Natural Resources Canada
Ressources naturelles Canada

Integrated data sets from a buried valley borehole, Champlain Sea basin, Kinburn, Ontario

B.E. Medioli, S. Alpay, H.L. Crow, D.I. Cummings, M.J. Hinton, R.D. Knight, C. Logan, A.J.-M. Pugin, H.A.J. Russell, and D.R. Sharpe

Geological Survey of Canada
Current Research 2012-3

2012

Canada

Geological Survey of Canada
Current Research 2012-3

Integrated data sets from a buried valley borehole, Champlain Sea basin, Kinburn, Ontario

B.E. Medioli, S. Alpay, H.L. Crow, D.I. Cummings, M.J. Hinton, R.D. Knight, C. Logan, A.J.-M. Pugin, H.A.J. Russell, and D.R. Sharpe

2012

ISSN 1701-4387
Catalogue No. M44-2012/3E-PDF
ISBN 978-1-100-19849-1
doi: 10.4095/289597

A copy of this publication is also available for reference in depository libraries across Canada through access to the Depository Services Program's Web site at http://dsp-psd.pwgsc.gc.ca

A free digital download of this publication is available from GeoPub: http://geopub.nrcan.gc.ca/index_e.php

Toll-free (Canada and U.S.A.): 1-888-252-4301

Recommended citation

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 2012-3, 16 p. doi: 10.4095/289597

Critical review

G. Brooks

Authors

B.E. Medioli (Barbara.Medioli@NRCan-RNCan.gc.ca)
S. Alpay (Sam.Alpay@NRCan-RNCan.gc.ca)
H.L. Crow (Heather.Crow@NRCan-RNCan.gc.ca)
M.J. Hinton (Marc.Hinton@NRCan-RNCan.gc.ca)
R.D. Knight (Ross.Knight@NRCan-RNCan.gc.ca)
C. Logan (Charles.Logan@NRCan-RNCan.gc.ca)
A.J.-M. Pugin (Andre.Pugin@NRCan-RNCan.gc.ca)
H.A.J. Russell (Hazen.Russell@NRCan-RNCan.gc.ca)
D.R. Sharpe (David.Sharpe@NRCan-RNCan.gc.ca)
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

D.I. Cummings (cummings1000@gmail.com)
12, rue Décarie
Gatineau, Quebec
J9H 2M3

Correction date:

Integrated data sets from a buried valley borehole, Champlain Sea basin, Kinburn, Ontario

B.E. Medioli, S. Alpay, H.L. Crow, D.I. Cummings, M.J. Hinton, R.D. Knight, C. Logan, A.J.-M. Pugin, H.A.J. Russell, and D.R. Sharpe

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 2012-3, 16 p. doi: 10.4095/289597

Abstract: Data from a 97 m continuously cored borehole (GSC-BH-JSR-01), near Kinburn, Ontario, contribute to our knowledge of the geology, hydrogeology, and geotechnical properties of clay-rich, glaciated basins, and, specifically, the Champlain Sea basin. Physical properties, downhole geophysics, portable XRF bulk-sediment geochemical composition, micropaleontological results, and pore-water geochemistry data are integrated with detailed, sedimentological descriptions to provide a multidisciplinary data set similar to the 'golden spikes' of southern Ontario. Seismic-reflection data provide a basin architectural framework in which to interpret these results. The Kinburn data set is interpreted to record the retreat of the regional ice sheet, the incursion of the Champlain Sea, and the withdrawal of marine waters from the basin during continued ice retreat and isostatic rebound. The sediment package sits within a bedrock basin and consists of a basal, coarse-grained unit (possibly an esker), overlain by nearly 90 m of clay-rich, marine sediments (locally known as leda clay), and is capped by an 8 m thick silt-rich, nonmarine facies. Ultimately, the sedimentological, stratigraphic, and geochemical data collected from the Kinburn Golden Spike will provide a better understanding of glaciomarine sediments within the Champlain Sea of eastern Ontario and western Quebec. The large thickness of mud, the preservation of pore water chemistry, and the multidisciplinary data sets make the Kinburn site a key reference site for the geology, hydrogeology, and seismic-hazard assessment of the Champlain Sea basin.

Résumé : Un sondage continu de 97 m (GSC-BH-JSR-01) situé près de Kinburn (Ontario) contribue à améliorer nos connaissances sur la géologie, l'hydrogéologie et les propriétés géotechniques des bassins glaciaires riches en argile, et du bassin de la Mer de Champlain en particulier. Les données sur les propriétés physiques, la géophysique en sondage, la composition géochimique de sédiments en vrac (déterminée par un analyseur portable à fluorescence de rayons X), l'analyse micropaléontologique, et la géochimie de l'eau interstitielle ont été intégrées à des descriptions sédimentologiques détaillées afin de produire un jeu de données multidisciplinaires similaire à ceux des sondages surnommés «golden spikes» (clous d'or), situés dans le sud de l'Ontario. Les données de sismique-réflexion fournissent un cadre architectural pour le bassin, permettant d'interpréter ces résultats. Selon les interprétations, le jeu de données de Kinburn documente le retrait de la nappe glaciaire dans la région, l'incursion de la Mer de Champlain et le retrait des eaux marines du bassin pendant le recul continu de la glace et le relèvement isostatique. L'ensemble des sédiments repose dans un bassin du socle rocheux et comprend une unité basale à grains grossiers (peut-être un esker), sur laquelle reposent près de 90 m de sédiments marins riches en argile (connus localement sous le nom d'argile à Leda), coiffés d'un faciès non marin, riche en silt, d'une épaisseur de 8 m. En fin de compte, les données sédimentologiques, stratigraphiques et géochimiques obtenues du sondage «golden spike» de Kinburn permettront d'avoir une meilleure compréhension des sédiments glaciomarins de la Mer de Champlain dans l'est de l'Ontario et dans l'ouest du Québec. La grande épaisseur de boue, la conservation des caractéristiques chimiques de l'eau interstitielle, et les jeux de données multidisciplinaires font du site de Kinburn un site de référence clé pour la géologie, l'hydrogéologie et l'évaluation des aléas sismiques dans le bassin de la Mer de Champlain.

INTRODUCTION – THE KINBURN "GOLDEN SPIKE"

During the past fifteen years, the Geological Survey of Canada (GSC), in collaboration with the Ontario Ministry of Environment and several conservation authorities, has collected data from continuously cored boreholes to investigate a variety of geological and hydrogeological settings in Ontario (Fig. 1; e.g. moraines, eskers, basin fills, buried valleys). These boreholes, informally referred to as "golden spike" boreholes (Sharpe et al., 2002), have commonly been drilled where the broader geological architecture was initially identified by seismic-reflection data. Coupled with seismic data, the borehole data provide valuable insight into their respective geological and hydrogeological settings. Golden spike and seismic data sets were first integrated as part of the regional hydrogeological study of the Oak Ridges Moraine (Fig. 1; Sharpe et al., 2002). More recently, similar data sets have been collected as part of source-water protection studies for the South Nation Conservation organization in Eastern Ontario (Fig. 1b, *see* Cummings and Russell, 2007).

Since 2006, a large integrated data set from golden spike boreholes and seismic transects has been amassed in the mud-rich Champlain Sea basin of eastern Ontario (e.g. Cummings et al., 2011). In 2008, following acquisition of seismic data, an anomalously thick succession of Champlain Sea sediments was cored and the well was completed with a piezometer in a partially filled bedrock valley in the western Champlain Sea basin, near the town of Kinburn, Ontario (Fig. 2). The borehole (GSC-BH-JSR-01, hereafter referred to as the Kinburn site) afforded the opportunity to establish a reference site for geological, groundwater, and seismic ground-motion studies in the Champlain Sea basin due to the thick clay-rich ('mud') basin setting. Reference sites such as this provide geoscience benchmarks in representative settings so that credible extrapolation and modelling can be made elsewhere (e.g. Nobleton site, Logan et al., 2008; Knight et al., 2008; *see also* Fig. 1 in this paper).

The Kinburn borehole also serves as a test site where measured geophysical properties (e.g. natural gamma, conductivity, magnetic susceptibility, density, and stiffness properties) of soft, clay-rich buried valley-fill sediments are being compared against in situ sediment properties obtained from core samples (e.g. pore-water conductivity, bulk sediment geochemistry, porosity (calculated from gravimetric moisture content), grain size, mineralogy, shear strength, and sensitivity). Downhole data have also been used to assess dynamic properties of soft sediments for studies of ground-motion response during local seismic events. A broadband seismograph station, installed on a soft-sediment site near the borehole, has recorded amplified seismic ground motions when compared to a bedrock seismograph station installed 2.4 km away. As the Champlain Sea sediments are regionally extensive throughout the St. Lawrence Lowlands and exist within seismically active areas of eastern Canada, this work is helping to foster a better understanding of the response of Champlain Sea sediments to ground shaking.

OBJECTIVES

This paper presents borehole data from a continuous core through a thick succession of clay-rich sediments from the western Champlain Sea basin. The borehole data set consists of i) downhole geophysical logs, ii) core sedimentology and physical properties, iii) geochemistry of sediments and pore water, and iv) micropaleontology. The borehole results are interpreted to assess facies and their depositional environments. The high-resolution surface seismic section is used to integrate the borehole results into the regional context. The contributions of these data to geological, hydrogeological, and seismic hazard assessment are also considered.

