5. Surveyed locations and elevations of installations

Installation	Northing	Easting	Ground surface elevation[1], (CGVD2013)	MW screen midpoint, VWP sensor, or casing bottom elevation[2]	MP elevation[3]
GSC-BC16-p1	5034233.05	460666.85	83.98	78.08	84.85
GSC-BC16-p2	5034230.14	460662.72	84.20	64.76	N/A
GSC-BC16	5034230.16	460661.26	84.34	36.95	85.13
GSC-VC2-p1	5033934.00	457962.02	83.89	80.48	85.06
GSC-VC2-p2	5033935.54	457961.14	83.89	70.42	N/A
GSC-VC2-p3	5033935.54	457961.14	83.89	55.88	N/A
GSC-VC2-p4	5033931.68	457960.09	83.84	42.64	N/A
GSC-VC2	5033929.14	457958.06	83.81	17.92	84.71

Notes: all measurements in m. [1] surveyed elevation, Canadian Geodetic Vertical Datum of 2013 (CGVD2013). [2] calculated from ground surface elevation. [3] MP elevation = measuring point elevation at top of inner PVC pipe (not the protective surface casing), calculated from ground surface elevation and the pipe stick up above ground surface.

Figure 35. GPS survey of GSC-VC2 with the rover in the foreground and the base station in the background; photograph by M.J. Hinton, NRCan photo 2022-350.

Conclusions

This GSC Open File documents the drilling and coring of two sites for geoscientific studies of Champlain Sea sediments near Bilberry Creek, Ottawa, in the fall of 2019. A total of 146 cores was collected in Shelby tubes for subsequent analysis. At site BC16, the entire 42.6 m thickness of the Champlain Sea sediments was penetrated; at site VC2, 65.9 m of approximately 80 m of sediments were penetrated. Two deep casings allow borehole geophysical logging. Four vibrating wire piezometers and two monitoring wells adjacent to the deep boreholes serve for monitoring hydraulic heads at different depths.

In general, geotechnical studies of Champlain Sea sediments are limited to shallower depths, whereas Shelby tube cores are rarely collected in hydrogeological studies. Hydrogeological studies are more likely to use a more rapid wireline coring technique in which longer cores are rapidly extruded from the core barrel on site (e.g., Medioli et al., 2012). Wireline coring can disturb cores and prevent proper core preservation for many geotechnical tests and CT scans. The collection and preservation of nearly continuous Shelby tube cores in this study provide the opportunity for detailed multidisciplinary analyses of Champlain Sea sediments in largely undisturbed cores. For example, sampling in Shelby tubes makes it possible for CT scans of sediments to obtain detailed images of sediment density, laminae and structures that are not possible from visual observations of wireline cores (Al-Mufti et al., 2022).

Experiences of both the coring of Champlain Sea sediments using Shelby tubes and the installation of piezometers provided new technical insights. The following suggested practices are for 3″ PVC casing/piezometer installations and the retrieval of 2⅞″ (7.3 cm) core using Shelby tubes in Champlain Sea sediments for future geological and hydrogeological studies:

- Installation of a deep 3″ PVC pipe with a well screen, which would serve both as access for borehole geophysical logging and as a piezometer, was not possible within the 4.0″ inner diameter (H-sized) casing. Additionally, wash boring with water and coring were not efficient inside 5.0″ inner diameter (P-sized) casing.
- An alternate approach for future studies would be to drill a first borehole to bedrock with a tricone bit before coring a second borehole. This first borehole could be drilled much more rapidly and with safeguards, such as a cemented surface casing and weighted drilling muds, for any potential flowing artesian conditions, if needed. This borehole would permit installation of a 3″ PVC pipe with a well screen to serve as a standpipe piezometer and accommodate borehole geophysical logging. This approach has several added advantages:
  1. drilling would define the depth to bedrock and the thicknesses of Champlain Sea sediments and till in advance of coring,
  2. the standpipe piezometer would permit sampling of water chemistry beneath Champlain Sea sediments and the measurement of hydraulic head to identify any flowing conditions at the bedrock contact, and
  3. coring of a second borehole would also benefit from advance knowledge of expected depths and stratigraphy based on geophysical logging of the first borehole. When completed, this second borehole could accommodate installation of a vertical nest of vibrating wire piezometers to monitor hydraulic heads and

vertical hydraulic gradients, if warranted. Alternately, pneumatic piezometers could be installed to the exterior of a slotted PVC casing to allow for additional hydraulic head and vertical gradient measurements.

