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Geology and paleoecology of a Middle Wisconsin fossil occurrence in Zorra Township, southwestern Ontario, Canada

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Abstract: Nonglacial deposits of Middle Wisconsin age are being discovered with increased frequency across a broad region of southern Ontario, Canada, and provide strong evidence for a time of significant ice withdrawal from the lower Great Lakes region. With each new discovery, a refined understanding of regional climatic and paleoecological environments is emerging. In this paper, we present the results of a sedimentological and paleoecological study of a subtill organic deposit in Zorra Township, southwestern Ontario. The organic deposit, which lies beneath Nissouri Phase Catfish Creek Till (Late Wisconsin), has been dated by accelerator mass spectrometry at between 50.5 and 42.9 ^{14}C ka BP. The organic remains are contained within slack water pond deposits infilling a channel incised into till either of Early Wisconsin or Illinoian age. The fossil assemblage appears to be strongly influenced by taphonomic processes, including degradation due to oxidation, bacterial and fungal decay, and glacial overriding. Reworking and (or) recycling and selective sorting as well as long-distance transport has also influenced the composition of the fossil assemblage preserved. Nonetheless, meaningful paleoecological information is still obtained from this record. Collectively, the pollen and plant macrofossils indicate a boreal-type pine–spruce forest with temperatures cooler than present. The absence of arctic tundra plants, as are found in many other deposits of similar age in the lower Great Lakes basin, is notable. A pond or wetland inhabited by shoreline herbs, shrubs, and trees was present at or proximal to the site. The freshwater mollusc and ostracode assemblages are consistent with a shallow water habitat with dense submerged vegetation. The terrestrial mollusc assemblage suggests a taiga or transitional taiga–tundra fauna. Together, these fossil groups provide one of the most comprehensive environmental reconstructions of Middle Wisconsin time (oxygen isotope stage 3 or OIS3) in southern Ontario and serve to build on the ever-increasing database of paleoecological information accumulating for this episode of the late Quaternary.

Résumé : Des dépôts non glaciaires d'âge wisconsinien moyen sont découverts de plus en plus fréquemment dans une vaste région du sud de l'Ontario (Canada) et fournissent des indices probants d'une période de retrait important des glaces de la région du bassin inférieur des Grands Lacs. Chaque nouvelle découverte permet une compréhension plus pointue des milieux climatiques et paléoécologiques régionaux. Nous présentons les résultats d'une étude sédimentologique et paléoécologique d'un dépôt organique qui sous-tend un till dans le canton de Zorra, dans le sud-ouest de l'Ontario. La datation par spectrométrie de masse par accélérateur du dépôt organique, qui sous-tend le till de Catfish Creek de la phase de Nissouri (Wisconsinien tardif), a donné des âges entre 50,5 et 42,9 ^{14}C ka BP. Les restes organiques sont contenus dans des dépôts d'étang d'eau stagnante qui remplissent un chenal creusé dans du till d'âge wisconsinien précoce ou illinoien. L'assemblage de fossiles semble être fortement influencé par des processus taphonomiques, dont la dégradation causée par l'oxydation, la décomposition bactérienne et fongique et le chevauchement glaciaire. Le remaniement et (ou) le recyclage et le tri sélectif, ainsi que le transport sur de longues distances ont également influencé la composition de l'assemblage de fossiles préservé. Le profil produit néanmoins des renseignements paléoécologiques utiles. Collectivement, les pollens et macrofossiles végétaux indiquent une forêt de pins–d'épinettes de type boréal caractérisée par des températures plus fraîches que les températures actuelles. L'absence de plantes de toundra arctique, comme il s'en trouve dans de nombreux dépôts d'âge semblable dans le bassin inférieur des Grands Lacs, est notable. Un étang ou marécage abritant des herbes, arbustes et arbres riverains était présent sur les lieux ou à proximité. Les assemblages de mollusques et d'ostracodes d'eau douce concordent avec un habitat d'eau peu profonde caractérisé par une dense végétation submergée. L'assemblage de mollusques terrestres semble indiquer une faune de taïga ou transitionnelle entre la taïga et la toundra. Collectivement, ces groupes de fossiles fournissent une des reconstitutions les plus complètes des conditions ambiantes au Wisconsinien moyen (étage 3 de la stratigraphie isotopique de l'oxygène ou OIS3) dans le sud de l'Ontario et s'ajoutent à la base de données paléoécologiques croissante sur cet épisode du Quaternaire tardif. [Traduit par la Rédaction]