THE CHAMPLAIN SEA BASIN

The Champlain Sea was a large inland sea that existed from ~11 500 to 10 000 ^{14}C years BP (Anderson, 1988). It formed when marine water inundated the isostatically depressed St. Lawrence Lowlands during the retreat of the Laurentide Ice Sheet (Parent and Occhietti, 1988). As a result of subsequent isostatic rebound, water levels fell continuously throughout the existence of the Champlain Sea (Rust and Romanelli, 1975). Moraines and eskers were deposited subglacially or at the ice front during ice retreat and then were blanketed by fine-grained sediment that aggraded in the Champlain Sea (Barnett, 1988; Fig. 2). By the early Holocene, the sea had regressed, marine deposition ceased, and the Ottawa River incised the clay-rich terrain to begin forming the present day topography (MacPherson, 1968).

The late Quaternary basin fill near Ottawa, first described by Johnston (1917), consists of diamicton (till) overlain by sand and gravel (eskers), which is in turn overlain by clay-rich, fine-grained sediment (Champlain Sea deposits known locally as leda clay; Fig. 2). North-south-trending bedrock striae and drumlins that ornament the till are generally interpreted as having been formed by southward-flowing ice (Richard, 1982a, b). Numerous studies of regional eskers were conducted in the 1970s and 1980s (e.g. Rust and Romanelli, 1975; Sharpe, 1988). Different components of eskers were identified, including 'subaqueous outwash', a dominant component of esker systems.

A detailed regional study of Champlain Sea sediments was conducted by Gadd (1986), based primarily on long, discontinuous cores. Three major fine-grained units were identified in his study: i) grey rhythmites ('varves', Unit II), ii) massive marine clays (Unit III), and iii) red-and-grey rhythmites (Unit IV). Gadd (1986) observed that these fine-grained units were locally overlain by sand

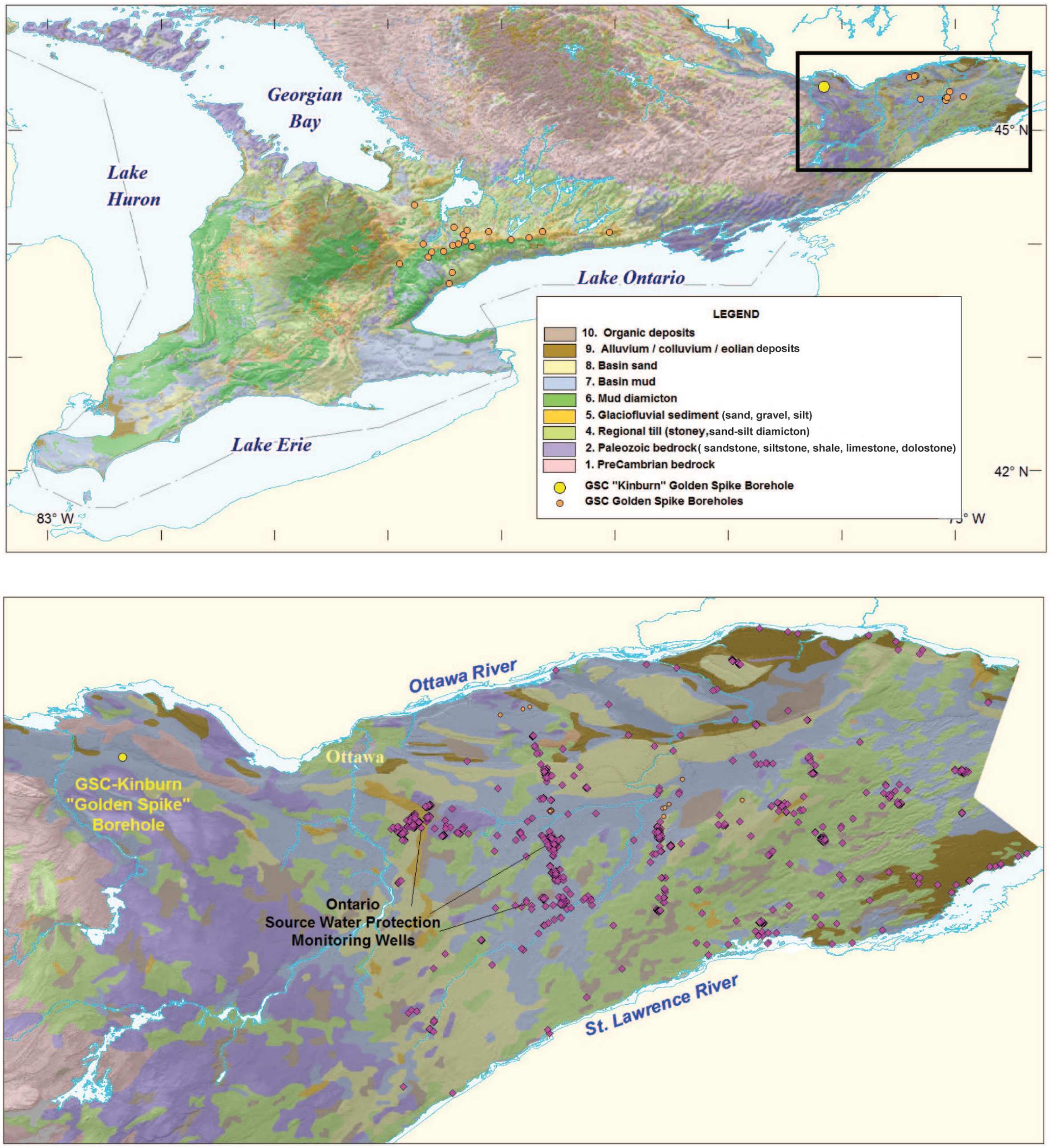

Figure 1. a) Map of eastern Ontario showing the Golden Spike sites that exist in both southern Ontario (Oak Ridges) and the South Nations boreholes. The locations are superimposed on the Quaternary Surficial Geology map of Ontario; **b)** Map of Ontario showing the water well monitoring network maintained by the Ontario Ministry of the Environment. The location of the Kinburn borehole (GSC-BH-JSR-01) site is shown on both maps.

Figure 2. Air photo A31837–105 taken 22/05/2002 1:15,000 of the Kinburn area, Ottawa valley, showing the location of the borehole on the flat clay plain (see insert map of Ontario for location of air photo). The red dashed line shows the location of the seismic section in Figure 3.

and interpreted the entire succession as being deposited in a deltaic environment during a forced regression of the sea. Later interpretations have argued that the basal grey rhythmites were actually deposited within the continuum of glaciolacustrine-glaciomarine-fully marine deposition (e.g. Rodrigues, 1987, 1988, 1992). Torrance (1988) reported an increasing then-decreasing pore-water salinity trend in Champlain Sea sediments that mirrors a similar trend reported in the regional micropaleontological assemblages (Anderson, et al., 1985; Rodrigues, 1988, 1992; Guilbault, 1989; Pair and Rodrigues, 1993).

STUDY SITE DESCRIPTION

The Kinburn site (lat. 45°22'59.5"N, long. 76°09'16.5"W) is located 2.8 km southeast of the town of Kinburn, Ontario, in an elongate, structurally controlled, northwest-southeast-trending bedrock depression within the broader Champlain Sea basin (Fulton, 1987; Fig. 2). A Paleozoic carbonate bedrock ridge bounds the depression to the south and west, whereas a Precambrian Shield ridge bounds it to the north and east (Richard, 1984). Based on seismic data (Fig. 3), the borehole was positioned to intersect a package of continuous, low-amplitude reflectors interpreted to be a thick (~100 m) succession of fine-grained sediments that overlies a mound-shaped reflection package interpreted to be a body of glaciofluvial sand and gravel, overlying the acoustic basement (bedrock). This initial seismo-stratigraphic interpretation was supported by the observation of similar successions elsewhere in the basin (e.g. Cummings et al., 2011), in addition to a similar succession exposed in an outcrop ~5 km to the northwest, near the town of Galetta.

METHODS

Data collection followed the basin-analysis methodology outlined by Sharpe et al. (2002). Prior to drilling the well, seismic-reflection data were collected using a landstreamer array towed behind a minibuggy minivibe source (e.g. Pugin, et al., 2004, 2006, 2007, 2009). Drilling was undertaken between September 4 and 15, 2008, by All Terrain Drilling Limited using a mud rotary technique. Core was collected in five-foot intervals using a wireline-attached PQ core tube (8.5 cm inner diameter). The borehole reached a total depth of 96.65 m with an overall core recovery rate of 93%. Core recovery varied between core runs. Some runs had more than 100% core recovery due to clay expansion whereas in run 17, core recovery was only 23.5%. Drilling was terminated near the base of the fine-grained succession because a strong, upward hydraulic gradient was anticipated at greater depth, based on data from neighbouring wells. The borehole was completed with a 2.5 inch (schedule 80) PVC piezometer installed to the base of the borehole with a 25 foot screen at its base. The completed well flowed slightly at surface, which necessitated installation of a packer, below which a submersible pressure transducer was installed so that water pressure variations could be monitored.

Immediately upon retrieval of each five-foot core run, subsamples were collected for pore-water geochemistry, shear strength, and moisture-content tests (*see* Table 1 for summary of samples). Recovered core was then sealed and stored at ambient temperatures at the Geological Survey of Canada (GSC) core repository at Tunney's Pasture, Ottawa, Ontario.