The microtremor (HVSR) survey proved to be a simple, cost- and time-effective approach to estimate the depth of Champlain Sea sediments overlying a till or bedrock horizon (Dietiker, 2020). If the depth of sediments is not well known or if there is a need to compare several potential drill sites, the survey can be a useful method to inform decisions about drilling location. A similar survey may be useful to define the distribution of sediment thickness around a drill site.

Other insights pertain specifically to the coring of sediments using Shelby tubes. Although most of these suggestions are not new insights, they arose specifically from experience during this coring project:

- The use of drilling mud in boreholes greater than approximately 30 m depth would ensure the efficient removal of drill cuttings from the borehole. It would also be an added safety measure, along with a cemented surface casing and barite on site as a mud additive for weight, if there is any possibility of flowing artesian conditions. The use of re-circulated mud would reduce the need and cost of having a water truck on site for the full duration of drilling.
- The piston sampler has the specific advantage that it can be pushed through any sediment that remains or settles inside the drill casing. Therefore, it ensures better control on sediment depth intervals collected within the Shelby tubes and prevents the potential overfilling of the Shelby tube using an open tube sampler. A key recommendation would be to ensure that the piston sampler design allows it to be rotated following deployment to allow for breaking of the core from its contact with the underlying *in-situ* sediment. Evidently, most piston samplers are capable of rotating the sample to break the contact, but the one used in the current study was not.
- To ensure accurate depth intervals for each retrieved core, it is important to record all lengths and depths carefully. Firstly, to ensure that the exact depth of both the casing and sampler are known for each sample, it is necessary to measure and record the lengths of the drill rods and casings, the casing shoe and the sampler(s). Metric and standard casing lengths are interchangeable and can result in cumulative depth errors if unrecognized. Secondly, it is essential to measure the depth to sediment inside the casing before deploying a corer, particularly if using an open tube sampler. A weighted measuring tape with a wide (e.g., 1-1.5″) flat bottom would prevent it from sinking into the loose cuttings. This measurement allows the calculation of the sampled core depth interval.
- Shelby tubes are not ideal for sampling in all conditions within Champlain Sea sediments. For example, in this study coring with Shelby tubes was less effective in zones where there were concretions, but there was no advance indication of their presence. Concretions tend to accumulate with cuttings inside the drill casing, however, removal of the concretions is possible by raising the casing and circulating the drilling fluid to displace the cuttings to the outside of the casing. If that is not possible, the only other effective method of concretion removal is through sampling, either in a Shelby tube, which may damage the tube and not be successful, or in a split spoon sampler, which does not provide an undisturbed sample in a core tube. Although Shelby tube coring is

not ideal for sandy sediment, retrieval of interbedded sandy and muddy sediments was effective in this study as the muds helped to retain coarser layers within the core tubes.

Documentation of drilling and coring details, as presented in this GSC Open File, is an essential reporting component that can influence the interpretation of the cores and provides critical baseline information for the multidisciplinary studies arising from these cores, boreholes and piezometric data.

Acknowledgments

We would like to thank the Rideau Valley Conservation Authority (RVCA), with the support of the City of Ottawa, for making this project possible and directly funding the coring initiative. Terry Davidson and Claire Milloy, RVCA, greatly simplified the GSC component of the project by leading and managing the contracting for the entire Bilberry Creek Project. Michel Kearney, City of Ottawa, secured the funding to make the coring possible. The GSC, Natural Resources Canada, supported this study through the Public Safety Geoscience and Groundwater Geoscience programs. The Archetypal Aquifer Project, led by Hazen Russell, GSC, provided funding to allow the installation of vibrating wire piezometers and monitoring wells. We thank Greg Brooks for proactively soliciting interest in coring thick sequences of Champlain Sea sediments in Eastern Ontario on our behalf. We gratefully acknowledge assistance with core preservation in the field from Alain Grenier and Heather Crow, GSC, and Magda Celejewski, University of Ottawa. Barbara Dietiker and Alain Grenier, GSC, conducted and interpreted the HVSR and elevation surveys, respectively. We wish to acknowledge Matt Pyne, GSC, who graciously provided the base map for Figure 1B. We are grateful to Heather Crow for helpful comments in her detailed review of this Open File Report. We would also like to thank the Bilberry Creek project consultant, GEMTEC, and several staff members, who participated in project management and oversaw drilling and coring in the field: John Cholewa, Susan Trickey, Adrian North, Michel Lalonde, and Brett Webster. The drilling subcontractor, Downing Estates Drilling, was professional and worked diligently to meet project goals. In particular, we would like to thank drill operator, Glenn Neill, and drilling assistant, Ian Dumoulin, who drilled most days with occasional substitutes, Jeff White, Dannick Bourguoin, and Steve Carrière.

