

Subsurface heterogeneity in the geological and hydraulic properties of the hummocky Paris Moraine, Guelph, Ontario¹

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Abstract: The advance and retreat of ice lobe margins of the Laurentide Ice Sheet formed moraines that are a prevalent feature throughout southwestern Ontario. In contrast to the well-studied stratified moraine complexes, recessional and end moraines have largely been ignored in the context of hydrogeological studies. Recent urban growth has led to development pressures on these moraines and a need to better understand their hydrogeology. This study presents data sets from the Paris Moraine near Guelph, Ontario, to examine its geomorphology, internal composition, and the corresponding hydraulic properties of these ice-marginal features. The moraine's geomorphic elements were mapped using high-resolution Global Positioning System transects, aerial photograph analysis, and ground truthing. Nine continuous sediment cores were recovered to determine the nature and distribution of subsurface sedimentary units and their relation to the regional stratigraphic framework. Cores were described in detail using standard sedimentological techniques, and significant sediment heterogeneity was observed in cross sections. Grain-size analyses of over 150 samples provide site-specific estimates of saturated hydraulic conductivity. In addition, saturated hydraulic conductivity was measured on 104 samples using the falling head permeameter method. This study found that different scales of sediment heterogeneity occur across the moraine and the associated till plain and outwash. In contrast, the hydraulic conductivity varies much less. It is expected that certain sedimentary units at specific depths will impact groundwater flow at the centimetre to hundreds of metres scale, which is significant in environmental site assessments or for understanding contaminant hydrogeological problems.

Résumé : L'avancée et le retrait des marges de lobes de la calotte glaciaire Laurentidien ont formé des moraines qui constituent un élément bien en évidence dans tout le sud-ouest de l'Ontario. Contrairement aux complexes de moraines stratifiées bien étudiés, les moraines terminales et de retrait n'ont pas fait l'objet de beaucoup d'études hydrogéologiques. L'urbanisation récente a mené à des pressions d'aménagement sur ces moraines et la nécessité de mieux comprendre leur hydrogéologie. L'étude présente des ensembles de données sur la moraine de Paris, près de Guelph (Ontario), afin d'examiner sa géomorphologie, sa composition interne et les propriétés hydrauliques correspondantes de ces éléments glaciaires marginaux. Les éléments géomorphologiques de la moraine ont été cartographiés par des transects GPS de haute résolution, l'analyse de photographies aériennes et des vérifications au sol. Neuf carottes de sédiments continues ont été obtenues dans le but d'établir la nature et la répartition des unités sédimentaires du sous-sol et leur relation avec le cadre stratigraphique régional. Les carottes ont été décrites en détail par des techniques sédimentologiques normalisées, et une importante hétérogénéité des sédiments a été observée dans les coupes. L'analyse granulométrique de plus de 150 échantillons fournit des estimations de la conductivité hydraulique en milieu saturé en différents sites. Cette dernière a en outre été mesurée sur 104 échantillons par la méthode du perméamètre à charge décroissante. L'étude a fait ressortir différentes échelles d'hétérogénéité des sédiments dans la moraine et la plaine de till et les dépôts d'épandage associés. La conductivité hydraulique varie beaucoup moins en comparaison. Il est prévu que certaines unités sédimentaires à différentes profondeurs auront une influence sur l'écoulement de l'eau souterraine à des échelles allant des centimètres aux hectomètres, ce qui constitue une constatation importante pour les évaluations environnementales de site et pour la compréhension des problèmes hydrogéologiques associés aux contaminants. [Traduit par la Rédaction]

Introduction

Moraines are a prevalent landform in southern Ontario, recording the advance and temporary standstill (in the retreat phases) of lobes of the Late Wisconsinan Laurentide Ice Sheet (Chapman and Putnam 1984; Barnett 1992). As positive relief features in the landscape, these moraines are often considered important zones for recharge, and some host complex and stratified aquifers that are an important source for nearby urban centres (Sharpe et al. 1996,

2014; Howard et al. 1997; Bajc and Shirota 2007; Bajc et al. 2014). While several interlobate stratified moraine complexes in southern Ontario have been the focus of comprehensive geological and hydrogeological studies (Barnett et al. 1998; Sharpe et al. 2004; Bajc et al. 2014), end and recessional moraines have generally not received the same attention from the international scientific community (Andersson 1998; Gartner Lee Ltd. 2004; Blackport Hydrogeology Inc. et al. 2009; Russell et al. 2009, 2013).

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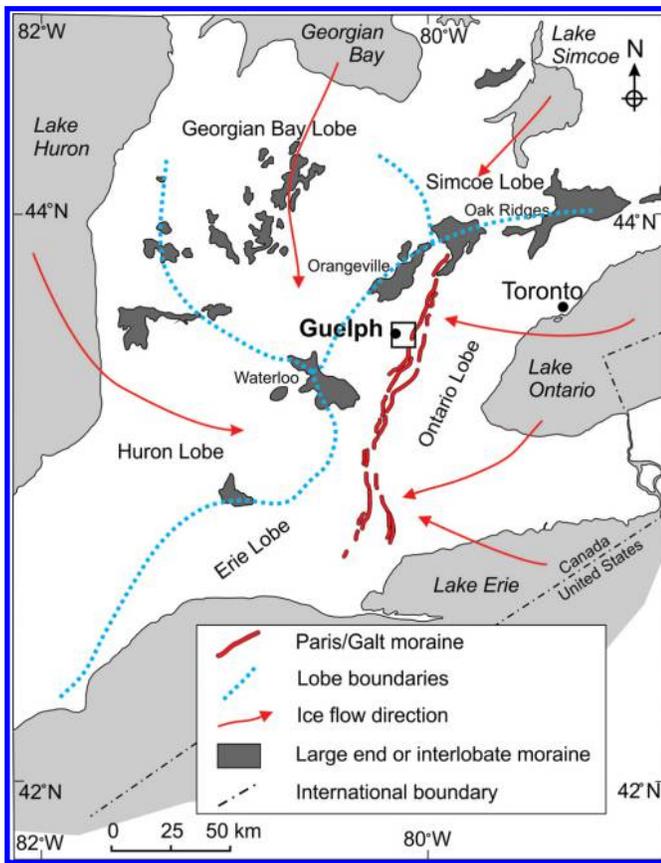
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Fig. 1. Map delineating the extent of the Paris–Galt moraines relative to larger stratified moraines that have been previously studied as well as distribution of various ice lobes of the Laurentide Ice Sheet and their corresponding ice-flow directions (modified from Barnett 1992). Study area identified by square box near Guelph. [Colour online.]



Hydrogeologically, end and recessional moraines are thought to be relatively less complex, and presumed to consist primarily of diamict (till) in contrast to the heterogeneous glacial stratigraphy including well-sorted aquifer materials more prevalent in interlobe settings. Despite this view, end and recessional moraines are considered important landscape elements of the hydrological system, particularly in the context of their hummocky topography and consequent ponding and slow depression-focused recharge to the underlying sand and gravel and bedrock aquifers (Bates and Metcalfe 2006; Blackport Hydrogeology Inc. et al. 2009; Ahrens 2012). Recent studies have suggested that end and recessional moraines may be more complex in terms of their internal composition (Russell et al. 2009, 2013; Kehew et al. 2012; see Paris Moraine aquitard facies in Burt and Dodge 2016), considering processes such as meltwater, sediment gravity flows, deformation by ice, and ponding may all be important in their development. These processes lead to substantial subsurface sediment heterogeneity that is likely to affect groundwater recharge and the transport and fate of contaminants at depth.

The Paris Moraine is located along the outer margin of the Wentworth Till plain, extending over 100 km from just north of Lake Erie to southeast of the City of Orangeville (Figs. 1, 2). This moraine delineates the maximum extent and a temporary standstill of the Lake Ontario – Lake Erie ice lobe during the retreat phase of the Mackinaw interstadial (Chapman and Putnam 1984; Barnett 1992). In the Guelph area, the moraine is characterized by a broad band of high-relief hummocky topography, with numerous kames (Karrow 1987). During early mapping of the Paris Moraine, geologists identified the feature’s variability, including the

nature of sediment types, at a regional scale. In the southern portion of the Paris Moraine, the diamict and associated sediments are sandy, whereas to the north, the moraine’s composition is described as a bouldery loam that can have a strong red colouration (northeast of the study area) and that is commonly associated with coarse outwash (Karrow 1968, 1987; Chapman and Putnam 1984). More recently, Bajc and Dodge (2011) found stratified sand and gravel make up a large proportion of the Paris and Galt moraines (southwest of the study area), along with coarse-textured Wentworth Till. Burt and Dodge (2016) identified a hydrostratigraphic unit for the Wentworth Till in the Paris Moraine northeast of the study area that was distinct from the hydrostratigraphic unit for the Wentworth Till exposed in the till plain based on the variable facies encountered in three high-quality boreholes and multiple water well records. Russell et al. (2013) documented similar subsurface heterogeneity at a regional scale using the provincial water well records and outcrops.

The Ontario Ministry of the Environment commissioned a study to inform their water resource management policies in the context of moraines (Blackport Hydrogeology Inc. et al. 2009). This report clearly identified the hydrogeological function of the Paris Moraine and several data or knowledge gaps related to its subsurface stratigraphy. The City of Guelph has undergone a detailed assessment of its subsurface geology, water budget, and the sustainability and vulnerability of its water supply (AquaResource Inc. et al. 2007; AquaResource Inc. 2010) as required by the Province’s Clean Water Act of 2006 (Ontario Ministry of the Environment 2009). The City of Guelph was subsequently identified as a community that would be encouraged to grow in the Ontario Places to Grow Act (Ministry of Infrastructure 2012), a government program designed to encourage sustainable growth and urban development in the area surrounding the Greater Toronto Area (GTA). As part of this program, the City of Guelph continues to assess the sustainability of its groundwater resources as the city and the region face significant land use change and increased urbanization. The Paris Moraine, which crosses the southeastern boundary of the City of Guelph, as well as other “Places to Grow” communities, is specifically facing increased urbanization pressures as these communities continue to develop to accommodate the growing population in the region (Blackport Hydrogeology Inc. et al. 2009). The lack of detailed subsurface information that could help constrain groundwater flow models has in part hampered these source water protection studies. In this context, this paper presents new geomorphic, sedimentological, and hydrogeological data that can be used to better characterize the subsurface heterogeneity within the Paris Moraine in the Guelph area and provide insight into the origin, subsurface heterogeneity, and hydrogeology of hummocky recessional and end moraines here and elsewhere.

Geological setting

The unconsolidated sediments and associated landforms overlying the Silurian-age bedrock in southern Ontario are mainly of glacial origin (Figs. 1, 2; Karrow 1968, 1987; Chapman and Putnam 1984; Barnett 1992). The northeast- to southwest-trending Paris Moraine is the most prominent feature in the Guelph area, with an extensive network of coarsely stratified sand and gravel deposits on adjacent outwash plains both in front of (northwest) and behind (southeast) the moraine. Drumlinized till plain and occasional eskers otherwise characterize the northwest and southeast region of the study area (Karrow 1968; Chapman and Putnam 1984). The thickness of unconsolidated sediments ranges from <10 to 20 m on the drumlinized till and outwash plains and up to ~45 m on the Paris Moraine.

The stratigraphy of unconsolidated sediments records various northwestern-directed advances and southeast-directed retreats of the Lake Ontario – Lake Erie ice lobe of the Laurentide Ice Sheet (Figs. 1, 2; Tables 1, 2). The most extensive glacial advance came

Fig. 2. Topographic and geological setting of the study area. (A) Hillshaded digital elevation model (Provincial Digital Elevation Model 2007) of the Guelph area highlighting the hummocky and high-relief terrain associated with the northeast–southwest-trending Paris Moraine. Note the Galt Moraine to the southeast of the Paris Moraine and the drumlins in the northwest part of the study area. (B) Surficial geology of the Guelph area highlighting the distribution of the two surficial till units (Ontario Geological Survey 2010).