A sediment core interval of 20 cm or longer was removed from one half of the split core for each run, stored in 500 ml high-density polyethylene bottles at 4°C, and reserved

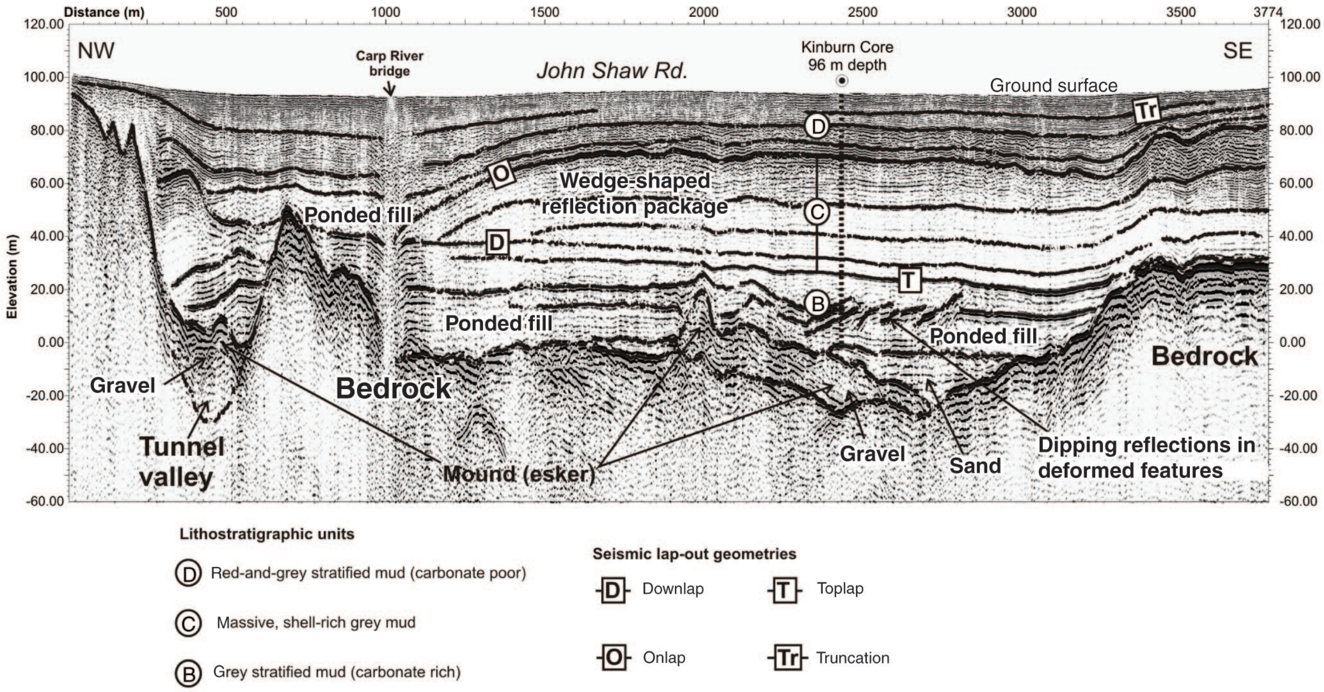

Figure 3. Interpreted seismic section showing the location of the borehole and the interpreted lithologies and structure.

Table 1. List of samples collected and analyzed from the Kinburn borehole.

Sample type	Number of samples
Moisture content	64
Shear strength	64
Sensitivity	64
Grain size	144
Total organic carbon and LOI	80
Bulk geochemistry	80
XRF gun	80
Micropaleontology	24
Pore-water geochemistry	56

for pore-water extraction and analyses of pore-water conductivity. Fifty-seven sediment samples were manually homogenized and a subset from each was loaded into 50 ml centrifuge tubes. The sediments were centrifuged at 13 000 rpm for 30 minutes at 5°C; afterwards, the supernatant was drawn off using an electronic pipette and placed into 4 ml high-density polyethylene vials. One distilled de-ionized water sample was also processed as a blank at the end of each centrifuge run. Pore-water conductivity was analyzed using a calibrated Accumet AR50 conductivity meter with up to a fivefold dilution with distilled de-ionized water for high salinity intervals. Measurements were made at room temperature and autocorrected to 25°C. Measurement repeats were conducted on random samples, the calibration standard was measured on a regular basis, and blanks were also measured regularly.

Sixty-four sediment samples were collected in 250 ml glass mason jars for analysis of water content and for drop-cone tests that were conducted at the GSC sedimentology laboratory in Ottawa within 48 hours of sample collection. The gravimetric water content was measured by weighing and oven drying sediment samples for 24 hours at 105°C following a protocol outlined by Girard et al. (2004). Drop-cone tests adhered to the protocol developed by the Swedish Geotechnical Institute (Hansbo, 1957).

Between October 14 and 27, 2009, the core was split, photographed and logged. The five-foot core runs were logged to centimetre-scale resolution. Eighty sediment subsamples were collected for grain size, total organic carbon, micropaleontology, and bulk sediment geochemistry. Grain size, total organic carbon and carbonate content of sediments were determined at the GSC sedimentology laboratory (Girard et al., 2004). The bulk sediment geochemistry analysis was contracted out to ACME Analytical Laboratories. Qualitative carbonate contents were assessed using a ranking of strong, moderate, weak, or no reaction to a dilute HCl solution.

A suite of downhole geophysical logs (passive natural gamma, apparent conductivity, magnetic susceptibility, and density) and a downhole shear-wave survey were collected between 2008 and 2010. An active gamma tool with a ^{137}Cs source was used to collect the calibrated density values. The downhole seismic logs provided accurate shear-wave velocities which assisted in the conversion of the seismic-reflection data to depth sections (*see* Hunter et al., 2007).

The minivibe was used as the source for the downhole shear-wave profiles, with two downhole three-component, north-orienting geophones as receivers.

In order to evaluate the potential for a portable XRF unit to determine trends in the bulk geochemical composition of the sediments, eighty samples were air-dried and disaggregated by mortar and pestle. The fine sand/silt/clay powders were analyzed using a Niton XL3t GOLDD hand-held XRF spectrometer (hereafter referred to as a pXRF analyzer). Each sample was analyzed four times using a dwell time of three minutes per analysis. The average of the four results was used to determine element concentrations. The results presented here are preliminary and have not yet undergone rigorous QA/QC; however, relative variations in elemental compositions related to coarsening- and fining-upward cycles compare well to the interpretation of the core and geophysical data presented herein.

Micropaleontological analysis (foraminifera and ostracodes) was conducted on disaggregated sediment samples by Jean-Pierre Guilbault (BRAQ-Stratigraphie). The fraction greater than 63 microns was analyzed. In order to concentrate specimens, 16 of the 24 samples were floated using a heavy liquid with a density value of 1.9. Both floated and heavy fractions were studied. Where the number of foraminifera exceeded 300, samples were split into aliquots.

RESULTS

Five main facies were intersected within the cored interval. Each facies is characterized by a distinct suite of lithological, micropaleontological, geochemical, and geophysical attributes (Fig. 4, 5, 6). From bottom to top these facies are as follows: A) interstratified silty clays and sand, B) grey rhythmites, C) massive marine clays, D) red and grey rhythmites and E) upper clayey silts (see Fig. 4). Within each facies, one or more subfacies were defined, based on sedimentology, geophysics and XRF geochemistry as described below.

Facies A — interstratified silty clays and sand

The lowermost facies was intersected from 91.5 m to 96.95 m depth, but the base of the facies was not penetrated. The facies is an overall fining-upward sequence of interbedded very fine to very coarse pebbly sands and clayey silts (Fig. 4 and 5j). This facies has moderate carbonate content, based on an acid test performed on the sediments, and is probably indicative of sediment provenance from a carbonate-rich terrain (Fig. 4). Total carbon values range from 1.3 to 1.8% and the carbon is mainly inorganic. Shells and microfauna are absent from this facies, which could favour an interpretation of a cold, marginal marine or estuarine depositional environment. The pore water conductivity is 15 mS/cm, suggesting an at least partial marine water source, unless the observed pore-water conductivity was caused by postdepositional advection or diffusion of ions downward from facies B.

The presence of sand, in relatively higher abundance than elsewhere in the core, is reflected by higher magnetic susceptibility values and slightly lower natural gamma counts (Fig. 6). Relatively higher shear-wave velocities, densities, and lower porosity values indicate the sediment is stiffer than the overlying materials. Grain size is generally variable within facies A compared with facies B. The natural gamma log response indicates two minor coarsening-upward sequences, which is supported by the grain-size data (Fig. 6). Mean material density in this unit is 1.94 ± 0.04 g/cm^3 (1σ, 346 readings). Relatively low apparent-conductivity values (<150 mS/m), coupled with elevated sensitivity values (>90) at the base of the facies suggest that the material is 'quick,' meaning that it could flow if disturbed.

The pXRF data display large fluctuations in elemental abundances that probably reflect preferential sampling of clay- or sand-rich horizons. This suggests that the pXRF data are very sensitive to grain size changes.

Facies B — Grey rhythmites

Facies B was intersected from 62 m to 91.50 m depth (Fig. 4) and conformably overlies the interstratified silty clay and sand facies (facies A) with a poorly defined gradational basal contact. The facies consists of massive clayey silts with occasional silty to very fine sand laminae and partings (72–91.5 m) overlain by regularly laminated sediments ranging from coarse to fine silt and silty clay (62–72 m). The facies fines upward from 91.5 to 72 m and then the trend becomes less pronounced from 72–62 m (Fig. 4, 6). Rhythmites are present from 72 m upward and occur as alternating darker and lighter grey bands. The lighter grey bands are coarser than the darker grey bands (Fig. 5g, i). Bioturbation occurs throughout the facies but is most apparent in the lower, more massive zone. In some parts of the core, subhorizontal black banding is visible on freshly split surfaces and is caused by the presence of hydrotroilite. Rhythmite thickness ranges from 1 to 2 mm to 10 cm and become less distinct upward. Silty partings are common. Clay balls (up to 2 cm in diameter) and drop grains (1–5 mm diameter) are present near the top of the facies (62–65 m). The carbonate content of facies B is lower than that of the underlying facies (weak to moderate reaction to HCl). Total carbon content ranges from 0.7 to 3.4% and carbon remains primarily of inorganic provenance. Shell fragments occur very sporadically and microfauna (foraminifera) are present but in very low numbers (Fig. 4).