References

Al-Mufti, O.N., Arnott, R.W.C., Hinton, M.J., Alpay, S. and Russell, H.A.J., 2022. Using computed tomography (CT) to reconstruct depositional processes and products in the subaqueous glaciogenic Champlain Sea basin, Ottawa, Canada. Geomorphology, 403. https://doi.org/10.1016/j.geomorph.2022.108165.

Alpay, S., Crow, H., Hinton, M.J. and Grenier, A., 2020. Geoscientific studies of Champlain Sea sediments, Bilberry Creek, Ottawa, Ontario: on-site preservation of cores. Geological Survey of Canada, Open File 8723, 23 pp. https://doi.org/10.4095/326109.

Anderson, T.W., 1988. Late Quaternary pollen stratigraphy of the Ottawa valley - Lake Ontario region and its application in dating the Champlain Sea. In: N.R. Gadd (Editor), The Late Quaternary Development of the Champlain Sea Basin. Special Paper 35. Geological Association of Canada, Ottawa, Canada, pp. 207-224.

Aylsworth, J.M., 2012. New Canadian Teaching Resources from Natural Resources Canada for Earthquakes, Landslides and Tsunamis (lesson plans, maps and event timelines) (Jaunary 2012). Geological Survey of Canada, Open File 7073, 7 p. + 48 PDF files, 317 pp. https://doi.org/10.4095/289872.

Aylsworth, J.M. and Lawrence, D.E., 2003. Earthquake-induced landsliding east of Ottawa: a contribution to the Ottawa Valley Landslide Project GeoHazards 2003, 3rd Canadian Conference on Geotechnique and Natural Hazards, The Canadian Geotechnical Society, Edmonton, Alberta, p. 57-64.

Aylsworth, J.M., Lawrence, D.E. and Guertin, J., 2000. Did two massive earthquakes in the Holocene induce widespread landsliding and near-surface deformation in part of the Ottawa Valley, Canada? Geology, 28(10): 903-906. https://doi.org/10.1130/0091-7613(2000)28<903:DTMEIT>2.0.CO;2.

Brooks, G.R., 2013. A massive sensitive clay landslide, Quyon Valley, southwestern Quebec, Canada, and evidence for a paleoearthquake triggering mechanism. Quaternary Research (United States), 80(3): 425-434. https://doi.org/10.1016/j.yqres.2013.07.008.

Brooks, G.R., 2019. Sensitive clay landslide inventory map and database for Ottawa, Ontario. Geological Survey of Canada, Open File 8600, 27 (+1 sheet) pp. https://doi.org/10.4095/315024

Brooks, G.R., Medioli, B.E., Aylsworth, J.M. and Lawrence, D.E., 2021. An updated compilation of radiocarbon dates relating to the age of sensitive-clay landslides in the Ottawa Valley, Ontario-Quebec. Geological Survey of Canada, Open File 7432, 98 pp. https://doi.org/10.4095/327843.

Cornforth, D.H., 2005. Landslides in practice : investigations, analysis, and remedial/preventive options in soils. J. Wiley, Hoboken, N.J., 596 pp.

Crow, H., Alpay, S., Hinton, M.J., Knight, R.D., Oldenborger, G.A., Percival, J.B., Pugin, A.J.-M. and Pelchat, P., 2017. Geophysical, geotechnical, geochemical, and mineralogical data sets collected in Champlain Sea sediments in the Municipality of Pontiac, Quebec. Geological Survey of Canada, Open File 7881, 51 pp. https://doi.org/10.4095/301664.

Crow, H., Hunter, J.A. and Motazedian, D., 2011. Monofrequency in situ damping measurements in Ottawa area soft soils. Soil Dynam. Earthquake Eng., 31(12): 1669-1677. https://doi.org/10.1016/j.soildyn.2011.07.002.