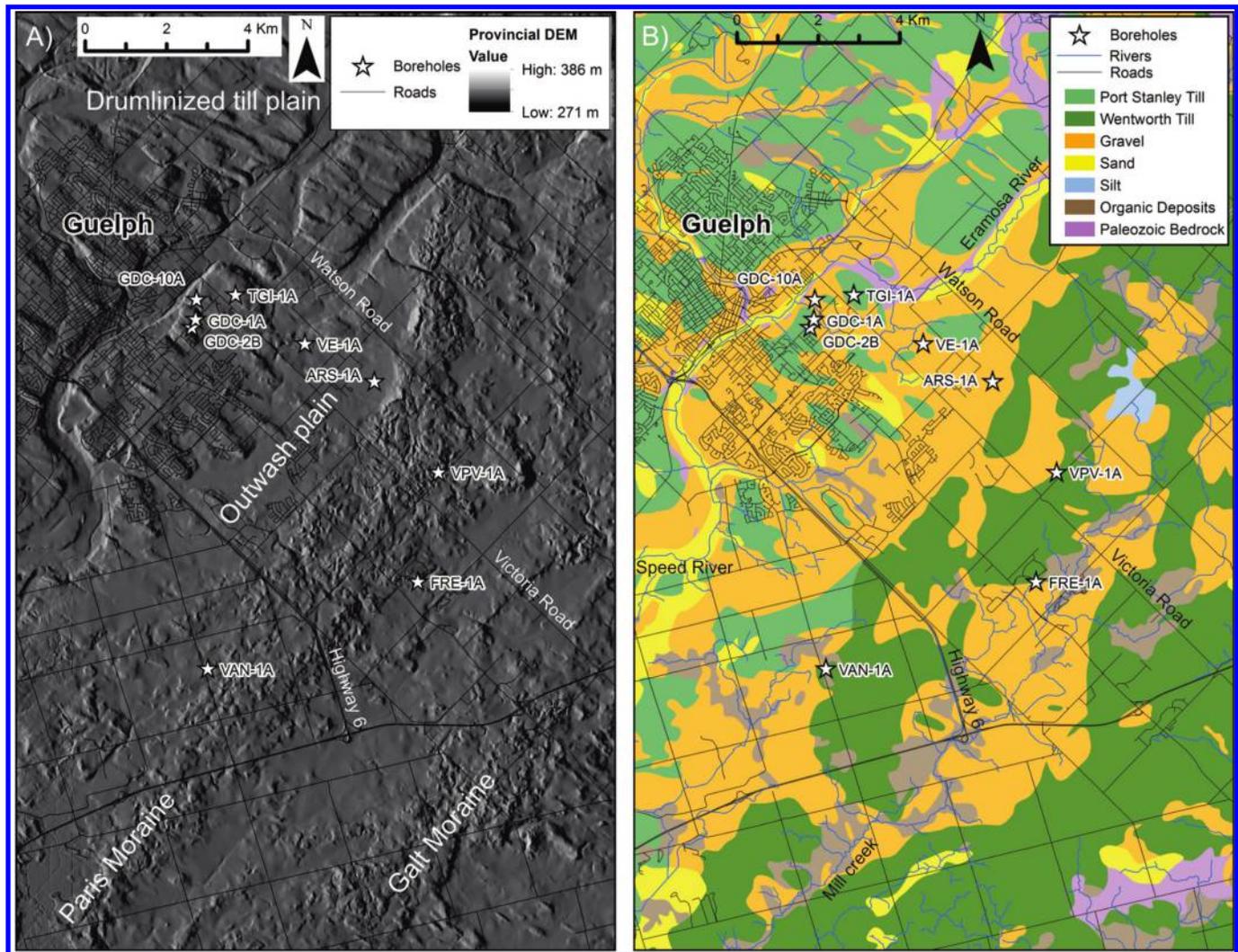


Table 1. Stratigraphy of the glacial sediments overlying Paleozoic bedrock in the study area.

Glacial phase	Northwest Guelph	Southeast Guelph
Mackinaw ^a or younger		Kame–Outwash
Mackinaw ^a	Kame–Outwash	Wentworth Till
Port Bruce ^a	Port Stanley Till	
Port Bruce ^a	Maryhill Till	Maryhill Till
Erie ^a	Kame–Outwash	Kame–Outwash
Nissouri ^a	Catfish Creek Till	Catfish Creek Till
Pre-Nissouri ^b	Canning Till or older	Canning Till or older

Note: After Karrow (1968, 1987), Barnett (1992), and Karrow et al. (2000).

^aMichigan Subepisode of the Late Wisconsinan glaciation.

^bMiddle to Early Wisconsinan.

from the north and took place during the Nissouri Phase, depositing the Catfish Creek Till throughout the region (Karrow 1987). In the Guelph area, erosion from Nissouri Phase ice and associated meltwaters removed the sediments of prior glacial advances and retreats, though limited exposure of a pre-Nissouri Till and stratified sediments have been described (Karrow 1987; Burt 2011) and referred to as Canning Till or older sediment. The Catfish Creek Till is generally a stony, silty, sand till that is identifiable in the

field by its overconsolidated and very dense nature, grey buff to olive colour, stratigraphic position below a clay till, and most often basal position in the overall stratigraphic sequence of Quaternary deposits (Karrow 1987; Bajc and Dodge 2011; Burt 2011; Table 2).

Above the Catfish Creek Till, Karrow (1987) identified kames or outwash stratified sediments and the Maryhill Till (renamed Middle Till in Karrow (1968)), which is fine-grained, clast-poor, and clayey silt to clay textured. Several studies associated these sediments with early fluctuations of the Erie–Ontario lobe advance during the Erie Phase (Karrow 1968; Barnett 1992; Burt 2011). Another significant advance of the Erie–Ontario lobe followed, and deposited the Port Stanley Till (Port Bruce Phase; Table 1). This till is exposed at the surface within the drumlinized till plain (Figs. 1, 2). In the Guelph area, the Port Stanley Till is sandy (composed of roughly 40% sand) and has a calcite/dolomite ratio of 0.7 (Karrow 1987; Table 2).

The Wentworth Till is the youngest till in the region, deposited during the Mackinaw Phase, and exposed to the southeast of Guelph within the Paris Moraine and beyond towards Lake Ontario (Table 1; Karrow 1968, 1987; Barnett 1992; Karrow et al. 2000; Bajc and Dodge 2011). In the Guelph area, the Wentworth Till has a sandy to silty sand texture, is usually buff in colour, and often bouldery or

Table 2. Till characteristics from Karrow (1968, 1987), Burt (2011), and Bajc and Dodge (2011).

Till	Characteristics, distribution, and ice lobe affinity
Wentworth Till	Sandy to silty sand diamict, usually buff in colour, and often bouldery or stony; occurs at surface above a clay layer; is thought to make up most of the Paris and Galt moraines in the Guelph area. Ice lobe affinity: Ontario–Erie lobe.
Port Stanley Till	Stony silty sandy (Guelph area) to stone-poor clayey silt (south of Guelph) diamict; occurs at surface throughout Guelph drumlins, north of the Paris Moraine. Ice lobe affinity: Erie lobe.
Maryhill Till	Originally referred to as the “Middle Till” by Karrow (1968); clast-poor clayey silt to clay diamict; glaciolacustrine origin proposed in some areas (e.g., Waterloo region and north of Guelph). Ice lobe affinity: Ontario–Erie lobe.
Catfish Creek Till	Regionally extensive unit; stony, silty to sandy diamict notable for its overconsolidation, grey buff to olive in colour; occurs at a lower stratigraphic position below a clay till; often referred to as “hardpan”; subdivided into two facies (fine and coarse) in the Waterloo region (Bajc and Dodge 2011). Ice lobe affinity: Huron–Georgian Bay–Simcoe lobe.
Canning Till	Coarse textured; not often preserved; often confused with the Catfish Creek Till. Ice lobe affinity: Ontario–Erie lobe.

stony, especially in the Paris and Galt moraines (Karrow 1968, 1987; Sadura et al. 2006; Table 2).

Methods

Three sets of data were collected in the different geomorphic settings or elements of the study area, namely drumlinized till plain, outwash plain, and morainal: topographic, geological (continuous core descriptions, interpolated cross sections, and grain size), and hydrogeological data (empirically derived and permeameter-based hydraulic conductivities).

A geomorphic element classification scheme and process like those developed by Sadura et al. (2006), Paul (1983), Krzyszkowski and Zieliński (2002), and Andrzejewski (2002) were used to characterize the land surface topography and map the geomorphology of the study area. High-resolution Global Positioning System (GPS) elevation surveys (nine transverse, three longitudinal to the moraine) were also carried out to further assess and quantify spatial variability in land surface profile across and along the Paris Moraine. The GPS surveys were completed using a vehicle-mounted, network real-time kinematic (RTK) GPS unit. This included Leica (Leica Geosystems, St. Gallen, Switzerland) GNSS survey-grade equipment, including an ATX1230 GG antenna, and a RX1250X controller. Location and elevation data were recorded approximately every 50 m, with a threshold accuracy of 10 cm, and readings were corrected for antenna height above ground surface.

Continuous sediment cores were recovered at nine sites across the region (Fig. 2), with three cores in each geomorphic element. Sites both on and off the Paris Moraine provide stratigraphic context for the subsurface sediments. Most of the cores were recovered using a rotasonic drill, with the exception of cores GDC-2B and VPV-1A (Fig. 2), which were recovered using mud rotary wireline (PQ) coring. Each core was photographed and logged (with centimetre resolution) to determine changes in the physical properties of the sediment, including grain size, sedimentary structures, colour (Munsell colour system), and clast characteristics (average and maximum size, lithology, roundness) (Evans and Benn 2004). Presence of faceting and striations on clasts were also noted where present. The texture classification scheme of Hambrey and Glasser (2003) was used and defines diamict as either clast poor or clast rich (1%–5% or 5%–50% clast content, respectively) and either sandy (>66% sand), intermediate (33%–66% sand), or muddy (<33% sand) based on its matrix texture.

Subsurface data visualization software (RockWorks 15 (RockWare Inc. 2009)) generated geological cross sections using data from new (nine continuous cores) and existing (1415 borehole records from the Ontario Ministry of Environment water well records, geotechnical reports, and unpublished University of Guelph reports) subsurface data. The data were standardized using the rule-based method of Russell et al. (1998) to reduce the number of unique descriptors to 14. The database of water well records was also screened for accuracy. Boreholes having no location data, a location with an accuracy of <300 m, or located in the centre of a lot were rejected. A subset of 201 boreholes was used in creating 23

lithologic cross sections (McGill 2012). Only the cross sections specifically drawn through the Paris Moraine hummocky geomorphic element are reported and discussed here. A Kriging algorithm in RockWorks 15 (RockWare Inc. 2009) that utilized the surface elevations of the entire 1424 boreholes in the database generated the ground surface profile along the cross sections.

The grain-size distribution of over 150 samples was determined by sieve and hydrometer analysis (Gee and Or 2002; Kroetsch and Wang 2008). Saturated hydraulic conductivity (K_{sat}) was then calculated from grain-size distributions using the Kozeny–Carman empirical equation (Vukovic and Soro 1992), based on its wide use in industry and because it is considered accurate over a wide range of sediments (Chapuis and Aubertin 2003). K_{sat} was also directly measured by falling head permeameter tests using standard methods on 104 disturbed samples (Reynolds et al. 2002). Calculated (K_{sat}) values were calibrated to local conditions by shifting the geometric mean of calculated values onto the geometric mean of the measured values (calibration factor of 3.86 m/s; Trapp 2015).

Once the saturated hydraulic conductivity values were plotted against lithology, hydrostratigraphic units (here defined as units with K_{sat} values within one order of magnitude of each other) were delineated for each core to establish the nature of variability within each geomorphic element. K_{sat} units were delineated by grouping adjacent lithologic units with similar K_{sat} values (± 1 order of magnitude), using the following criteria: (i) When both measured and calculated K_{sat} values are available for a sample, the measured value is given priority (Kasenow 2002). (ii) If differing K_{sat} values occur in a single lithologic unit, they are separated in distinct hydrostratigraphic units at the halfway point between the two sample points. (iii) Where a unit has a single K_{sat} value differing from the next unit in succession, these are separated at the lithologic boundary. (iv) When a measured or calculated K_{sat} value is unavailable for a lithologic unit, it is assigned to the adjacent unit, which has a similar lithology. Once a K_{sat} unit has been delineated, it is assigned the geometric mean (K_{Ca}) of all the measured and calculated K_{sat} values within the unit.