The grey rhythmite facies shows a notable decrease in magnetic susceptibility compared to the underlying interstratified silty clays and sand unit. The unit fines upward slightly, as indicated by the natural gamma log, grain-size data and sediment descriptions (Fig. 6). Mean density in

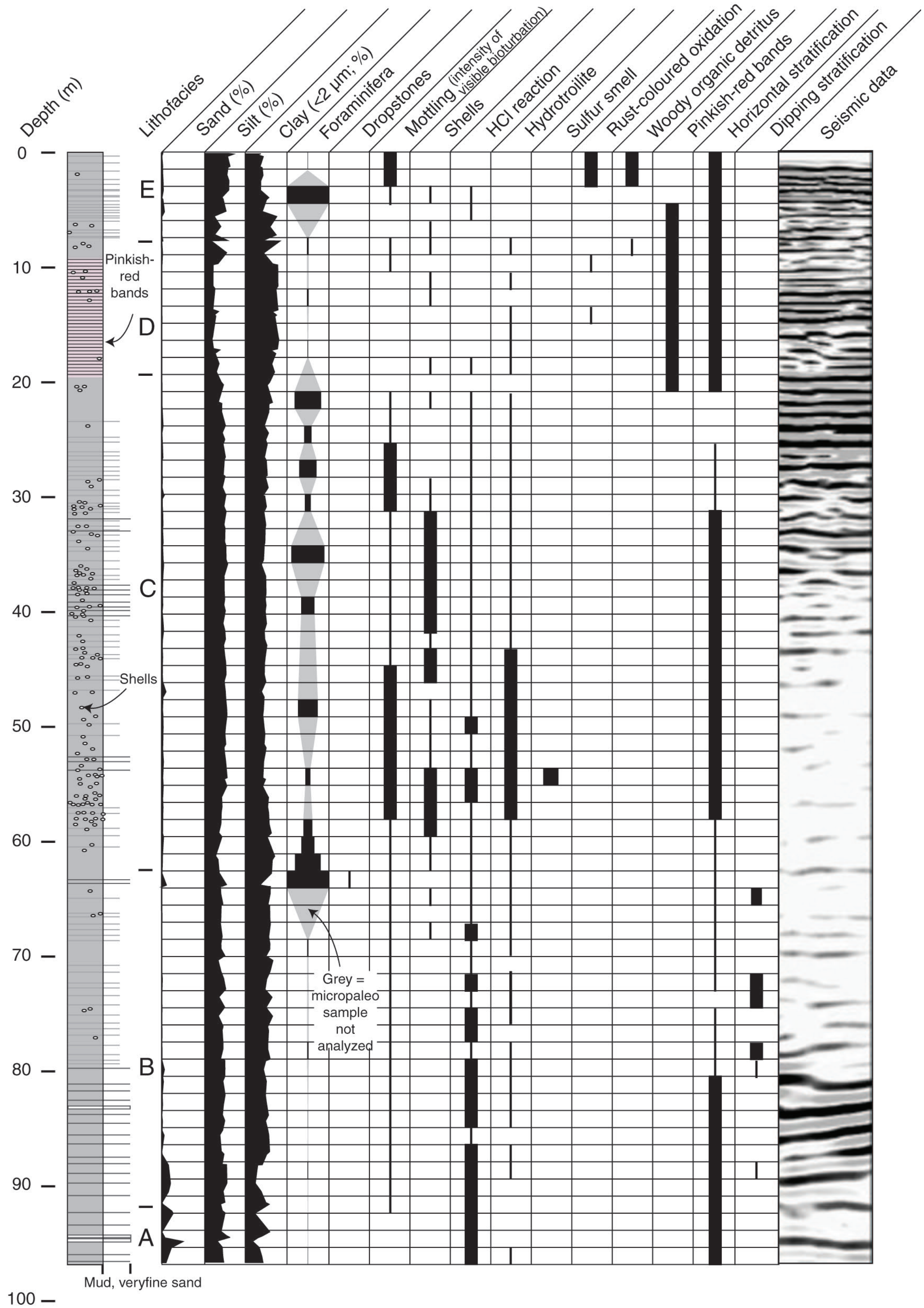

Figure 4. Summary of the borehole stratigraphy and sedimentology showing the abundance of various sedimentary components, as well as the abundance of foraminifera and a depth slice of the seismic reflection profile for the area surrounding the borehole location.

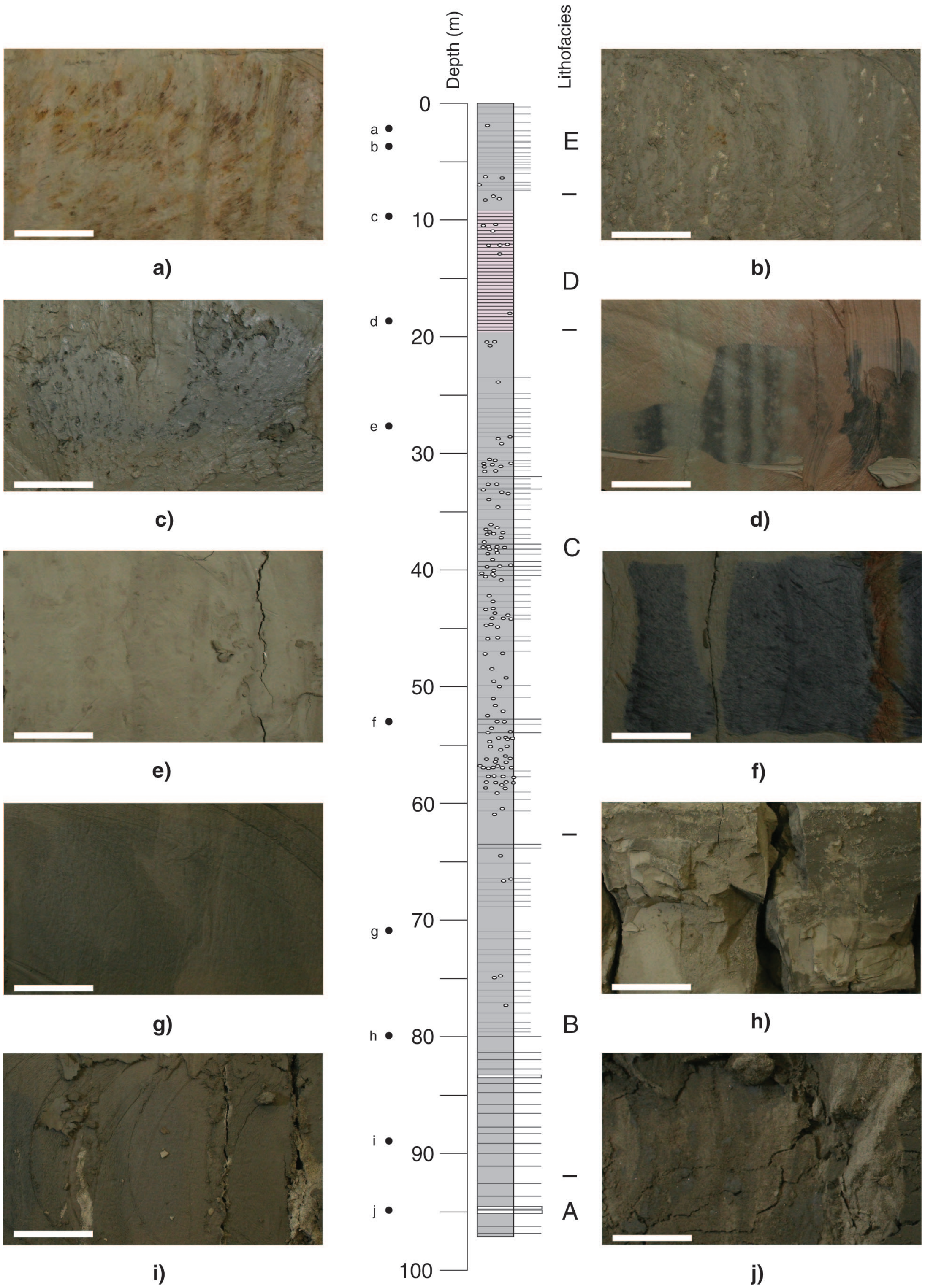

Figure 5. Core photos. The location of each photograph is shown against the core log. Scale bars are 3 cm in length. Photos **a)** and **b)** show the typical appearance of the upper muddy silt in which silt occurs as both laminae and little blebs of coarser sediment within finer sediment. The facies is typically bioturbated and contains oxidized organic detritus. Photos **c)** and **d)** depict the upper red and grey rhythmites. The classic alternating red and grey beds are visible in d) but begin to fade toward the top of facies C where the concentration of organic detritus increases. The thickness of the rhythmites varies considerably even within short intervals and the hydrotroilite concentrations occur across bedding, as seen in d). Photos **e)** and **f)** show the massive marine clay that commonly contains hydrotroilite. The hydrotroilite is visible on fresh exposures of the core but quickly fades as it is oxidized. Photos **g)**, **h)** and **i)** show the basal light and dark grey rhythmites. Photo **j)** represents the interstratified silty clay and sand facies.