Crow, H., Paradis, D., Grunewald, E., Liang, X.X. and Russell, H.A.J., 2021a. Hydraulic Conductivity from Nuclear Magnetic Resonance Logs in Sediments with Elevated Magnetic Susceptibilities. Groundwater, 60(3): 377-392. https://doi.org/10.1111/gwat.13158.

Crow, H., Pyne, M., Hunter, J.A., Pullan, S.E., Motazedian, D. and Pugin, A., 2007. Shear wave measurements for earthquake response evaluation in Orleans, Ontario. Geological Survey of Canada, Open File 5579, Ottawa, ON, 26 pp. https://doi.org/10.4095/223897.

Crow, H.L., Enkin, R.J., Percival, J.B. and Al-Mufti, O.N., 2021b. Mineralogical properties of Champlain Sea sediments and their effects on borehole geophysical logs, western Quebec. Geological Survey of Canada, Open File 8763, 68 pp. https://doi.org/10.4095/327855.

Crow, H.L., Enkin, R.J., Percival, J.B. and Russell, H.A.J., 2020a. Downhole nuclear magnetic resonance logging in glaciomarine sediments near Ottawa, Ontario, Canada. Near Surf. Geophys., 18(6): 591-607. https://doi.org/10.1002/nsg.12120.

Crow, H.L., Hunter, J.A., Pugin, A.J.-M., Pullan, S.E., Alpay, S. and Hinton, M.J., 2014. Empirical geophysical/geotechnical relationships in the Champlain Sea sediments of Eastern Ontario. Chapter 20, In: J.-S. L'Heureux (Editor), Landslides in Sensitive Clays: From Geosciences to Risk Management. Advances in Natural and Technological Hazards Research 36. Springer, Dordrecht, pp. 253-263. https://doi.org/10.1007/978-94-007-7079-9_20.

Crow, H.L., Pugin, A.J.M., Dietiker, B., Paradis, D., Brewer, K., Cartwright, T., Griffiths, M. and Russell, H.A.J., 2020b. Lithological and hydrogeological properties from a downhole geophysical dataset in the Vars-Winchester esker, Ontario. In: H.A.J. Russell and B.A. Kjarsgaard (Editors), Southern Ontario groundwater project 2014–2019: summary report. Geological Survey of Canada, Open File 8536, pp. 147-157. https://doi.org/10.4095/321100.

Cummings, D.I., Gorrell, G., Guilbault, J.P., Hunter, J.A., Logan, C., Ponomarenko, D., Pugin, A.J.M., Pullan, S.E., Russell, H.A.J. and Sharpe, D.R., 2011. Sequence stratigraphy of a glaciated basin fill, with a focus on esker sedimentation. Bull. Geol. Soc. Am., 123(7-8): 1478-1496. https://doi.org/10.1130/B30273.1.

Dietiker, B., 2020. Geoscientific studies of Champlain Sea sediments, Bilberry Creek, Ottawa, Ontario: firm ground depth estimation through microtremor Horizontal-to-Vertical

Spectral Ratios (HVSR). Geological Survey of Canada, Open File 8729, 14 pp. https://doi.org//10.4095/326172.

Fulton, R.J., 1987. Quaternary geology of the Ottawa region, Ontario and Quebec. Geological Survey of Canada, Paper 86-23, 47 pp. https://doi.org/10.4095/122374

Gadd, N.R., 1980. Maximum age for a concretion at Green Creek, Ontario. Géog. Phys. Quat., 34: 229-238. https://doi.org/10.7202/1000400ar.

Gadd, N.R., 1986. Lithofacies of Leda clay in the Ottawa basin of the Champlain Sea. Geological Survey of Canada, Paper 85-21, 44 pp. https://doi.org/10.4095/120619.

Hinton, M.J. and Alpay, S., 2020. Constraining groundwater flow in Champlain Sea muds. In: H.A.J. Russell and B.A. Kjarsgaard (Editors), Southern Ontario groundwater project 2014–2019: summary report. Geological Survey of Canada, Open File 8536, pp. 203-215. https://doi.org/10.4095/321106.

Hunter, J.A., Crow, H.L., Brooks, G.R., Pyne, M., Motazedian, D., Lamontagne, M., Pugin, A.J.M., Pullan, S.E., Cartwright, T., Douma, M., Burns, R.A., Good, R.L., Kaheshi-Banab, K., Caron, R., Kolaj, M., Folahan, I., Dixon, L., Dion, K., Duxbury, A., Landriault, A., Ter-Emmanuil, V., Jones, A., Plastow, G. and Muir, D., 2010. Seismic site classification and site period mapping in the Ottawa area using geophysical methods. Geological Survey of Canada, Open File 6273, 80 pp. https://doi.org/10.4095/286323.