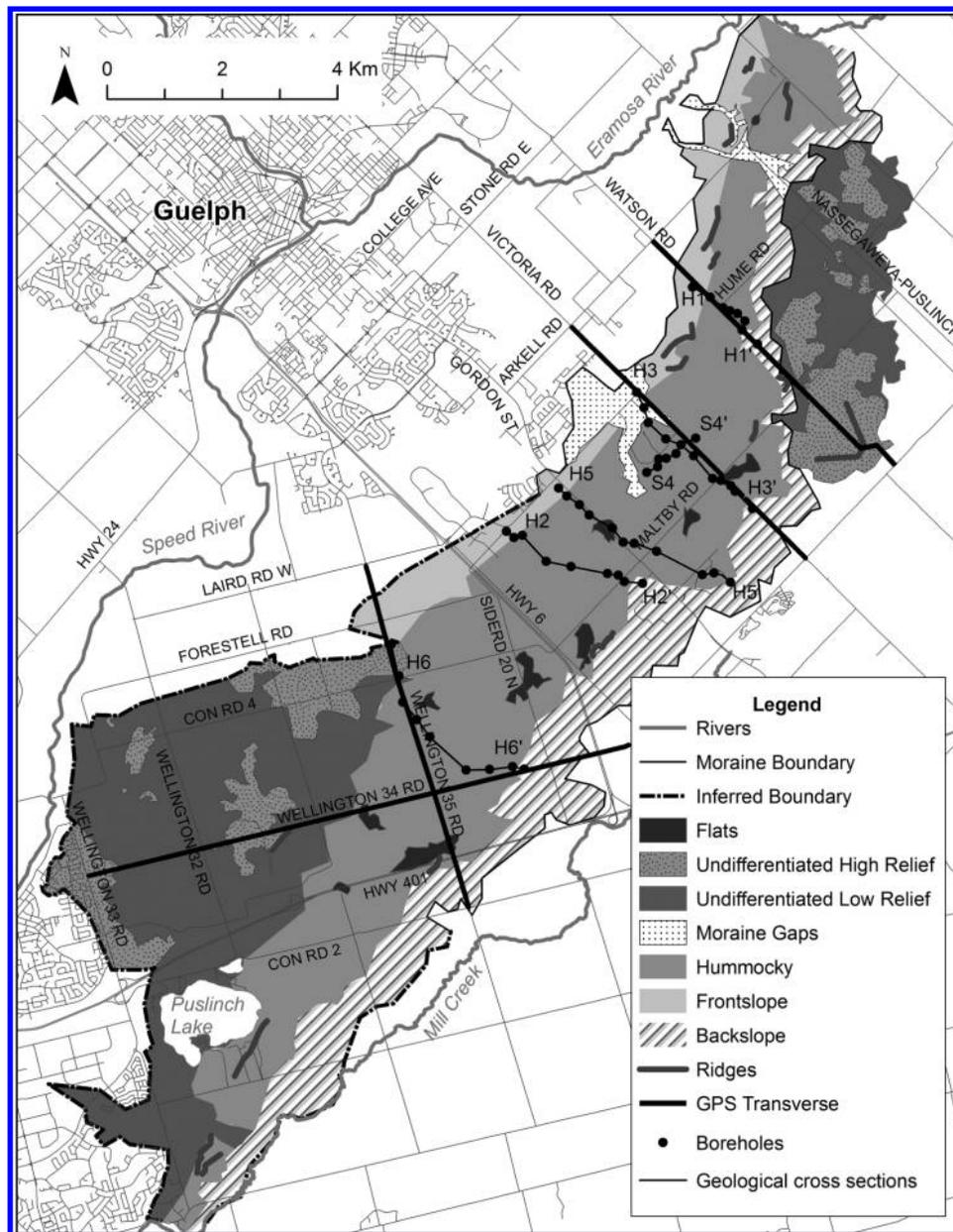
Results

Geomorphic elements of the Paris Moraine

The Paris Moraine is a landform composed of several geomorphic elements. In addition to the frontslope, hummocky, and backslope elements previously recognized by Sadura et al. (2006), this study has also identified ridge, flat, moraine gap, and undifferentiated high- and low-relief elements of the moraine (Fig. 3). The moraine surface has a maximum elevation of 385 m a.s.l. (above sea level). Its maximum slope angle of 23° is observed in the frontslope geomorphic element. The hummocky element, which forms the core of the moraine, is the most prominent geomorphic element, covering an area of 40.25 km².

The frontslope element is defined in the Guelph area as the area on the Paris Moraine where the slope increases from relatively flat-lying (i.e., the outwash and till plains) to the top of the highest

Fig. 3. Map of the Paris Moraine geomorphic elements observed in the Guelph area. Locations of high-resolution GPS surveys, geological boreholes, and cross sections (reported in Figs. 4 and 8 and Table 3) are also identified.



frontal hill where the land surface profile becomes irregular (hummocky) and the hummocky element begins (Fig. 3). The frontslope element rises approximately 28 m above the outwash plain at the Arkell Research Station (ARS-1A; Fig. 2); however, the topography varies across the length of the frontslope element. Some sections of the frontslope element contain abrupt, relatively steep sloped ridge–hillcrest features (e.g., near site ARS-1A (Figs. 2, 3) and along Watson Road (Fig. 4)), whereas along other topographic sections, the land surface is gently rolling, leading to the higher topographic relief of the moraine, on either side of Highway 6 (Fig. 2) and along Victoria Road and Wellington Road 35 (Fig. 4). The frontslope element at Victoria Road (Fig. 4) is closely associated with a moraine gap element (Fig. 3). Meltwater likely modified this slope when the moraine was breached.

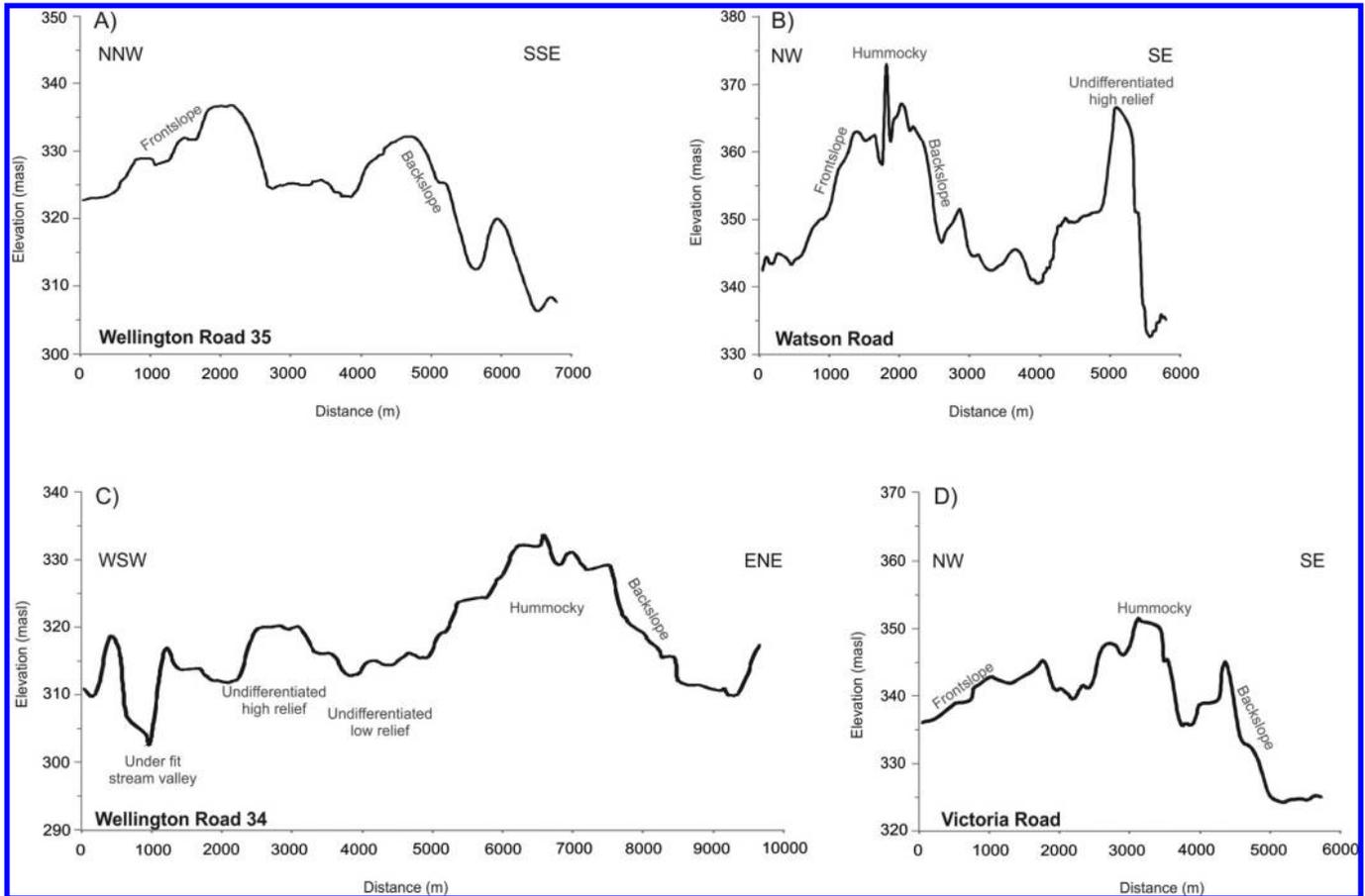
The hummocky geomorphic element is characterized as having irregular surfaces of hummocks (knobs) and depressions (Figs. 2, 3).

The hummocks and depressions vary in size, morphology, and connectivity to other hummocks. Hummocks have heights ranging from 4 to 28 m and widths of between ~200 and 1600 m or greater. Furthermore, locally connected depressions exist between the hummocks, sometimes connected to a moraine gap element.

The backslope element begins at the top of the southeastern-most hillcrest or hummock of the moraine and extends down-slope to where the slope levels off onto the adjacent flat-lying outwash plain (Figs. 2, 3). This slope is not necessarily one continuous slope, but can also include gently rolling segments that have some degree of terracing. In contrast to the frontslope element, the steepness of the backslope element is much more consistent along the moraine axis.

Other geomorphic elements of the Paris Moraine include moraine gaps, flats, and ridges (Figs. 2, 3). Moraine gaps are the channel-like features or gullies that originate on the moraine, cut

Fig. 4. High-resolution GPS elevation profiles along (A) Wellington Road 35, (B) Watson Road, (C) Wellington Road 34, and (D) Victoria Road. See Fig. 3 for location of transects. All the transects except Wellington Road 34 were run perpendicular to the general northeast–southwest trend of the Paris Moraine.



perpendicularly through the moraine front, and can locally be seen to continue through or beyond the front slope of the moraine, connecting to valleys that contain underfit streams. They form low to moderate relief within and in front of the moraine. The most northerly one is connected to a deeply entrenched dry valley. Many flat-lying to very gently rolling areas termed “flat elements” exist inside the hummocky element of the moraine (Figs. 2, 3). They do not have a preferred orientation and sometimes correspond to modern swamp and lacustrine environments. Lastly, the ridge elements are semicontinuous linear hillcrests associated with a steep slope on at least one side of the hillcrest. They are parallel to the Paris Moraine axis and are located in the hummocky element at the front slope or back slope interface (Figs. 2, 3). Although they are distributed throughout the length of the moraine in the study area, they are more common towards the north, where they generally form the steep front slope and hillcrest of the moraine.