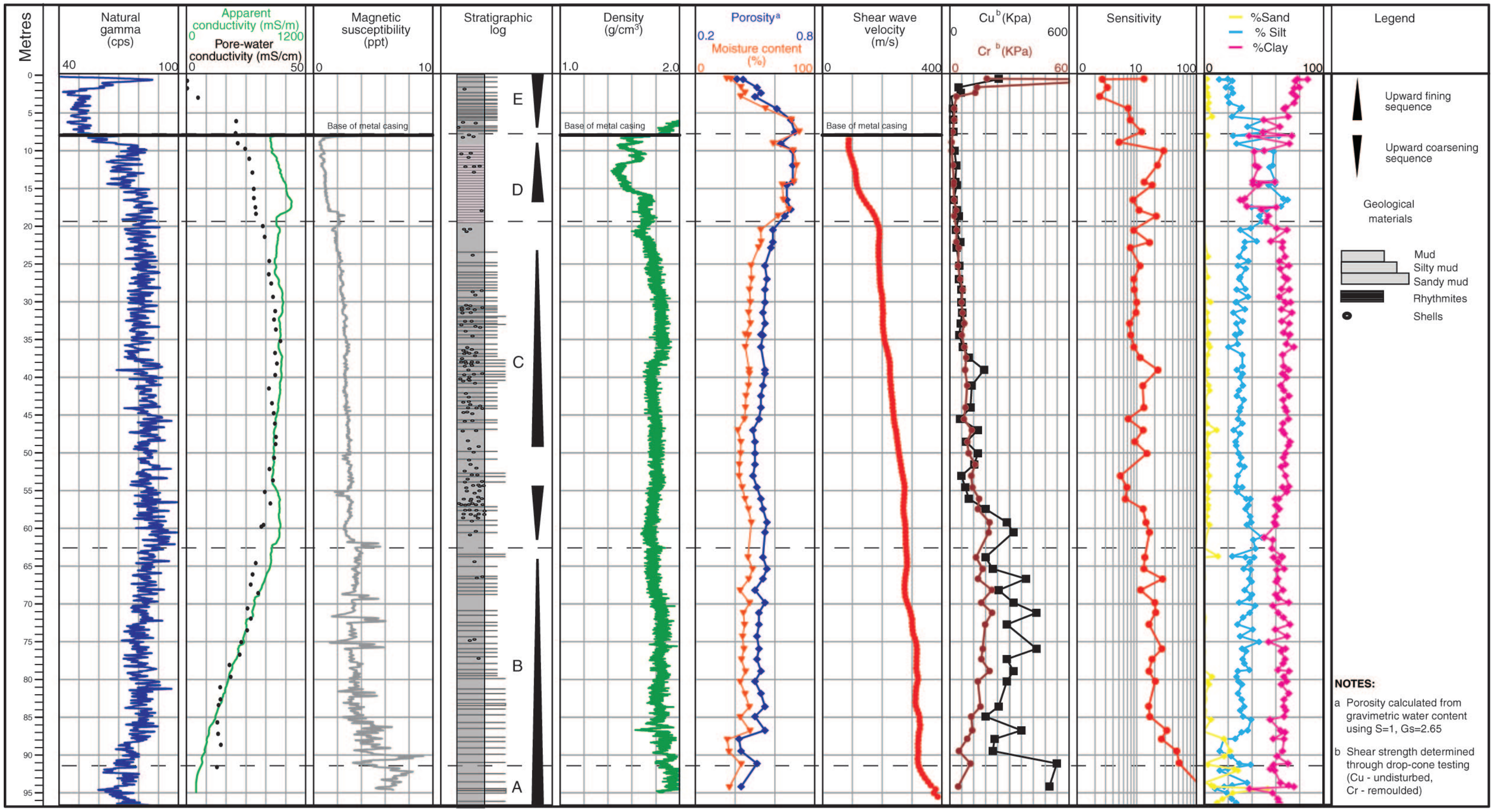

Figure 6. Geophysical, geochemical (pore water), geotechnical, and geological logs from BH-GSC-JSR-01. Shear strength testing (undisturbed, Cu; remolded, Cr) was carried out by the GSC sedimentology lab, on core samples within 24 to 48 hours of collection. Samples were unconfined and strengths were determined using drop cone testing. Sensitivity is computed using the ratio of Cu:Cr.

facies B is 1.83 ± 0.05 g/ cm^3 (1σ, 2950 readings). Shear-wave velocities decrease steadily upward with decreasing overburden pressure. The significant upward increase in the apparent conductivity readings (from 150 to 900 mS/m) likely represents the increasing pore-water conductivity observed from 15 mS/cm at the base of the facies upwards to 35 mS/cm at approximately 62 m depth. Sensitivity values continue to fluctuate near the sensitive threshold (20) and range from 11 to 50.

The pXRF results show that Ca generally decreases upwards whereas Mn, Fe, As, Rb, Cu, Zn, V, and S all increase toward the top of facies B (Fig. 7). The relative changes in these values correspond closely to the overall subtle, fining-upwards trend from the base of the core to the top of the rhythmite facies (Fig. 6).

Facies C — Massive marine clay

Massive marine clay was recovered from 19 m to 62 m depth. The basal contact is gradational due to the gradual disappearance of the underlying grey rhythmites. Facies C consists of massive silty clay/clayey silt with clay concentrations ranging from 40 to 70% (Fig. 4 and 5e, f). The silty clay is dark grey and generally massive in appearance with rare, very thin sandy/silty laminations and partings. Shells (tentatively identified as *Portlandia sp.*) are abundant to very abundant but are very fragile and crumble when extracted from the core. Bioturbation, mostly observed as a mottled texture, is common through the facies, particularly between 47 and 60 m, and 32 and 28 m depth. This coincides with the appearance of black staining within the sediment. This staining fades as the sediment is oxidized and is most like due to the presence of hydrotroilite. Overall, the facies fines upward, although three subtle coarsening-upward cycles can be observed within the larger unit. The deposits show a weak reaction to an acid carbonate test. The total carbon content is higher than the underlying facies (0.8 to 2.3%) and the organic carbon content is 1 to 2% per sample. Foraminifera and ostracodes increase sharply in abundance at the base of the marine clay and remain in moderate to high concentrations throughout the facies (Fig. 4).

The natural gamma log shows a minor coarsening-upward trend at the base of facies C followed by an overall fining-upward trend. The limited variation in the gamma, magnetic susceptibility, and apparent conductivity logs agrees with the massive texture observed in core (Fig. 6). Mean density in facies C is 1.79 ± 0.05 g/cm^3 (1σ, 4300 readings). The pore-water conductivity of this interval of massive marine clay ranges from 38 to 47 mS/cm and approaches the conductivity of seawater (~54 mS/cm), as also reflected by the elevated apparent conductivity from the geophysical logs (>900 mS/m). Shear-wave velocities decrease uniformly upward, with decreased overburden pressure. Sensitivity values are low but vary vertically from approximately 5 to 22.

Relative changes in pXRF-determined elemental values correspond very well with a minor basal coarsening-upwards sequence determined by the natural gamma log (Fig. 7). From 62 m upwards to 55 m there is a decrease in K, Mn, Fe, As, Rb, Cu, Zn, Cr, Ti, and V and a corresponding increase in Ca, Sc, and S. The highest values of S measured in the core occur at 55 m; the S values decrease upwards to below detection near the top of the core. In addition, from 55 m upward to the top of the facies at 19 m, elemental abundances for Mn, Fe, As, Rb, Cu, Zn, Ti, and V all increase in value whereas values for Ca, Sc, and S decrease.

Facies D — Upper red and grey rhythmites

Red and grey rhythmites occur from 8.5 m to 19 m depth and have a sharp lower boundary. Facies D consists primarily of silty clay with some clayey silt that occurs as beds of reddish- and greyish-rhythmically-laminated sediments with a minimum of 109 rhythmite pairs counted in the recovered core interval. Beds are 5 and 50 cm thick and thicken upward (Fig. 4 and 5c, d). Black banding and/or mottling (due to the presence of hydrotroilite) occurs and can be subhorizontal or cross rhythmite boundaries (Fig. 5d). The clay-size fraction increases from 65 to 80% in the depth interval between 20 and 16.5 m and then decreases to 45% at the top of facies D as the rhythmites become indistinguishable (Fig. 6). Rhythmites above 13 m contain shells. Facies D contains very low carbonate and carbon content (0.2 to 0.7%). The majority of the carbon is inorganic. Foraminifera occur in low abundances (Fig. 4) and the taxa present are suggestive of brackish waters.

Apparent conductivity from geophysical logs increases from 900 to 1050 mS/m over the depth interval between 19 and 17 m and then decreases upwards to 840 mS/m to the base of the metal casing at 8 m depth (Fig. 6). However, the pore-water conductivity decreases from 35 to 26 mS/cm over the same interval which indicates a decrease in salinity. The shear-wave velocity decreases upward to the base of the casing at 8 m. Mean density values are 1.61 ± 0.09 g/ cm^3 (1σ, 1050 readings). The sediment shows a slight sensitivity increase (18 to 28) from 16.5 to 9.9 m upward within facies D. Porosity remains very high in the 63 to 70% range throughout the facies. The base of facies D also has a distinct seismic-reflection boundary consistent with the sharp sedimentological boundary.

The pXRF results display a significant change in many elements within facies D. Potassium concentrations markedly increase at the base of the facies and then decrease significantly upwards (Fig. 7). Calcium, however, decreases at the base and maintains low values throughout the facies. Manganese, Fe, As Ni, Cu, Cr, and V all show an overall upward increase within the facies. Rubidium shows a large increase at the base of the facies and then decreases upwards toward the top of the borehole. The inverse applies for Sr and Sc (Fig. 7).