Johnston, W.A., 1917. Pleistocene and recent deposits in the vicinity of Ottawa, with a description of the soils. Geological Survey of Canada, Memoir 101, 69 pp. https://doi.org/10.4095/101671.

Logan, C., Cummings, D.I., Pullan, S., Pugin, A., Russell, H.A.J. and Sharpe, D.R., 2009. Hydrostratigraphic model of the South Nation watershed region, south-eastern Ontario. Geological Survey of Canada, Open File 6206, 17 pp. https://doi.org/10.4095/248203.

Medioli, B.E., Alpay, S., Crow, H.L., Cummings, D.I., Hinton, M.J., Knight, R.D., Logan, C., Pugin, A.J.-M., Russell, H.A.J. and Sharpe, D.R., 2012. Integrated data sets from a buried valley borehole, Champlain Sea basin, Kinburn, Ontario. Geological Survey of Canada, Current Research 2012-13 (Online), 16 pp. https://doi.org/10.4095/289597.

Motazedian, D., Torabi, H., Hunter, J.A., Crow, H.L. and Pyne, M., 2020. Seismic site period studies for nonlinear soil in the city of Ottawa, Canada. Soil Dynam. Earthquake Eng., 136. https://doi.org/10.1016/j.soildyn.2020.106205.

Nastev, M.N., Parent, M.P., Ross, M.R., Howlett, D.H. and Benoit, N.B., 2016. Geospatial modelling of shear-wave velocity and fundamental site period of Quaternary marine and glacial sediments in the Ottawa and St. Lawrence Valleys, Canada. Soil Dynam. Earthquake Eng., 85: 103-116. https://doi.org/10.1016/j.soildyn.2016.03.006.

Paradis, D., Pugin, A.J.M., Crow, H.L., Oldenborger, G.A., Russell, H.A.J. and Melaney, M., 2020. Hydrogeophysics data acquisition for the characterization of hydraulic properties of the Vars-Winchester esker, southeastern Ontario. In: H.A.J. Russell and B.A. Kjarsgaard (Editors), Southern Ontario groundwater project 2014–2019: summary report. Geological Survey of Canada, Open File 8536, pp. 131-138. https://doi.org/10.4095/321098.

Parent, M., Ross, M., Howlett, D. and Bédard, K., 2021. 3D model of the Quaternary sediments in the St. Lawrence valley and adjacent regions, southern Quebec and eastern Ontario. Geological Survey of Canada, Open File 8832, 26 pp. https://doi.org/10.4095/329082.

Pugin, A.J.M., Crow, H.L., Brewer, K., Cartwright, T., Dietiker, B., Griffiths, M. and Paradis, D., 2020. High-resolution seismic reflection profiles for groundwater studies of the Vars-Winchester esker, southern Ontario. In: H.A.J. Russell and B.A. Kjarsgaard (Editors), Southern Ontario groundwater project 2014–2019: summary report. Geological Survey of Canada, Open File 8536, pp. 139-146. https://doi.org/10.4095/321099.

Richard, S.H., 1982. Surficial geology, Ottawa, Ontario-Québec. Geological Survey of Canada "A" Series Map 1506A, Scale 1:50000. https://doi.org/10.4095/109231.

Richard, S.H., 1990. Radiocarbon dates from the western basin of the Champlain Sea. Geological Survey of Canada, Paper 89-22, 13 pp. https://doi.org/10.4095/127751.

Torrance, J.K., 1988. Mineralogy, pore-water chemistry and geotechnical behaviour of Champlain Sea and related sediments. In: N.R. Gadd (Editor), The Late Quaternary development of the Champlain Sea basin. Geological Association of Canada Special Paper 35, St. John's, Nfld., pp. 259-280.

Wagner, F.J.E., 1970. Faunas of the Pleistocene Champlain Sea. Geological Survey of Canada, Bulletin 181, 104 pp. https://doi.org/10.4095/102325.

Wang, B., 2020. Geotechnical investigations of an earthquake that triggered disastrous landslides in eastern Canada about 1020 cal BP. Geoenvironmental Disasters, 7(1). https://doi.org/10.1186/s40677-020-00157-9.