Closely associated with the Paris Moraine are undifferentiated geomorphic elements that consist of both high- and low-relief features (Figs. 2, 3). Although they have a very similar geomorphic appearance and topographic relief as the hummocky element and are spatially closely related to the moraine (Fig. 3), these undifferentiated high-relief elements are separate from the main linear high relief of the Paris Moraine. In the northeast part of the study area (Nassegaweya–Puslinch; Figs. 2, 3), the well-defined back slope element clearly separates the undifferentiated elements from the main body of the moraine. In the southern part of the study area, north of Puslinch Lake (Figs. 2, 3), relatively expansive low-relief areas separate the high-relief elements from the main

body of the moraine. Their origin is uncertain; Karrow (1968) mapped the ones in the north end of the study area as kames (Karrow 1968).

Subsurface lithofacies

Nine cores revealed a wide variety of lithofacies, including the following: (i) diamict, exhibiting a range of matrix textures (muddy to sandy) and clast abundance (clast poor and clast rich); (ii) mud (silt and clay); (iii) sand, including very fine to very coarse sand; and (iv) gravel (Figs. 5, 6; McGill 2012).

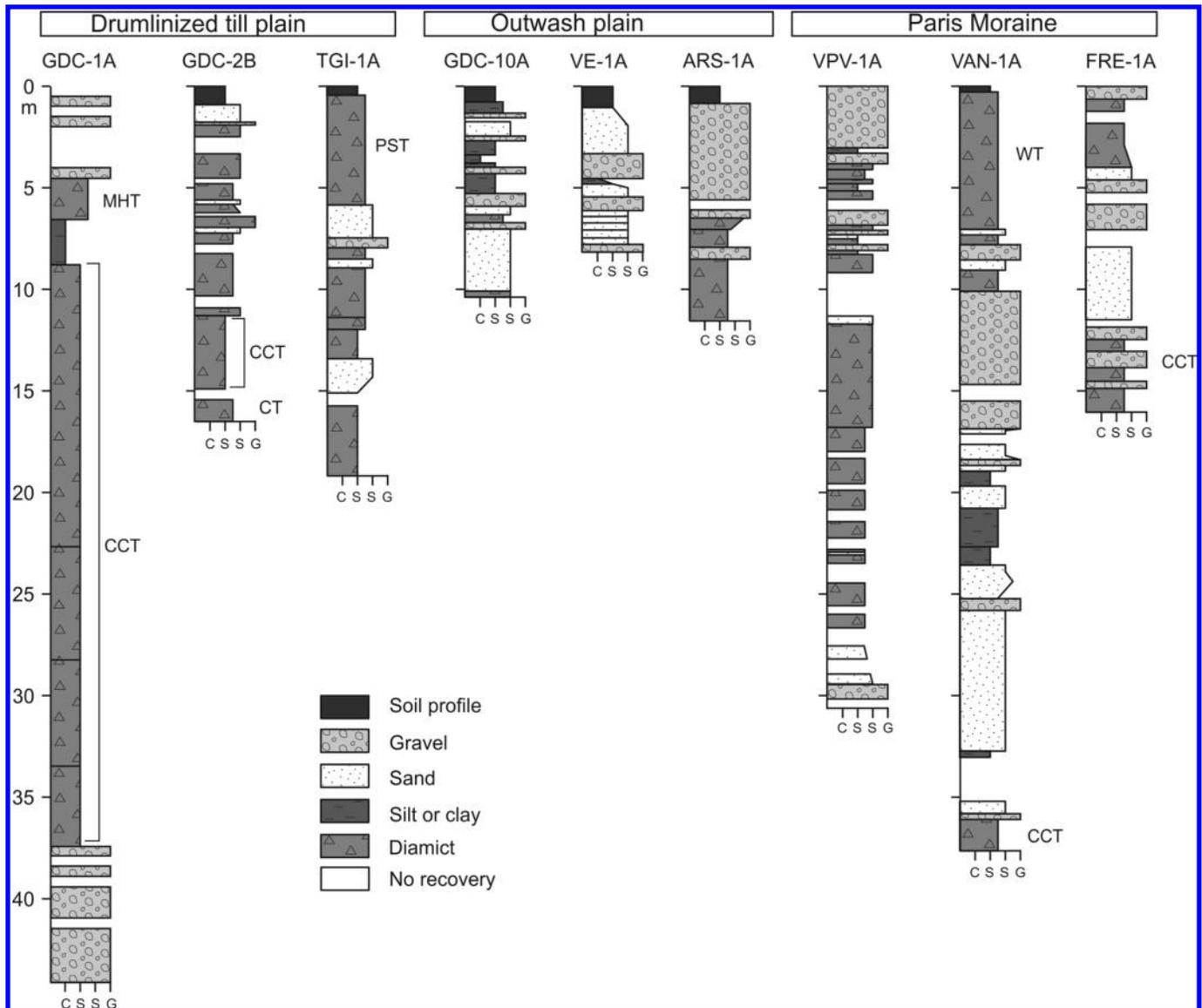
Diamict

Diamict (1%–50% gravel content; Hambrey and Glasser 2003) occurs in almost all cores (eight of nine) and occurs in beds tens of centimetres to several metres in thickness (Fig. 5). Diamict is very poorly to poorly sorted, matrix-supported with angular to sub-rounded clasts, and variable matrix texture (muddy to sandy) and clast abundance (clast poor to clast rich) both within and between beds (Fig. 6). Of the diamict samples that were analysed for grain size (number of samples, $n = 70$), 63% were classified as intermediate diamict (33%–66% sand in the matrix), 21% as muddy diamict (<33% sand in the matrix), and 16% as sandy diamict (>66% sand in the matrix), following Hambrey and Glasser’s (2003) textural classification scheme (Fig. 7). Silt is an important component of the diamict, with 96% of the samples analysed containing >20% silt; only 23% of samples had >10% clay content (Fig. 7).

Most of the diamict is massive, though occasionally diamict units have crude layering related to changes in gravel size and abundance or presence of thin discontinuous stringers of silt.

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Fig. 5. Simplified lithostratigraphic logs in each type of glacial setting of the study area. All the boreholes were drilled 3 m into bedrock. Note the logs in this figure are drawn to start at the sediment–bedrock interface. Correlations to the regional stratigraphic framework are made where possible based on distinguishing characteristics outlined in Table 2. CCT, Catfish Creek Till; C S S G, clay, silt, sand, gravel; CT, Canning Till; MHT, Maryhill Till; PST, Port Stanley Till; WT, Wentworth Till.



clay, or sand or a light-coloured material that appears to be crushed carbonate rock (Fig. 6c). It is unclear if the carbonate rock is a primary (limestone or dolostone clasts that have undergone glacial comminution during deposition) or secondary feature related to high friction and drill overheating this very dense material (Smith and Rainbird 1987). However, the absence of this rock in other very dense diamict suggests these are primary constituents. Limestone, dolostone, shale, and sandstone (listed in order of abundance) are the most abundant lithologies, with a minor amount of granite or metamorphic rocks. Occasionally, the diamict contains bullet-shaped, striated, and (or) faceted clasts.

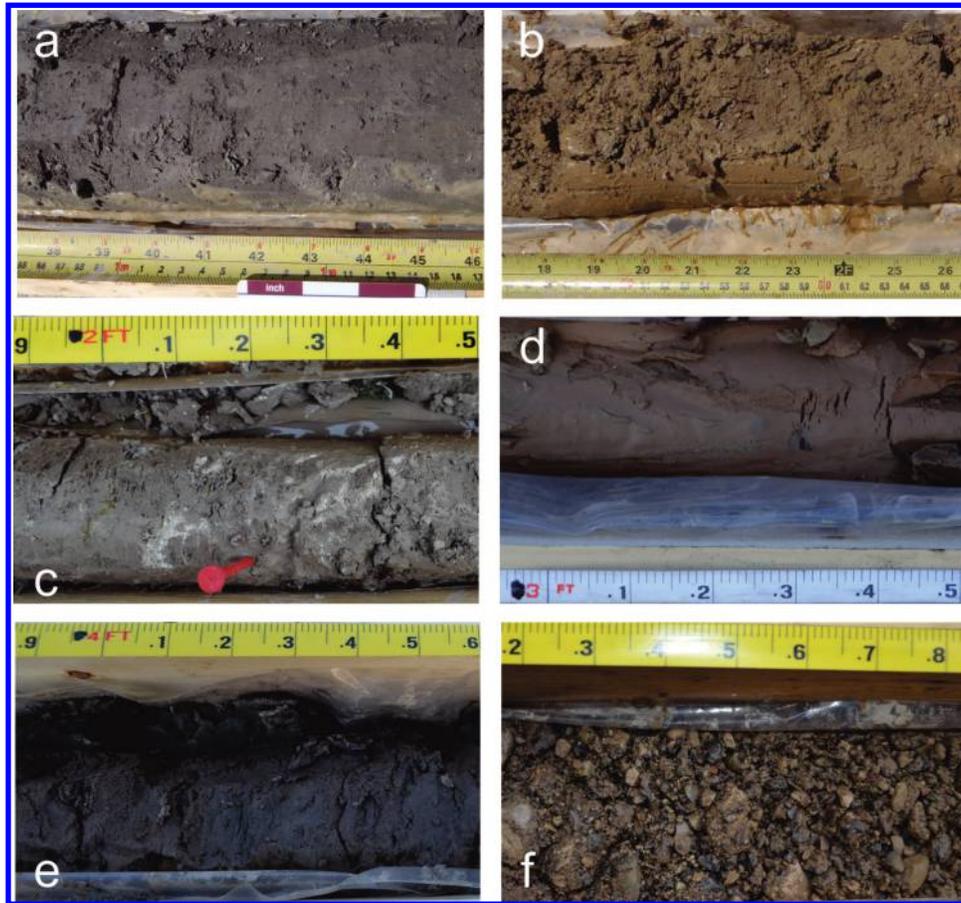
Some of the diamict is more compacted with depth, whereas in other places, it is generally very dense or overconsolidated (e.g., thick package of diamict in core GDC-1A, all the diamict in core TGI-1A, and the basal diamict in cores VAN-1A and FRE-1A; Fig. 5). Using the Munsell soil colour classification, the diamict varies in colour from brown (greyish, yellowish, pale, light, moderate,

dark, very dark) to grey (light, moderate, dark, olive, brownish) (Figs. 6a–6c). Some diamict units exhibit a weak red colour (e.g., in cores GDC-1A, ARS-1A; Fig. 5). A similar red colouration has been reported in Paris Moraine deposits to the northwest of the study area. Karrow (1968, 1987) and Chapman and Putnam (1984) attributed this red colour to the inclusion of weathered Queenston shale that outcrops to the south of Guelph.

Mud

Mud occurs in five of nine cores and occurs in beds from centimetres to <2 m in thickness (Fig. 5). Most mud beds are moderately to well sorted. Silt-sized particles dominate over clay-sized particles, though a few beds consist of both silt and clay (Fig. 6d) or are clay dominated (e.g., clay in core VAN-1A; Fig. 5). Sedimentary structures within mud include faint laminations, interbedded mud with fine sand, or deformed beds with inclusions of fine sand, silt, or clay.

Fig. 6. Photographs displaying the representative sedimentary facies observed in the cores: (a) medium dark grey overconsolidated and clast-poor muddy diamict (core GDC-2B, 12.50–14.02 m depth); (b) dark yellowish brown clast-rich sandy diamict (core GDC-2B, 4–4.4 m depth); (c) greyish brown overconsolidated clast-rich muddy diamict with deformed stringers (core TGI-1A, 18.6–18.9 m depth); (d) silty clay (core GDC-10A, 3.35–3.65 m depth); (e) moderately sorted very fine to fine sand (core VE-1A, 5.2–5.5 m depth); (f) sandy gravel (core VAN-1A, 13.11–14.63 m depth). Note the scales in photographs (a) and (b) are in centimetres and inches (1 in. = 2.54 cm), whereas the scales in photographs (c)–(f) are in decimal feet (1 ft = 0.3048 m). The colours describing the sediments are based on the Munsell colour classification system. [Colour online.]



Sand

Sand beds occur in seven of nine cores and are centimetres to several metres in thickness (Figs. 5, 6e). Sand is moderately to very well sorted, ranging in grain size from very fine to very coarse sand. Some beds contain a significant component of silt (20%–50%), and others contain a significant component of gravel (1%–50%). In core VAN-1A (Fig. 5), the thick package of sand below 23 m depth contains inclusions of silt, diamict, and gravel. The sand can be massive, normally or reverse graded, and faintly planar laminated. It should be noted, however, the rotasonic drilling method used for seven of the nine cores could have destroyed some of the sedimentary structures as is often reported by field geologists.