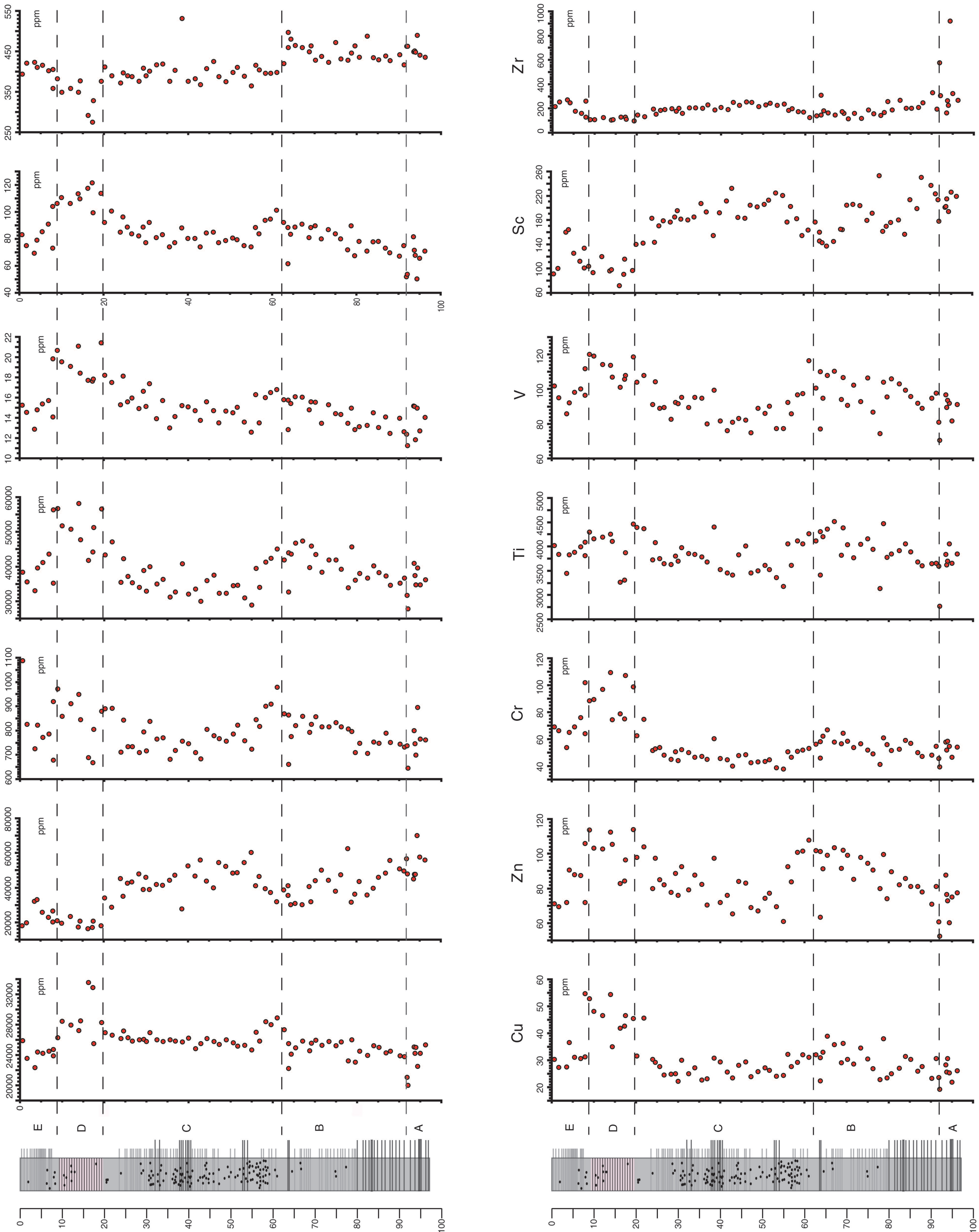

Figure 7. Variations in elemental abundance correspond well with the fining- and coarsening-upward cycles for many elements. The increase in Cu, Zn, Cr, V, Mn, Fe, As, and Rb, with a corresponding decrease in Ca near the top of the profile, reflects a significant change in provenance from the underlying sediments.

Facies E — Upper clayey silt

The uppermost facies occurs from 0 to 8.5 m depth. The lower boundary is gradational from the upper red and grey rhythmite facies into a brown, bioturbated, clayey silt facies containing organic matter (Fig. 4 and 5a, b). Some lamination is evident in this sequence and consists primarily of silty partings. The carbonate content is negligible and the total carbon is less than 1%. In situ shells and microfauna are rare near the base of facies E and become completely absent at the top (Fig. 4).

The presence of metal casing from the surface to 8 m obscures the responses of the apparent conductivity, magnetic susceptibility, and density geophysical probes, and mutes the response of the natural gamma probe. Geotechnical lab tests, on samples recovered from facies E, indicate a significant drop in porosity and rise in sediment shear strength, consistent with a high-velocity zone identified in the upper 5 m of sediment. This crust (with shear-wave velocities ranging from 200 m/s to 400 m/s) was identified by Eden and Crawford (1957), who attributed it to either post-glacial freeze-thaw cycles when the seabed was exposed, or drying and cracking of the seabed in areas where marine sediments became raised.

Pore-water conductivity decreases from 25 mS/cm at the base of facies E to nearly zero at ground surface with the sharpest decrease from 25 mS/cm to 6 mS/cm between 6 and 3 m depth. The observed decrease suggests that active groundwater flow is restricted to the upper 3 m.

Potassium, Mn, Fe, As, Rb, Cu, Zn, Cr, Ti, and V all display a marked decrease in concentration when compared with facies D (Fig. 7). Calcium, Sc and Zr concentrations increase within facies E to a peak at approximately 3 m depth.

FACIES INTERPRETATION

Facies A — Interstratified silty clays and sand

The lowermost facies encountered in the borehole is interpreted as having been deposited in a cold, fresh or nearly fresh (~10‰), deepwater environment. These deposits are interpreted as forming after the formation and infill of the underlying glacial bedrock valley (*see* seismic profile — Fig. 3). This is supported by the coarse-grained sediments in facies A and the presence of current structures, granular lags, and alternating coarse and fine beds. This facies corresponds to the lowermost portion of Gadd's (1986) unit II.

Facies B — Grey rhythmites

The grey rhythmites are believed to have been deposited in a deepening, quiescent, moderately high salinity, glaciomarine environment. This interpretation is based primarily on a gradual, linear increase in both pore-water conductivity and apparent conductivity. Pore-water conductivities increase from 15 to 35 mS/cm or salinities of approximately 9 to 22‰. Furthermore, the formation of rhythmites suggests quiescent but fluctuating sediment influx. The rhythmites may be varves recording alternating seasonal layers. The rhythmite thickness increases up-core, suggesting an increase in sedimentation rate, until they gradually grade into the overlying massive marine clays. We interpret this facies to correspond to Gadd's (1986) unit II which is described as being composed of alternating bands of light and dark grey fine silt and silty clay with *Portlandia arctica* shells.

Facies C — Massive marine clays

This facies represents the maximal salinity conditions within the Champlain Sea, as evidenced from the high apparent and pore-water conductivities, the massive nature of the silty clay / clayey silt deposits and the increased diversity and abundance of marine foraminifera and ostracodes. The maximum pore-water conductivity of 47 mS/cm corresponds to an approximate salinity of 31‰. This value is comparable to the highest salinity observed at Plaisance (approximately 36‰) by Torrance (1988). However, it is much greater than any salinity measured in the westernmost portion of the Champlain Sea basin west of Ottawa (5‰, Torrance (1988)). Foraminiferal species are consistent with an ongoing deep, cold-water environment (J.P. Guilbault, pers. comm). Facies C sedimentologically corresponds to Gadd's (1986) unit III (massive shelf and/or prodelta) which is described as being massive, vaguely stratified, silt and silty clay, grading upward into interbedded, colour-banded silty and clay cycles with hydrotroilite and *Portlandia arctica* present (facies D in this paper).

Facies D — Upper red and grey rhythmites

The underlying massive marine mud of facies C gradually transitions to red and grey rhythmically laminated silty clay. While shells and foraminifera are still present, they occur in reduced numbers and diversity, suggesting increased stress on the benthic environment, likely related to reduced salinity. The decrease in pore-water conductivities indicate that salinity may have decreased from approximately 22‰ at 18.3 m to approximately 16‰ at 9.0 m depth, demonstrating that salinities are well above those of freshwater. However, the exponential decline in pore-water conductivity within this range could suggest a rapid change in Champlain Sea salinity and subsequent upward diffusion of salt such that interpretation of past salinity should consider the possible effects of diffusion. Facies D represents the regression of the Champlain Sea from the Ottawa area and facies D probably represents a conformable transition from the underlying facies whereby the ice margin moved further north, resulting in an increase in the relative abundance of clay and decrease in silt. Therefore, facies D is interpreted as being deposited in a quiescent ice-distal glaciomarine setting. The sedimentation rate was probably lower than during deposition of the underlying muds. The cyclic alternation between red and grey beds suggests seasonal influence on sedimentation and may mean the rhythmites are varves, or annual cycles. Facies D corresponds to Gadd's (1986) unit IV (littoral / estuarine / high terrace) which is described as rhythmically, texturally or colour banded (red and grey) silt and clay beds with very fine sand partings that increase to bed-scale upwards.

Facies E — Upper clayey silt

The uppermost facies is interpreted as having been deposited in a freshwater environment. Brackish pore waters in the lowermost portion of this unit may represent either the final transition to a freshwater environment or could be the result of upward diffusion of saline waters after deposition. Facies E is devoid of in situ shells and only one sample contains foraminifera reworked from older sediments. Bioturbation is abundant. The presence of decomposing organic matter and rootlets near the top of the facies is consistent with deposition in an overbank / fluvial terrace environment as interpreted by Gadd (1986). Facies E is interpreted to correspond to Gadd's (1986) unit A or A-B (fluvial terrace and transitional fluvial), associated with the establishment of the proto-Ottawa River and modern drainage in the region.

CONTRIBUTIONS FROM THE KINBURN DATASET

Key monitoring or reference sites within representative geological settings (e.g. clay basins or sand plains) contribute to an improved understanding of the specific study site, as well as provide broader insight into specific types of geological and hydrogeological settings (LeGrand and Rosen, 1998). The Kinburn site, characterizing a clay basin, provides one such example. The applications to geological, groundwater and seismic hazard studies are highlighted through a number of examples below.

Geology and stratigraphic architecture

The basin architecture can be inferred from the seismic-reflection profile (Fig. 3). Bedrock underlying the basin is quite irregular with evidence of buried valley structures in the area of the borehole. Valleys are believed to be partly infilled with glaciofluvial gravels and sands. Further to the southeast, the bedrock is also overlain by gravel and sand fill that may have been deposited within a broad glaciofluvial system and, in part, by eskers. It is possible that coarse sediment is continuous along such valleys since esker systems are common across the northern portion of the western Champlain Sea basin (Sharpe and Shaw, 1989; Cummings et al., 2011). The very top of these sediments may have been penetrated by the borehole (facies A) but the underlying glaciofluvial sand and gravel unit, believed to be the regional aquifer, was not penetrated. The sand and gravel unit is believed to be over-pressured as flowing conditions are present in the piezometer and in a number of nearby wells.

Although there are local architectural complexities (Fig. 3; onlap, downlap etc.), seismic facies occur as a series of basically planar, tabular units overlying the coarse deposits to obscure bedrock topography. These seismic facies comprise three major units that have been identified in core as silty clay / clayey silt facies. The change from grey silty clay rhythmites, to massive marine clays, to red and grey rhythmites is interpreted to be due to changes within the Champlain Sea and to the proximity to glacier ice through time; the local settings progressed from lower to higher salinity glaciomarine to marine, due to regional ice retreat and marine water incursion. There may also have been changes in freshwater discharge fluxes into the marine waters (as in Fig. 3, Cummings et al., 2011). In addition, the Ottawa Valley area experienced changes in basin geometry due to isostatic uplift of the ice-depressed land through time (Barnett, 1988).

Bedrock shows less relief in the main basin where Paleozoic carbonates underlie unconsolidated sediment, although bedrock valleys oriented parallel to glacial flow do occur. High-amplitude reflectors above bedrock may be interpreted as thin, discontinuous till common to the regional basin, as well as discontinuous, coarse sediment (sand and gravel). There are several reflector packages within the thick sequences above the coarse sediment that contain three mud units: i) thin, lower rhythmically laminated mud, ii) massive mud and iii) colour-banded mud. These mud units are regional in distribution and have been both recognized in seismic profiles and confirmed in logging of several boreholes east of Ottawa (Gadd, 1986, Cummings et al., 2011).

Salinity variations in Champlain Sea sediments and pore waters

While it has been suggested that fresh water leaching by molecular diffusion has been responsible for decreases in pore water salinity (Quigley et al., 1983), the Kinburn data set will permit for a more detailed analysis of greater resolution with respect to the changes in salinity. Facies A and B at Kinburn (equivalent to unit II of Gadd, 1986) are at least 35 m thick and are, to our knowledge, the thickest observation of this unit in the western Champlain Sea basin. Consequently, this site likely has the best record of the transition from freshwater to saline conditions at the onset of the Champlain Sea for the region. The slow, steady upward increase in microfauna (specifically foraminifera) diversity and abundance suggest a salinity trend from fresh to brackish conditions at the base of the core upward into marine conditions in facies C. This result is consistent with the apparent conductivity log and the pore water conductivity data which also indicate a gradual rise in salinity within the lower laminated mud (facies B) to a maximum within the massive marine mud (facies C).

Evidence from microfauna, apparent conductivity and pore water conductivity suggest that salinity decreased as the red and grey rhythmites were deposited. The final transition to freshwater and fluvial conditions likely occurs within the lower portion of the clayey silt of facies E. Additional analyses of pore water chemistry and modelling of the possible effects of post-depositional diffusion will allow for a better understanding of the salinity record of the Champlain Sea basin.

Seismic hazard and downhole geophysics

Analysis of the downhole shear wave velocities show a low velocity layer that extends from 8 m to approximately 20 m depth, with velocities ranging from 100 m/s to 200 m/s. This correlates with the elevated porosities (0.6–0.7) and reduced densities (1.4–1.7 g/cm^3). A higher velocity zone underlies this facies where shear wave velocities increase uniformly with increasing overburden pressures, reaching 260 m/s at the top of the granular sand lag (92 m), at the base of the borehole.

As the Kinburn site is affected by frequent low-strain earthquakes (M1.0-M3.0) from the West Quebec Seismic Zone, a seismic monitoring site has been established on soft sediment near the borehole. It will record ground response to weak motion seismic shaking. A companion site has been installed on nearby bedrock and will allow for the comparison of sediment-to-rock spectral amplifications. These data, coupled with the results from the Kinburn borehole, provide information to better understand how basin geometry and sediment properties affect ground motions on a thick, broad suite of fine-grained Champlain Sea deposits.

Experimental pXRF technology

Bulk geochemistry, as determined by a portable XRF, closely reflects both the grain size results and the downhole geophysical logs. The method is cost-effective and provides rapid information that reflects changes in sediment input patterns, provenance, and deposition. Similar to results of Cuven et al. (2010), pXRF results are sensitive to grain size variability. Elemental values show changes that correspond to a fining-upward sequence, an overlying, short, coarsening-upwards sequence, a second fining-upward sequence, and a final coarsening-upward sequence in the top 8 m of the borehole. However, the most significant change in elemental abundances are observed in facies D between 19 and 8 m and suggest a shift to a source area higher in metals and lower in Ca. This change in elemental abundances is interpreted as a shift in sediment provenance from Paleozoic carbonate source rocks to Precambrian Shield source rocks. The down-core geochemical variations add important independent evidence to emerging interpretations of sediment provenance.

The shape of the curves for apparent conductivity from the geophysical logs and pore water conductivity deviate from one another in the interval between 22 and 8 m depth (mostly facies B). Apparent conductivity represents the total conductivity detected within the interval and includes both the solid phase and the aqueous phase. In this case, it appears that the increase in apparent conductivity may be due to increased metal concentrations (K, Mn, Fe, Rb, Cu, Zn, Cr, and V) in the solid phase as shown in the pXRF results (Fig. 7); the pore water conductivity decreases upward through this interval (Fig. 6).

SUMMARY

- The Kinburn core was collected within a basin analysis framework for regional hydrogeological analyses and monitoring (see Sharpe et al., 2002). A multidisciplinary approach has been employed with the objective to collect high-quality data and advance the understanding of the geological history of the area. Understanding of the geological history, depositional models, paleogeography, and basin fluids provides a means of proposing a predictive geological and hydrogeological framework for realistic extrapolation of results to other areas of the basin.
- An important objective of combined borehole and seismic studies is to provide reliable subsurface information to develop an accurate subsurface geological model that allows credible prediction of the groundwater system, in addition to a better understanding of the basin evolution, changes in sediment provenance and in depositional environment.
- The Kinburn site documents a buried bedrock valley setting within the Champlain Sea. The core intercepts most of the Champlain Sea mud-rich succession and documents the transition from fresh or low salinity glaciomarine settings to progressively higher salinity glaciomarine to fully marine depositional environments with an eventual return to estuarine and fluvial processes.
- The Kinburn borehole has been well characterized and, as such, is an ideal candidate for characterizing the hydrogeological behaviour of a clay aquitard in a buried valley aquifer setting. This site will provide a better understanding of the salinity record of the Champlain Sea basin. The Champlain Sea muds form a key aquitard because of their low permeability and significant spatial extent in eastern Ontario and southern Quebec.
- Installation of two seismographs on sediment and bedrock near the borehole and measurements of engineering properties on the recovered samples are contributing to a

greater understanding of weak motion and soft sediment amplification behaviour during seismic-induced ground motions. These results contribute to ongoing urban seismic hazard research being supported by NRCan's Public Safety Geoscience Program and the Canadian Seismic Research Network.

- Finally, the convergence of multidisciplinary data sets on the "golden spike" borehole near Kinburn, Ontario, allows for a more detailed interpretation and understanding of the geological history and contributes to a predictive framework for the hydrogeological setting of a regional aquifer type.

ACKNOWLEDGMENTS

We would like to thank Heather Brodie-Brown and Brian Stratton at the Ontario Ministry of the Environment and the Mississippi-Rideau Conservation Authority Source Protection Region for making this study possible. George Gorrell is thanked for his assistance. André Beauchamp and Jacques Pinard made core logging possible. Invaluable core logging assistance came from Shane Ghouralal and Raguvind Gounder. We also wish to acknowledge Claudia Moore, in the GSC-Ottawa Sedimentology Laboratory, who diligently extracted pore water and measured pore water conductivities.