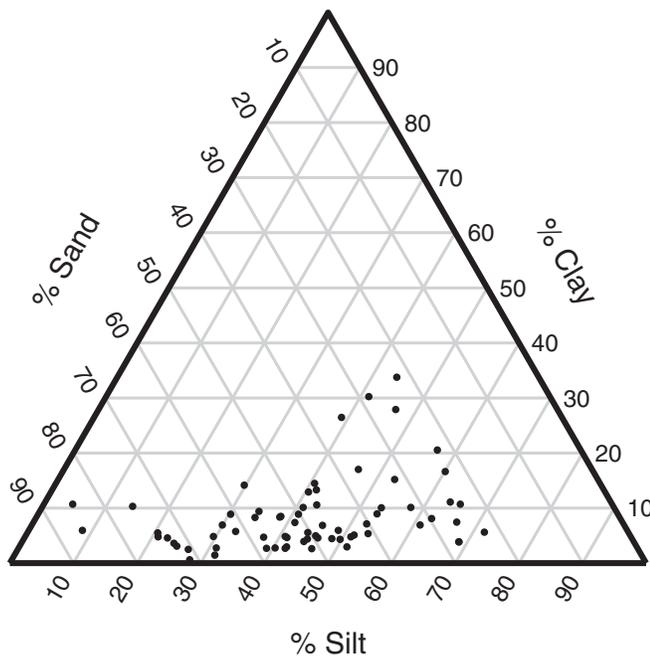
Gravel

Gravel (>50% gravel content) occurs in eight of nine cores and occurs in beds from tens of centimetres to several metres in thickness (Fig. 5). The gravel is very poorly to poorly sorted, clast-supported to matrix-supported with very angular to rounded clasts, and a silty sand matrix. Most gravel contains granule to <3 cm pebbles, with some units containing cobbles. Sandy gravel occurs in some beds and are moderately to well sorted (Fig. 6f). Some of the gravel is crudely bedded, with bedding delineated by changes in sorting, texture, and the abundance of gravel-sized clasts. Limestone, dolostone, shale, and sandstone (listed in order of abundance) are the most abundant lithologies, with a minor amount of granite or metamorphic rocks.

Lateral and vertical distribution of sedimentary facies

The depth to bedrock in the study area varies depending on the geological setting, with relatively thin deposits under the outwash plain, moderately thick deposits under the drumlinized till plain, and consistently thicker deposits underneath the Paris Moraine. One exception is the >40 m sediment that infills a localized buried bedrock valley underneath the drumlinized till plain. Diamict dominates the subsurface of the drumlinized till plain to the northwest of the moraine (cores GDC-2B, GDC-1A, and TGI-1A; Fig. 5) with occasional beds of sand, gravel, or clay, whereas stratified sediments dominate the subsurface below the outwash plain (cores GDC-10A, VE-1A, and ARS-1A; Fig. 5). Laterally extensive diamict associated with localized stratified sediments are also commonly reported in borehole logs of geotechnical reports and Ontario Ministry of the Environment water well records (McGill 2012). Based on both the higher and lower quality borehole records from the drumlinized till plain, these stratified sediments occur on a relatively small scale in terms of lateral extent (tens of metres) and thickness (<10 m). In the outwash plain borehole records, stratified sediments dominate, but there are still many diamict units present, with dimensions of hundreds of metres laterally, and up to 10 m thick (McGill 2012). In contrast, the subsurface of the Paris Moraine in the study area exhibits heterogeneity. For example, core VPV-1A contains primarily diamict, and cores VAN-1A and FRE-1A contain variable stratified sediments

Fig. 7. Ternary diagram for the textural composition of diamict samples ($n = 70$), with 63% of diamict samples being classified as intermediate diamict (33%–66% sand). Silt is also the dominant fine-grained component in these samples, with only 23% of samples having >10% clay.



that are bounded by basal and surficial diamict. In all three geological settings, the basal diamict often, but not always, occurs at the sediment–bedrock interface.

Geologic cross sections through the hummocky element reveal a similar heterogeneity (Fig. 8). The cross sections drawn are between 1.6 and 3.7 km long, and the average depth to bedrock ranges from 28.89 to 32.81 m. The most common lithology encountered in the cores of the hummocky element, by total thickness, is an intermediate diamict followed by muddy diamict, 27% and 24% of the total core thickness recovered, respectively (Table 3). However, it is important to note that over 40% of the total sediment within the Paris Moraine are facies other than the diamict, including various types of sand (18%), gravel (14%), and mud (10%; Table 3). Commonly, the stratified sediments (gravel, sand, or mud) are present between a basal and surficial diamict. When looking at the cross sections in more detail, the sediment composition varies significantly laterally within the hummocky element of the Paris Moraine. For example, sand comprises almost 40% of cross section H6–H6'; and gravel comprises almost 34% of cross section H1–H1' (Table 3). In some cases, the entire succession of sediment below the hummocky element is composed of facies other than diamict (e.g., borehole records at 750 and 3000 m on cross section H5–H5' and at the site ~700 m along cross section H1–H1' and northwest of Concession Road on cross section H6–H6'). These borehole records with stratified sediments are located in close proximity to sites where the subsurface sediment is almost entirely diamict (e.g., site at 750 m on cross section S4–S4'; Fig. 8). The front-slope and back-slope elements have similar compositional variation, although the back-slope element appears to contain more mud and sandy mud than the front-slope and hummocky elements (McGill 2012).

Interpretation of lithofacies

In several continuous cores, the overconsolidated nature, the stratigraphic position, or the similarity in texture and colour with regionally mapped tills (Table 2) indicates that the diamict can be

correlated with subglacial tills associated with specific advances (Fig. 5). The distinct basal till observed in core GDC-2B (Fig. 5) exhibits discolouration that is indicative of pedogenic weathering (paleosol), and its characteristics are very similar to sediments observed by Burt (2011) in their borehole BH40-OF-2010. They interpreted the diamict as a pre-Catfish Creek Till. Karrow et al. (1982) also observed a similar paleosol north of the Eramosa River in the City of Guelph that was radiocarbon dated to >45 000 years, suggesting that preservation of a pre-Catfish Creek (Early to Middle Wisconsinan) stratigraphy is possible in this area. The diamict that infills the bedrock valley overlying the basal gravel in core GDC-1A (Fig. 5) and other similar overconsolidated basal olive-grey diamict in the region are interpreted as Catfish Creek Till (CCT; Fig. 5) associated with the Nissouri Phase ice advance. These diamict units are distinguished based on their (i) physical characteristics (clast rich, silty to sandy texture, olive-grey colour, and overconsolidated) and (ii) stratigraphic position (Table 2).

A few of the diamict units contain additional evidence of subglacial deposition such as striated and faceted clasts (Catfish Creek Till in core GDC-2B; Fig. 5) or deformed stringers of silt, clay, sand, and crushed stone (e.g., multiple diamict beds in core TGI-1A and basal Catfish Creek Till in cores VAN-1A and FRE-1A; Fig. 5). These deformed stringers indicated some degree of glacetectonic deformation or sediment–rock comminution (Boyce and Eyles 2000; Evans et al. 2006). The uppermost diamict of core TGI-1A is correlated to the Port Stanley Till of the Port Bruce Phase. This interpretation is based on its stratigraphic position, and very dense, overconsolidated nature, and is supported by the surficial mapping of Karrow (1968, 1987). In other cores, the diamict beds are interpreted as products of meltout, or sediment gravity flows in an ice-marginal (front-slope or back-slope) position or supraglacial setting (Boulton 1972; Johnson et al. 1995). In this context, the uppermost diamict in core VAN-1A (Fig. 5), mapped as Wentworth Till by Karrow (1968), is associated with the Wentworth ice advance but is unlikely to be deposited subglacially.

The sand and gravel facies are interpreted as glaciofluvial outwash deposited either in front of the Paris Moraine or as outwash filling depressions created by the uneven topography of the ice and the ice margin (Karrow 1968, 1987; Sadura et al. 2006). Channelized and thin unconfined fluid flows as well as debris flows created debris aprons of sand and gravel along the moraine front-slope (near site ARS-1A; Sadura et al. 2006). Lastly, the mud lithofacies includes sediments that accumulated in localized meltwater ponds located within the moraine or in front of the moraine and within the outwash or drumlinized till plain (Karrow 1968, 1987; Johnson et al. 1995; Boone and Eyles 2001).

Geological conceptual model of the Paris Moraine

The surface and subsurface data compiled for this study allow the development of a geological stratigraphic framework for the Paris Moraine in the Guelph area, which starts with the erosion of the underlying bedrock (event a; Fig. 9). Based on the stratigraphic position of sediments overlying bedrock, the oldest Quaternary sediments classified as pre-Nissouri Phase deposits are the Canning Till in core GDC-2B, and gravel rubble infilling a bedrock valley in core GDC-1A (Fig. 5; event b in Fig. 9). The basal gravel in core GDC-1A likely formed by in situ weathering of the underlying bedrock or is colluvium deposited along the steep walls of the bedrock valley (Steelman et al. 2017). Stratigraphically, this rubble may be preglacial, associated with pre-Catfish Creek ice or may be associated with the overlying diamict (Table 1). A subsequent ice advance from the north during the Nissouri Phase deposited the Catfish Creek Till (event c; Fig. 9), which is preserved in four of the nine cores (Figs. 6a, 9).

To the northwest of the Paris Moraine, sometime after the deposition of Catfish Creek Till, Port Bruce Phase till (Maryhill and Port Stanley) was deposited and preserved in some places (e.g., site TGI-1A; Fig. 9). Most of the other diamict encountered in the study



Fig. 8. Cross sections through the hummocky geomorphic element. See Fig. 3 for locations of cross sections. All but cross section S4–S4' are perpendicular to the general northeast–southwest trend of the Paris Moraine. The black tick marks denote outer limits of the hummocky element. The original 14 lithological descriptors that captured secondary textures (McGill 2012) have been simplified for reproduction here to include only the dominant texture (e.g., silty sand simplified to sand); full details available in McGill (2012). Vertical exaggeration = 20. [Colour online.]

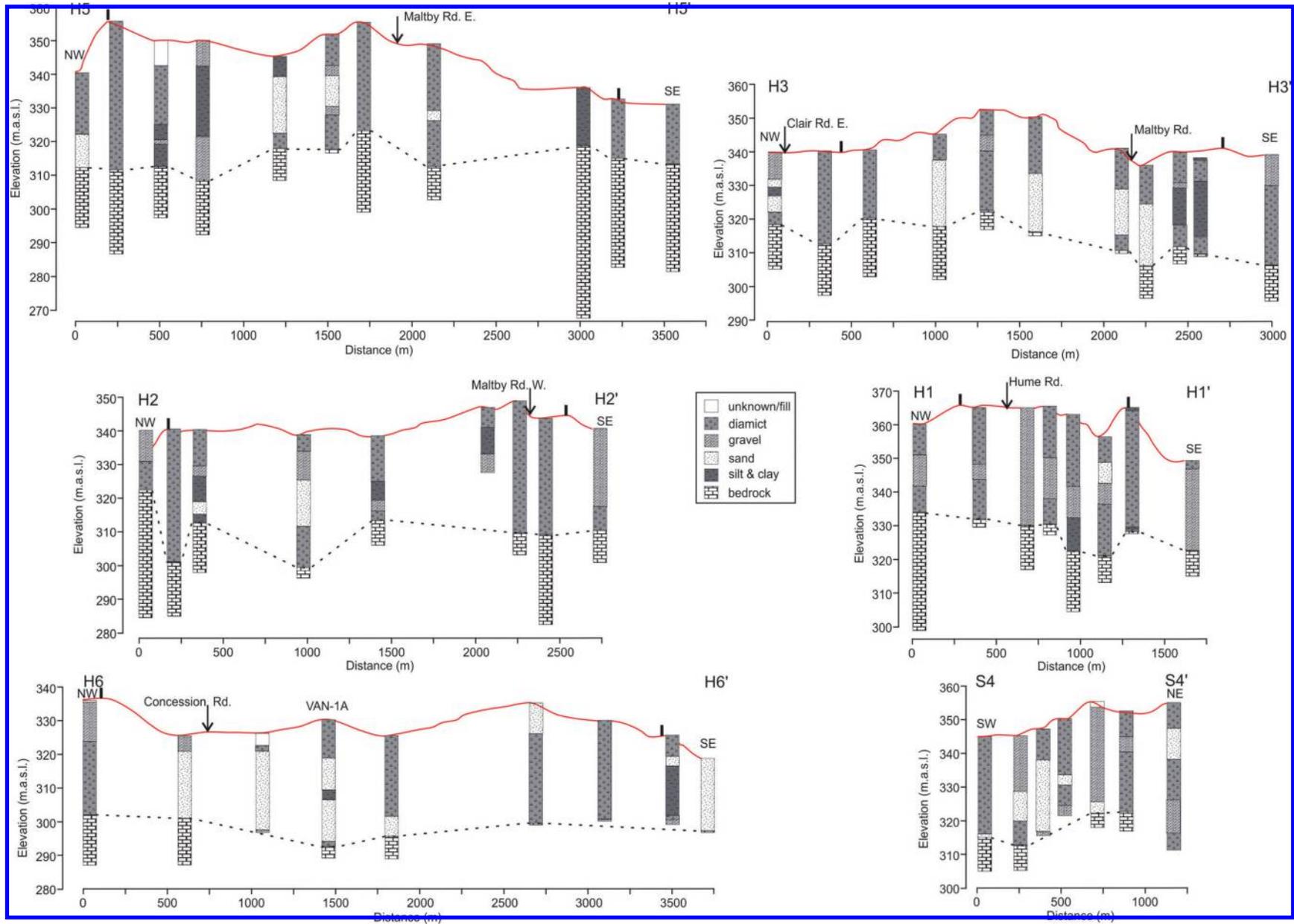
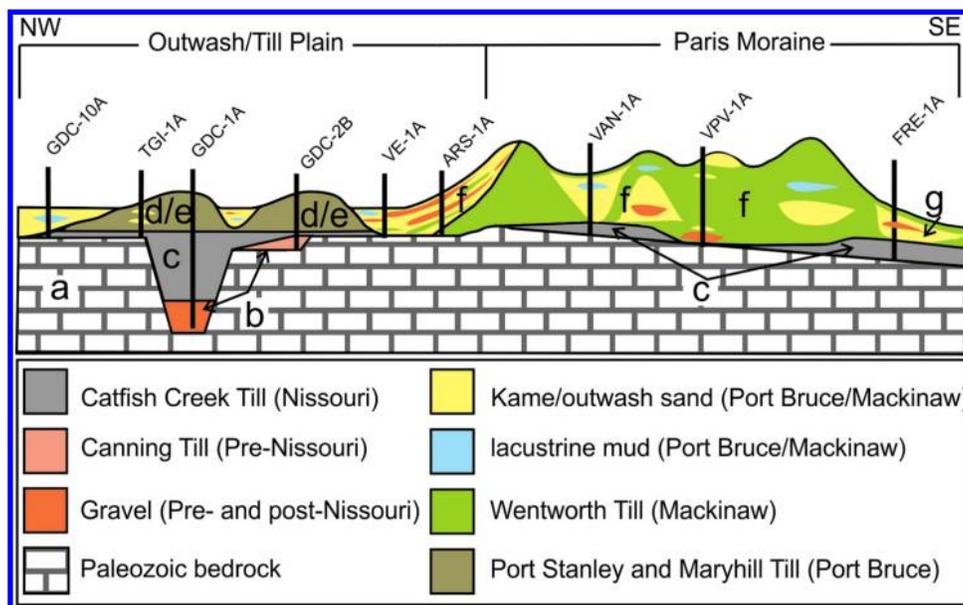


Table 3. Material composition within hummocky cross sections (see Fig. 3 for locations).

Material	H1-H1' (%)	H2-H2' (%)	H3-H3' (%)	H5-H5' (%)	H6-H6' (%)	Average (%)
Gravel	33.84	8.80	0.59	8.98	3.11	11.06
Gravelly sand	2.53	0.00	11.28	5.81	3.22	4.57
Intermediate diamict	20.58	11.10	41.81	37.70	21.72	26.58
Mud	0.63	8.80	0.36	9.93	0.00	3.94
Muddy diamict	34.47	33.37	17.70	20.38	14.53	24.09
Muddy sand	0.00	6.82	12.11	3.17	0.00	4.42
Sand	0.00	1.97	3.56	1.06	39.75	9.27
Sand and gravel	0.00	5.78	0.00	0.00	0.00	1.16
Sandy diamict	0.00	20.56	0.00	0.53	14.22	7.06
Sandy gravel	3.79	0.00	1.78	0.42	0.00	1.20
Sandy mud	4.17	2.79	10.81	9.40	1.49	5.73
Unknown	0.00	0.00	0.00	2.64	1.96	0.92

Fig. 9. Schematic conceptual model of the Paris Moraine with the sequence of events (a through g) responsible for the sedimentary succession across the study area. See text for detailed discussion. Not to scale; the distance along the section is approximately 9 km. The thickness of glacial deposits varies from ~10 m beneath the outwash plain to over tens of metres beneath the drumlinized till plain and Paris Moraine. The locations of cored holes along the section are approximated. Stratigraphic nomenclature used in legend corresponds to the regional stratigraphic framework presented in Table 1.



area are less compacted, and they, together with stratified mud, sand, and gravel, are interpreted as ice-marginal debris flow and glaciofluvial sediment deposited during the Port Bruce and Erie phases (undifferentiated event d/e; Fig. 9), similar to the deposits of the ice-contact land systems tract described in a modern glacial landscape of Iceland by Slomka and Eyles (2015).

In the southeast part of the study area, the bulk of the Paris Moraine sediments is associated with the Mackinaw Phase (event f; Fig. 9) (Barnett 1992; Karrow et al. 2000), when the Wentworth Till was deposited (Karrow 1968, 1987) as observed at the top of core VAN-1A (Fig. 5). As the moraine formed during the Mackinaw Phase, meltwater streams draining the ice sheet deposited outwash sediments within and in front of the moraine, eroding into and eventually aggrading onto the Port Stanley Till and older deposits northwest of the moraine (event f; Fig. 9). The meltwater and ice-marginal debris flows also created the frontslope ice-contact fans mapped at site ARS-1A (event f; Fig. 9) (Sadura et al. 2006; Slomka and Eyles 2015). During this phase, erosional channelized breaches (Karrow 1987) or moraine gap elements formed in several places along the moraine front (Fig. 3).

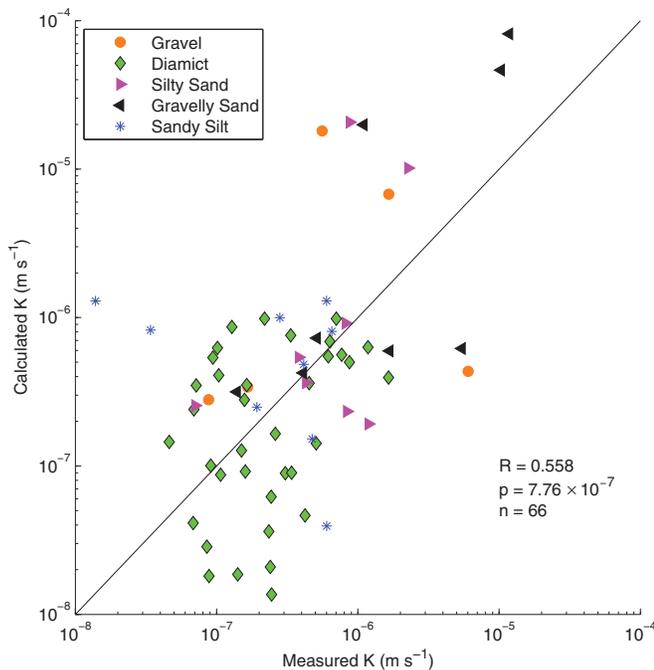
Lastly, the backslope element and the underlying sediment suggest reworking by glaciofluvial processes as well as ponding of

water as the ice retreated further to the southeast to the position of the nearby Galt Moraine (event g; Fig. 9).

Heterogeneity in the hydraulic conductivity of ice-marginal deposits

In groundwater management studies, including those carried out for source water protection in Ontario, hydraulic properties of glacial sediments are most often inferred from lithological descriptions, and hydraulic conductivity is calculated from a few, select grain-size distribution curves. In some cases, permeameter measurements of hydraulic conductivity are taken on subsamples from core. These two methods use disturbed, as opposed to in situ, sediment samples from the core and are therefore considered less accurate than in situ hydraulic testing. However, this data can provide order of magnitude estimates of hydraulic conductivity that are suitable to set groundwater flow model parameters (Freeze and Cherry 1979). Hydraulic conductivity values calculated from grain-size distributions often exhibit significant scatter when compared with laboratory permeameter tests on disturbed samples (Fig. 10); this relationship has been demonstrated for a range of sediment types in other studies (Rosas et al. 2014). However, this method has been used widely in hydrogeology (Freeze

Fig. 10. Scatter plot of calculated (based on grain-size distributions) against measured (from laboratory permeameter tests) saturated hydraulic conductivity (K) for different lithologies: gravel ($n = 5$); diamict ($n = 36$); gravelly sand ($n = 8$); silty sand ($n = 8$); sandy silt ($n = 9$). p , probability value; R , correlation coefficient. [Colour online.]



and Cherry 1979), and when all the data are considered together, there is significant correlation between the calculated and measured values (Fig. 10).

The high sampling density for grain size and permeameter analyses from the nine cores demonstrates the heterogeneity in the hydraulic properties of glacial deposits in their stratigraphic and physiographic context (Fig. 11). The drumlinized till plain contains a relatively low degree of K_{sat} variability, with K_{Ga} values ranging from 8.36×10^{-8} to 4.15×10^{-7} m/s (Figs. 11A–11C). Considering the data from each borehole separately, the cores GDC-2B, GDC-1A, and TGI-1A contain a single hydrostratigraphic unit. This is expected based on the relative lack of lithologic variability. Many of the high- and low-quality borehole data include descriptions of thick diamict associated with some thin beds of stratified sediments. The slightly higher K_{sat} value in the lower sand bed of core TGI-1A (at 13.66 m depth) is not a separate hydrostratigraphic unit, as the sand bed is thought to be laterally discontinuous and because it is based on an empirically calculated K_{sat} value that inherently is less accurate, with values up to 1.5 orders of magnitude different from measured values (Rosas et al. 2014; Trapp 2015). It is interesting to note that despite some variability in terms of silt content or degree of consolidation, the diamict units have relatively consistent hydraulic properties. In contrast, based on hydraulic data from site TGI-1A, monitoring well ports in the lowermost diamict are characterized by much slower pumping compared with coarser diamict units above 15 m (Best et al. 2015). This is likely due to the loss of structure and consolidation; demonstrating how the use of disturbed sediment samples imposes important limitations on estimating K_{sat} .

The sediments that underlie the outwash plain have a relatively higher degree of K_{sat} variability, with values ranging from 2.88×10^{-7} to 2.19×10^{-5} m/s (Figs. 11D–11F), when compared with the sediments of the drumlinized till plain. Comparing the data from each borehole, only the sediments in core ARS-1A represent a single hydrostratigraphic unit, whereas sediments in cores GDC-10A and VE-1A comprise three and two hydrostratigraphic units,

respectively. This increase in K_{sat} heterogeneity is expected, as these sediments are lithologically more variable, with thinner beds of stratified and variable sediments dominating, rather than more extensive and homogenous diamict beds.