REFERENCES

Anderson, T.W., 1988. Late Quaternary pollen stratigraphy of the Ottawa valley—Lake Ontario region and its implications in dating the Champlain Sea; *in* The Late Quaternary Development of the Champlain Sea Basin, (ed.) N.R. Gadd; Geological Association of Canada, Special Paper 35, p.207–224.

Anderson, T.W., Mott, R.J., and Delorme, L.D., 1985. Evidence for a pre-Champlain Sea glacial lake phase in Ottawa Valley, Ontario, and its implications; *in* Current Research, Part A; Geological Survey of Canada, Paper 85-1A, p. 239–245.

Barnett, P.J., 1988. History of the northwestern arm of the Champlain Sea; in The Late Quaternary Development of the Champlain Sea Basin, (ed.) N.R. Gadd ;Geological Association of Canada Special Paper 35, p. 25–36.

Cummings, D.I. and Russell, H.A.J., 2007. The Vars-Winchester esker aquifer, South Nation River watershed, Ontario, CANQUA Fieldtrip Guidebook, June 6th, 2007; Geological Survey of Canada, Open File 5624, 68 p. doi:10.4095/224424

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; Geological Society of America Bulletin, v. 123, p. 1478–1496. doi:10.1130/B30273.1

Cuven, S., Francus, P., and Lamoureux, S.F., 2010. Estimation of grain size variability with micro X-ray fluorescence in laminated lacustrine sediments, Cape Bounty, Canadian High Arctic; Journal of Paleolimnology, v. 44, p 803–817. doi:10.1007/s10933-010-9453-1

Eden, W.J. and Crawford, J.B., 1957. Geotechnical properties of Leda clay in the Ottawa area; National Research Council of Canada, Research Paper No. 37 of the Division of Building Research, Ottawa, ON, 5 p.

Fulton, R.J. (ed.), 1987. Quaternary geology of the Ottawa Region, Ontario and Quebec; Geological Survey of Canada, Paper 86-23, 47 p.

Gadd, N.R., 1986. Lithofacies of Leda clay in the Ottawa Basin of the Champlain Sea; Geological Survey of Canada, Paper 85-21, 44 p.

Girard, I., Klassen, R.A., and Laframboise, R.R., 2004. Sedimentology laboratory manual, Terrain Sciences Division; Geological Survey of Canada, Open File 4823, 134 p. 1 CD-ROM. doi:10.4095/216141

Guilbault, J.-P., 1989. Foraminiferal distribution in the central and western parts of the late Pleistocene Champlain Sea basin, Eastern Canada; Géographie physique et Quaternaire, v. 43, p. 3–26.

Hansbo, S., 1957. A new approach to the determination of the shear strength of Clay by the Fall-Cone Test; Royal Swedish Geotechnical Institute, Proceedings no. 14, Ivar Hæggströms Boktryekeri AB, Stockholm, 47 p.

Hunter, J.A., Burns, R.A., Good, R.L., Aylsworth, J.M., Pullan, S.E., Perret, D., and Douma, M., 2007. Borehole shear wave velocity measurements of Champlain Sea sediments in the Ottawa-Montreal Region; Geological Survey of Canada Open File 5345, 1 CD-ROM. doi:10.4095/223226

Johnston, W.A., 1917. Pleistocene and recent deposits in the vicinity of Ottawa, with a description of the soils; Geological Survey of Canada, Memoir 84, 69 p.

Knight, R.D., Russell, H.A.J., Logan, C., Hinton, M.J., Sharpe, D.R., Pullan, S.E., and Crow, H.L., 2008. Regional hydrogeological studies: the value of data collected from continuously cored boreholes; GeoEdmonton'08/ GéoEdmonto2008: 61st Canadian Geotechnical Conference and the 9th Joint CGS/IAH-CNC Groundwater Conference, proceedings; p. 1484–1491.

LeGrand, H.E. and Rosen, L., 1998. Putting hydrogeological site studies on track; Ground Water, v. 36, p. 193. doi:10.1111/j.1745-6584.1998.tb01079.x

Logan, C.E., Knight, R.D., Crow, H.L., Russell, H.A.J., Sharpe, D.R., Pullan, S.E., and Hinton, M.J., 2008 Southern Ontario "Golden Spike" data release: Nobleton borehole; Geological Survey of Canada, Open File 5809, 29 p. doi:10.4095/225026

MacPherson, J.B., 1968. The physiographic evolution of the Montreal archipelago; The Canadian Geographer. Geographe Canadien, v. 12, p. 254–265. doi:10.1111/j.1541-0064.1968.tb00775.x

Pair, D.L. and Rodrigues, C.G., 1993. Late Quaternary deglaciation of the southwestern St. Lawrence Lowland, New York and Ontario; Geological Society of America Bulletin, v. 105, p. 1151–1164. doi:10.1130/0016-7606(1993)105%3c1151:LQDOTS%3e2.3.CO%3b2

Parent, M. and Occhietti, S., 1988. Late Wisconsian deglaciation and Champlain Sea invasion in the St. Lawrence Valley, Quebec; Géographie physique et Quaternaire, v. 42, p. 215–246.

Pugin, A.J.-M., Larson, T.H., Sargent, S.L., McBride, J.H., and Bexfield, C.E., 2004. Near-surface mapping using SH-wave and P-wave seismic land-streamer data acquisition in Illinois; Leading Edge (Tulsa, Okla.), v. 23, p. 677–682. doi:10.1190/1.1776740

Pugin, A.J.-M., Sargent, S.L., and Hunt, L., 2006. SH and P-wave seismic reflection using landstreamers to map shallow features and porosity characteristics in Illinois; *in* Proceedings, SAGEEP'06 (Symposium on the Application of Geophysics to Engineering and Environmental Problems), Seattle, Washington, April 2–6, 2006, published on CD-ROM.

Pugin, A.J.-M., Hunter, J.A., Pullan, S.E., Cartwright, T., Douma, M., Good, R.L., and Burns, R.A., 2007. Buried-channel imaging using P- and SH-wave shallow seismic reflection techniques, examples from Manitoba, Canada; *in* Proceedings, SAGEEP'07 (Symposium on the Application of Geophysics to Engineering and Environmental Problems), Denver, Colorado, April 1–5, 2007, p. 1330–1338.

Pugin, A.J.-M., Pullan, S.E., and Hunter, J.A., 2009. Multi-component high resolution seismic reflection profiling; The Leading Edge, v. 28, p. 1248–1261936–945.

Quigley, R.M., Gwyn, Q.H.J., White, O.L., Rowe, R.K., Haynes, J.E., and Bohdanowicz, A., 1983. Leda clay from deep boreholes at Hawkesbury, Ontario. Part I: geology and geotechnique; Canadian Geotechnical Journal, v. 20, p. 288–298. doi:10.1139/t83-032

Richard, S.H., 1982a. Surficial geology, Winchester, Ontario; Geological Survey of Canada, Map 1491A, scale 1:50 000. doi:10.4095/119408

Richard, S.H., 1982b. Surficial geology, Russell, Ontario: Geological Survey of Canada, Map 1507A, scale 1:50 000. doi:10.4095/109232

Richard, S.H., 1984. Surficial geology, Arnprior, Ontario-Quebec; Geological Survey of Canada, Map 1599A, scale 1:50 000. doi:10.4095/120014

Rodrigues, C.G., 1987. Late Quaternary invertebrate faunal associations and chronology; *in* Quaternary geology of the Ottawa Region, Ontario and Quebec, (ed.) Fulton, R.J.; Geological Survey of Canada, Paper 86-23, p. 155–176.

Rodrigues, C.G., 1988. Late Quaternary invertebrate faunal associations and chronology of the western Champlain Sea Basin; *in* The Late Quaternary Development of the Champlain Sea Basin, (ed.) Gadd, N. R.; Geological Association of Canada Special Paper 35, p. 155–176.

Rodrigues, C.G., 1992. Successions of invertebrate microfossils and the late Quaternary deglaciation of the central St Lawrence Lowland, Canada and United States; Quaternary Science Reviews, v. 11, p. 503–534. doi:10.1016/0277-3791(92)90010-6

Rust, B.R. and Romanelli, R., 1975. Late Quaternary subaqueous outwash deposits near Ottawa, Canada; *in* Glaciofluvial and Glaciolacustrine Sedimentation, (ed.) A.V. Jopling and B.C. McDonald; SEPM Special Publication 23, p. 177–192.

Sharpe, D.R., 1988. Glaciomarine fan deposition in the Champlain Sea; in The Late Quaternary Development of the Champlain Sea Basin, (ed.) N.R. Gadd; Geological Association of Canada, Special Paper 35, p. 63–81.

Sharpe, D.R. and Shaw, J., 1989. Erosion of bedrock by subglacial meltwater, Cantley, Quebec; Geological Society of America Bulletin, v. 101, p. 1011–1020. doi:10.1130/0016-7606(1989)101%3c1011:EOBBSM%3e2.3.CO%3b2

Sharpe, D.R., Hinton, M.J., Russell, H.A.J., and Desbarats, A.J., 2002. The need for basin analysis in regional hydrogeological studies: Oak Ridges Moraine, Southern Ontario; Geoscience Canada, v. 29, p. 3–20.

Torrance, J.K., 1988. Mineralogy, pore-water chemistry, and geotechnical behaviour of Champlain Sea and related sediments; *in* The Late Quaternary Development of the Champlain Sea Basin, (ed.) N.R. Gadd; Geological Association of Canada, Special Paper 35, p. 259–275.

Geological Survey of Canada Project AM1002