The sediments within the Paris Moraine have the highest degree of K_{sat} variability, with values ranging from 1.25×10^{-7} to 8.48×10^{-4} m/s (Figs. 11G–11I). A single hydrostratigraphic unit characterizes site VPV-1A, whereas the other two cores (VAN-1A and FRE-1A) have three and five hydrostratigraphic units, respectively. The lack of heterogeneity in core VPV-1A is expected due to its similarity with sediments that occur in the drumlinized till plain (mostly composed of diamict). The higher degree of K_{sat} heterogeneity seen in cores VAN-1A and FRE-1A is expected due to the increased presence of stratified sediment, often in alternating thinner beds.

The hydrostratigraphy based on saturated hydraulic conductivity (K) estimates (Fig. 11) deviates significantly from hydrostratigraphy defined purely based on texture and lithology, supporting the findings of Maxey (1964) who stated that hydrostratigraphic boundaries often cross lithologic boundaries. K_{sat} values reflect variation in grain size and sorting, which sometimes, but not always, coincide with changes in lithology. For example, this study found similar K_{sat} values for units of different lithology (e.g., muddy sand and diamict or gravel and diamict). Grain-size distributions and sorting greatly influence K_{sat} values through the calculation of porosity estimated from the uniformity index C_u . As a result, gravel and diamict, whose hydraulic conductivity is determined using the matrix (particle size <2 mm), may have a very similar grain-size distribution and sorting, leading to very similar K_{sat} values. Likewise, a muddy, poorly sorted sand and a diamict may have similar K_{sat} values. This is evident in the sediments from the subsurface of the outwash plain and core VAN-1A in the Paris Moraine (Figs. 11D–11F, 11I). In contrast, there is a much tighter relationship between lithology and K_{sat} values in core FRE-1A (on the backslope of the moraine), where the gravel is sandier than the diamict, and the sand is much better sorted with much lower mud content (Fig. 11H). Deposits of the same lithology or samples from one lithological unit can also have very different K_{sat} values if the grain-size distribution or sorting changes throughout the unit, either vertically or laterally (e.g., the uppermost gravel bed in core ARS-1A (Fig. 11F) and sand (at 26–30 m depth) in core VAN-1A (Fig. 11I)). The degree to which this variability impacts recharge or contaminant transport in the subsurface needs to be considered when using K_{sat} values.

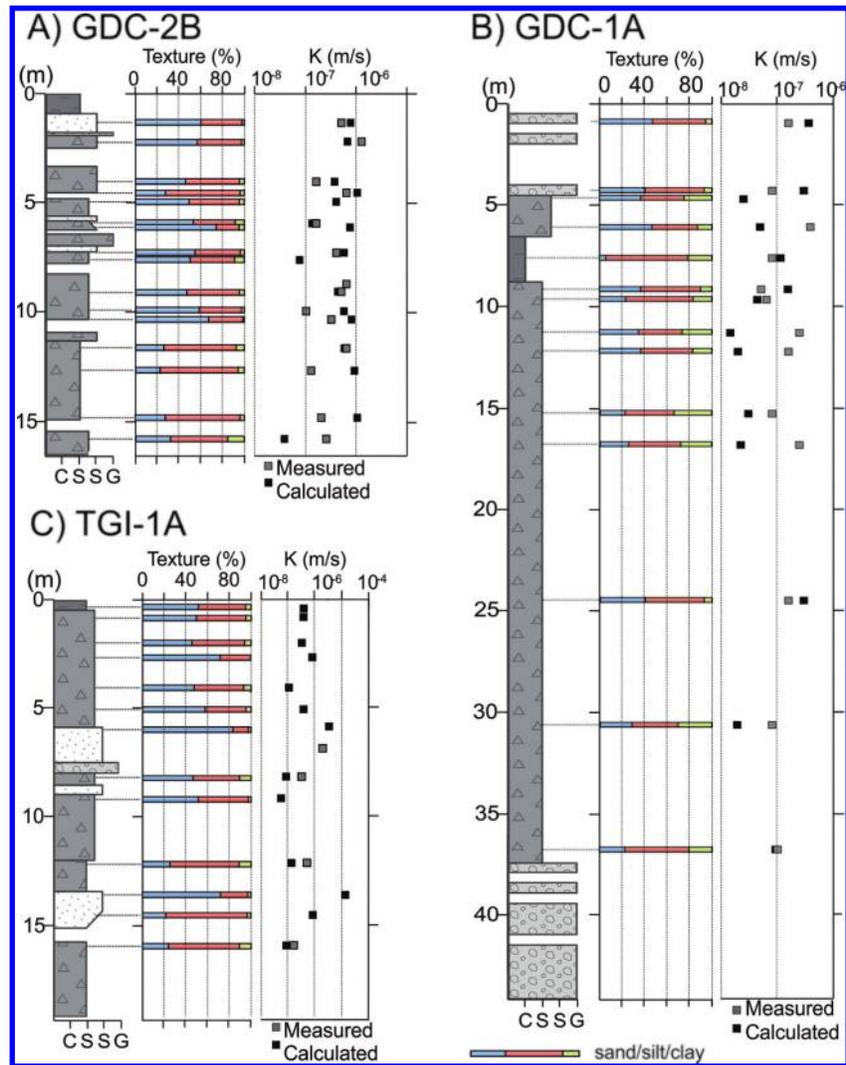
Discussion

The Paris Moraine as an indicator of active ice

Karrow (1968) and Barnett (1992) referred to the Paris Moraine as an end moraine based on its location at the outer edge of the Wentworth Till plain, marking the maximum extent of Wentworth ice. The Paris Moraine can also be considered a recessional moraine, as it records the stationary or minor readvance of an ice margin during an overall retreat phase (Karrow 1968; Barnett 1992). Karrow (1968) also characterized the Paris Moraine as having a hummocky surface with well-defined hummocks and depressions.

Others have classified similar features as “hummocky moraine”. These form under a wide variety of settings and conditions (Sharpe 1988; Benn 1992; Johnson et al. 1995; Andersson 1998; Eyles et al. 1999; Boone and Eyles 2001; Lukas 2005; Evans 2009), causing some debate over the origin of specific hummocky moraines (Benn 1992; Evans 2009). Some studies suggest hummocky moraines form by subglacial deformation of soft fine-grained till (Eyles et al. 1999; Boone and Eyles 2001), whereas others emphasize the role of ice-marginal processes. A stagnant ice margin can generate a chaotic distribution of hummocks (“uncontrolled” model; Johnson et al. 1995; Ham and Attig 1996). In contrast, an active ice margin can generate closely spaced recessional moraines,

Fig. 11. Geological log, grain-size distribution of sediment samples, and measured and calculated saturated hydraulic conductivity from each site of the (A–C) drumlinized till plain, (D–F) outwash plain, and (G–I) Paris Moraine. Where present, horizontal lines in the graph of hydraulic conductivity delineate the hydrostratigraphic unit boundaries (see methods for more information on how these units were defined). [Colour online.]



which reflect successive debris-rich bands in the ice margin (“controlled” model) (Benn 1992; Evans 2009). These controlled moraines are reworked during deglaciation by gravitational and glaciofluvial processes, and ultimately, topographic inversion, resulting in a hummocky topography (Evans 2009).

The hummocky topography of the Paris Moraine together with its flat elements and ridges (Fig. 3) is consistent with the geomorphic characteristics of other hummocky moraines, where flat elements are interpreted as lacustrine deposits accumulating in depressions (the ice-walled lake plains of Johnson et al. 1995; Boone and Eyles 2001; Evans 2009; Curry and Petras 2011), and ridges record crevasse infilling or thrusting and push associated with minor seasonal ice margin fluctuations (Ham and Attig 1996; Evans 2009; Fig. 3). Sadura et al. (2006) provide corroborating evidence for ice-push features in their ground-penetrating radar surveys of the Paris Moraine near ARS-1A, where many of the ridge elements occur (Figs. 2, 3).

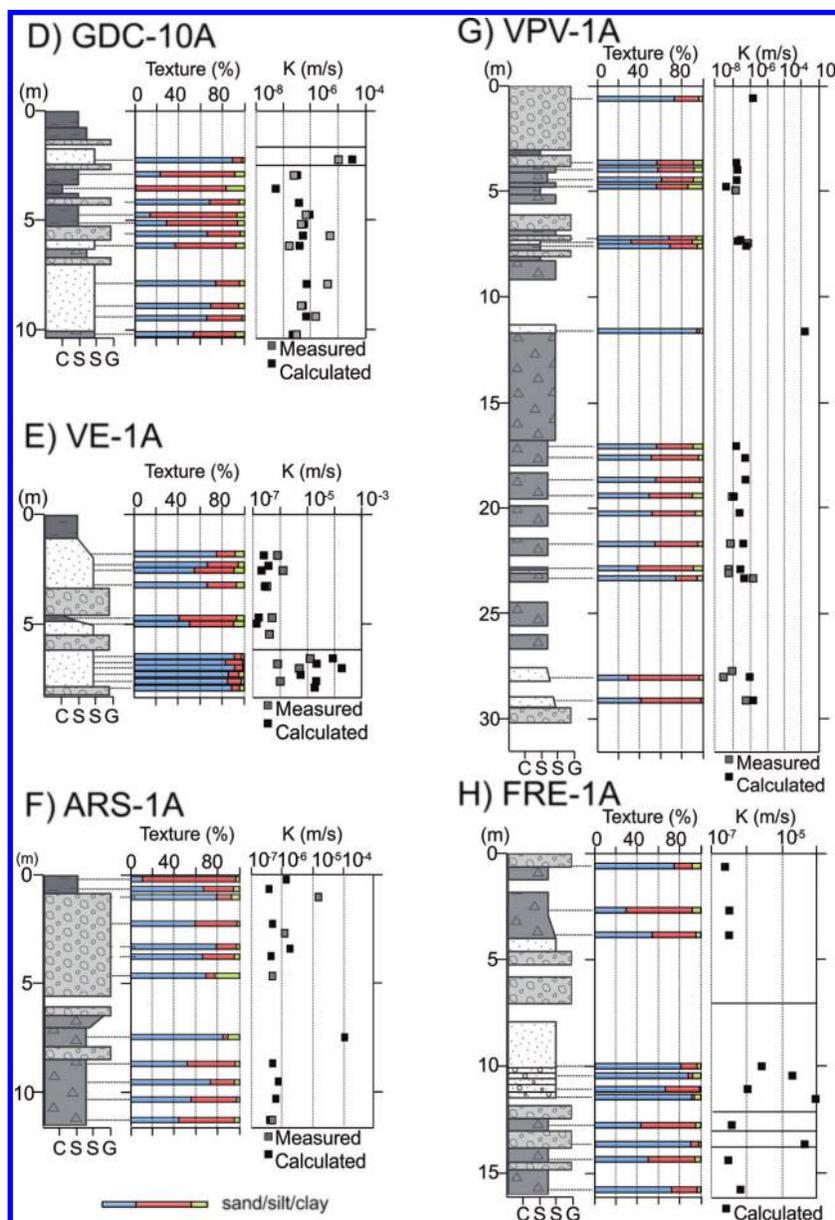
The subsurface in the Paris Moraine is composed of variable assemblages of sediment types ranging from a thick succession of diamict to thick deposits of stratified sediments (gravel, sand, and mud), and successions of stratified sediments between a basal and surficial diamict. The variability of the sedimentary succession within the Paris Moraine suggests that formation by subglacial

deformation of soft till is unlikely (Eyles et al. 1999; Boone and Eyles 2001). Instead, we believe the hummocky terrain and the variable subsurface composition are a product of differential melting of the glacier surface and subsequent infilling of topographic lows by stratified sediments through in situ meltout, sediment gravity flows, ponding, and deposition by meltwater flows (Karrow 1968; Johnson et al. 1995; Ham and Attig 1996). Such a process is described as trough filling and relief inversion in a moraine setting (Boulton 1972; Paul 1983; Boone and Eyles 2001; Evans 2009).

It is difficult to identify the relative influence of stagnant versus active ice and correspondingly distinguish between an uncontrolled versus controlled moraine model for the Paris Moraine (Benn 1992; Johnson et al. 1995; Ham and Attig 1996; Evans 2009). However, several features suggest the Paris Moraine developed as a controlled hummocky moraine influenced by active ice. First, as mentioned earlier, the ridge elements likely represent ice-push features associated with seasonal fluctuations of an active ice margin. Second, the association of hummocky topography with up-ice drumlins southeast of the Paris Moraine indicates active ice, and polythermal conditions during glacial recession in this region (cold-based ice margin with wet-based ice forming drumlins up ice, resulting in compressional debris-rich bands at the ice mar-

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Fig. 11 (continued).



gin). These features are consistent with the controlled moraine model of Evans (2009) and those documented in Wisconsin (Ham and Attig 1996; Clayton et al. 2001; “Landsystem B” of Colgan et al. (2003)). Third, the presence of a steep ice-contact fan along the frontslope element at the Arkell Research Station (Sadura et al. 2006) and abundant glaciofluvial sediments within the moraine (Figs. 5, 8) suggest abundant debris was generated, which requires wet-based active ice. Lastly, at the regional scale, the Paris Moraine is closely associated with the Galt recessional moraine (Figs. 1, 2), and in some places, the Galt and Paris moraines are combined into one broad hummocky moraine belt (Barnett 1992; Bajc and Dodge 2011; Russell et al. 2009), as would be expected in a controlled moraine setting characterized by deglacial modification of these closely spaced recessional features.

In sum, although it can still be considered an end moraine, we propose the term “hummocky end moraine” as perhaps more appropriate for this section of the Paris Moraine. It not only captures its geomorphic expression but also implies variable depositional processes during its formation and consequently subsurface

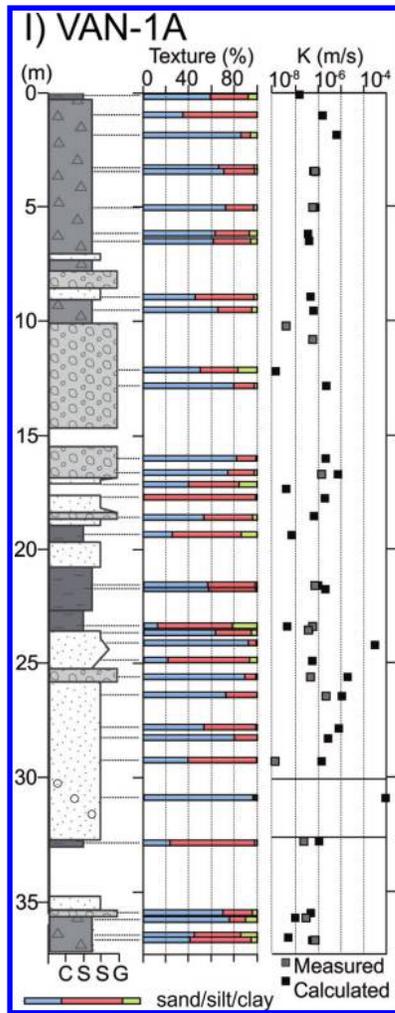
heterogeneity in the sediments that make up this hydrogeologically important landmark.

Hydrogeological implications

The findings of this study have two main hydrogeological implications. The hummocky element, which is the most areally extensive geomorphic element of the Paris Moraine, will likely impact recharge to the underlying bedrock aquifer at a regional scale by providing numerous topographic lows where water can accumulate and slowly recharge the underlying aquifers (Sloan 1972; Bates and Metcalfe 2006; Blackport Hydrogeology Inc. et al. 2009; Russell et al. 2009; Ahrens 2012). In addition to the geomorphic influence on the groundwater flow regime, the heterogeneity of the subsurface sediments and their hydraulic properties will most likely have an impact on groundwater flow, time of travel, and distribution of recharge or possible contaminants at depth.

Depression-focused recharge exists in different kinds of glacial settings (e.g., Sloan 1972; Hayashi et al. 2003; Berthold et al. 2004; Kiesel et al. 2010; Blackport et al. 2014), where the scale of depres-

Fig. 11 (concluded).



sions, their origin, and the sediments that underlie them vary. In the end, the impact of depression-focused recharge on the local groundwater flow system depends on the characteristics of the depressions (size and configuration), water table configuration, the presence of permafrost or the evolution of seasonal thaw, and the nature of the underlying subsurface sediments and their corresponding hydraulic properties (Sloan 1972; Hayashi et al. 2003). Here, we focus on the effect of subsurface sediment heterogeneity in a hummocky moraine setting.

Using geochemical, geological, and hydrogeological data collected at sites TGI-1A, ARS-1A, and VAN-1A (Fig. 2), Best et al. (2015) demonstrated how subsurface variability can affect groundwater recharge and the distribution of nitrate at depth (Fig. 12). In that study, the diamict-dominated succession in core TGI-1A located on the drumlinized till plain had increasingly older groundwater ages with depth (Fig. 12a), based on tritium analyses, and nitrate was reduced before reaching the underlying bedrock aquifer. In contrast, the coarse-grained sediments of core ARS-1A and the laterally discontinuous basal diamict in the outwash plain allowed faster infiltration of surface water and contaminants at depth (Fig. 12b) as evidenced by modern groundwater in the top of bedrock and high concentrations of both nitrate and *Escherichia coli* (Best et al. 2015). Lastly, a two-layered groundwater flow system exists at site VAN-1A, defined by a middle unit of mud (~22 m depth) separating two aquifer units (sand and gravel) and modern groundwater at depth (Fig. 12c); this suggests that lateral changes in sediment types typical of the Paris Moraine allow the water to

bypass this mud aquitard (Best et al. 2015). Considering the variable succession of sediments encountered in the moraine, these three scenarios (Fig. 12) are all possible at a local scale, making it particularly difficult to predict recharge rate, groundwater flow, and the fate of potential contaminants in this setting.

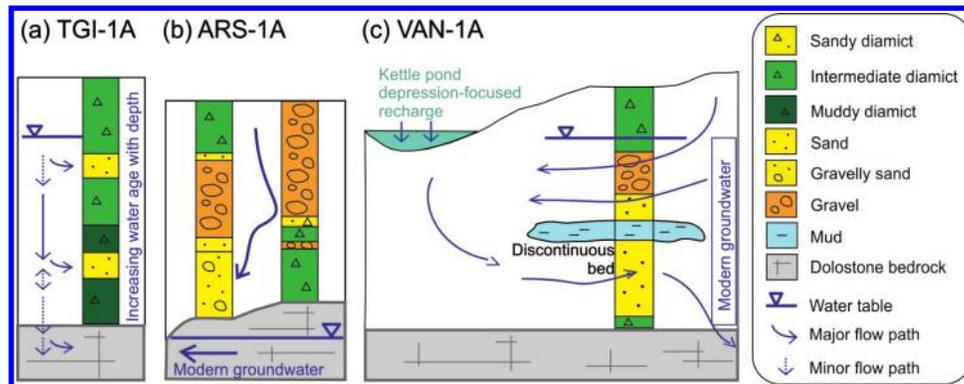
Burt and Dodge (2016) analysed the subsurface materials within the Paris Moraine ~20 km north-northeast of the current study. Burt and Dodge (2016) noted that although it was predominantly composed of the Wentworth Till, the moraine has significant variability in composition to warrant classification as a distinct hydrostratigraphic unit from the adjacent Wentworth Till aquitard. By doing so, Burt and Dodge (2016) recognized the morainal sediments may not always behave as an aquitard, considering the coarse-grained nature of the Wentworth Till and presence of interbedded meltwater sediments. The data presented here are consistent with recent studies that suggest that the Paris Moraine is not solely composed of diamict (Russell et al. 2009; Bajc and Dodge 2011; Burt and Dodge 2016). Significant lithological and hydrogeological variability occurs within the moraine on the hundreds of metres scale (Figs. 5, 8, 11G–11I) and over at least three orders of magnitude for hydraulic conductivity (Figs. 11G–11I, 10^{-7} – 10^{-4} m/s). In this context, and given the controlled moraine model for the Guelph area, the sedimentary sequence of each hillock may be different and may or may not have an underlying basal-subglacial diamict unit that could retard vertical flow. Consequently, the subsurface of the Paris Moraine in the Guelph area should be treated as a “hybrid hydrostratigraphic unit” (cf. Atkinson et al. 2014) in groundwater modelling efforts.

The impact of subsurface heterogeneity in sediment and hydraulic properties on groundwater modelling efforts will vary, depending on the scale and purpose of the model. At the local scale, a detailed hydrogeological characterization of heterogeneity is warranted to define its impact on the groundwater flow regime or contaminant pathways, considering the wide range of hydraulic conductivities (8.48×10^{-4} to 1.25×10^{-7} m/s; Fig. 11) and to identify the complex geometry and connectivity of coarser-grained units in this type of ice-marginal setting (Boulton 1972; Paul 1983; Golder Associates Ltd. 2006; Blackport Hydrogeology Inc. et al. 2009; Evans 2009; Best et al. 2015). At the large scale, the hydraulic conductivity of the moraine sediments is relatively consistent ($K_{Ga} = 6.14 \times 10^{-7}$ m/s), even in places where the subsurface is lithologically variable (e.g., site VAN-1A). At this large scale, the use of one hydrostratigraphic unit may well be appropriate when trying to estimate regional-scale recharge to underlying bedrock aquifers and discharge into nearby groundwater-fed streams under various climate change scenarios. As noted earlier though, the calculated hydraulic conductivity is influenced by the textural similarity and poorly sorted nature of the various sediment facies within the study area. This relationship may not be observed in other hummocky moraines and longitudinally along the Paris Moraine, depending on the site-specific processes that took place during moraine formation, and the nature of the sediments that were eroded up ice and brought to the ice margin (e.g., Russell et al. 2013; Burt and Dodge 2016). In addition, as mentioned previously, there are limitations in the method used for estimating hydraulic conductivity, such that additional hydraulic data should be used to define hydrostratigraphic units in this area.

Conclusions

This study investigated the geological, geomorphic, and hydrogeological aspects of the Paris Moraine in the Guelph area. The Paris Moraine is made up of various geomorphic elements, including a core belt of hummocky topography, frontslope and back-slope elements, as well as flat, ridge, and moraine gap elements. Analysis of nine cores down to the underlying Paleozoic bedrock and from the moraine and the adjacent outwash and drumlinized till plain revealed the nature and distribution of diamict, gravel,

Fig. 12. Conceptual diagram depicting how different subsurface sediment successions affected groundwater flow and contaminant transport at three of the study sites: (a) TGI-1A; (b) ARS-1A; (c) VAN-1A (modified from Best et al. 2015). At site TGI-1A, groundwater flow and nitrate were affected by the overconsolidated and muddy diamict at depth. At site ARS-1A, the coarse-grained and loose nature of both the gravel and diamict as well as the laterally discontinuous basal diamict allowed for faster infiltration of water and contaminants into the underlying bedrock aquifer. At site VAN-1A, a laterally discontinuous mud unit in the middle of the succession affects groundwater flow, though the subsurface heterogeneity within the moraine allows recharge of modern groundwater down to bedrock. [Colour online.]



sand, and mud facies. Analysis of these data together with cross sections of preexisting borehole records was used to develop a geological conceptual model within the regional stratigraphic framework. Numerous saturated hydraulic conductivities were calculated based on grain-size distribution, as well as measured using laboratory permeameter tests. These data provide a sense of variability in K_{sat} in this type of ice-marginal setting, both in terms of magnitude and spatial distribution. The Paris Moraine can be characterized as a hummocky recessional moraine with heterogeneous sediments containing a range of hydraulic conductivities. Based on the geomorphic and subsurface data, the Paris Moraine is interpreted to have developed as a controlled hummocky recessional moraine, with variable sediments accumulating in topographic lows as a result of in situ meltout, gravity flows, ponding, and meltwater reworking. Heterogeneity in hummocky moraines will have the most impact on groundwater recharge or contaminant transport at the local scale (centimetres to hundreds of metres) due to the juxtaposition of sediment types with very different hydraulic conductivities and laterally discontinuous aquifer and aquitard units. Consequently, site-specific analysis of the subsurface including detailed logging of core down to bedrock and calibration of this geological data with hydraulic data are particularly important when considering land use changes on the moraine. These kinds of detailed studies are recommended for groundwater resource assessments of water quality and water supply to inform the development of municipal water-well installations, aggregate extraction, and urban expansion.

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