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Introduction

The recent discovery of fossiliferous sediments below and between multiple tills in a limestone quarry exposure at Zorra, southwestern Ontario, Canada, is the latest event in a history of related geological investigations extending back into the middle of the nineteenth century. Hinde (1878), anticipated by Bigsby (1829), described Scarborough Bluffs exposures, near Toronto, Ontario, as revealing fossiliferous sediments below tills, which he interpreted as evidence for alternating cold and warm intervals. Coleman, in a career-long sequence of publications beginning in 1894, described evidence of interglacial conditions in the Don Valley and Don Brickyard at Toronto and made it world famous at the Twelfth International Geological Congress, held in Canada in 1913 (Coleman 1894, 1913). These Toronto sites then remained for decades the sole established occurrence of Quaternary interglacial fossils in southern Ontario.

A half-century later, several developments converged to create an explosion of knowledge about Late Quaternary life and history: radiocarbon dating became available; Dreimanis undertook stratigraphic study of Lake Erie shorebluff exposures at Port Talbot, south of London, Ontario, where he described a multi-till sequence overlying cool-climate fossiliferous sediments (Dreimanis 1957); palynology became available, particularly through the work of Terasmae (1958); and a systematic Quaternary geology mapping program became established by the Ontario Department of Mines. Dreimanis' work established a second reference Quaternary stratigraphic sequence, after Toronto, for all other studies in southern Ontario. The mapping program led to further discoveries of buried organic deposits, such as Woodbridge (White 1975), Innerkip (Cowan 1975), Clarksburg (Warner et al. 1988), and Glen Allan (Karrow 1993). Workers in the region adopted the general and informal term "subtill organics" to refer to fossil occurrences below and between glacial deposits. For practical purposes, the term and concept are open-ended downward, embracing such deposits of any age.

The latest phase of development of research methodology was brought about by large budget increases in the past decade for drilling and subsurface investigation based on water resources assessment and protection. The discovery at Zorra quarry was the result of one such three-dimensional Quaternary mapping project covering the Brantford–Woodstock area undertaken by the Ontario Geological Survey (OGS) (Bajc and Dodge 2011). Detailed lithostratigraphical and sedimentological analyses of several exposures in this quarry, accompanied by fossil pollen, plant macrofossil, ostracode, mollusc, and vertebrate analyses of subtill organics at the site, provide one of the most comprehensive pictures of a Middle Wisconsin-age (oxygen isotope stage 3 OIS3) environment in southern Ontario so far.

Regional geologic setting

The Zorra quarry, owned and operated by Lafarge North America Inc., is situated in southwestern Ontario close to the Highway 401 corridor, approximately 30 km east-northeast of the city of London (Fig. 1). It is located between the 33rd and 35th lines of Zorra Township just north of Provincial Highway 2 (Universal Transverse Mercator (UTM) 507 894 m west, 4 771 796 m north, North American Datum 1983 (NAD 83), Zone 17) (Fig. 2). Quarrying of Middle Devonian limestones of the Lucas and Amherstburg formations (Detroit River Group) has been ongoing at the site since the mid-1950s for a variety of products, including Portland and white architectural cement, high-purity limestone products, and natural aggregates.

The Lucas and Amherstburg formations are two of a series of westward-dipping, Devonian-aged formations that occur along the eastern flanks of the Michigan Basin in southwestern Ontario. Older, Silurian and Ordovician units consisting of dolostones, shales, siltstones and gypsiferous evaporites occur to the east below the Onondaga and Niagara escarpments, respectively (Fig. 3). To the west occur younger, Middle and Upper Devonian limestones and shales (Armstrong and Carter 2010).

Notable lithologies, easily recognized as pebbles, cobbles, and boulders within the glacial drift and providing an indication of source lobes or provenance include the following: (i) Proterozoic diamictites, quartzites, and jasper conglomerates originating from the north shore of Lake Huron approximately 370 km to the north; (ii) white to pale-blue Grenville marbles sourced 250–300 km to the northeast on the Precambrian Shield; (iii) red and green shales and siltstones of the Queenston Formation that crop out 100–200 km to the east below the Niagara Escarpment; (iv) cherty limestones of the Bois Blanc Formation that form the caprock of the Onondaga Escarpment 20–25 km east of the quarry site; (v) grey shales of the Hamilton Group that subcrop 50 km to the west and contain distinctive spiriferid brachiopods; and (vi) black, pyritiferous, organic-rich shales of the Kettle Point Formation that occur beneath and south of the southern tip of Lake Huron approximately 85 km to the west.

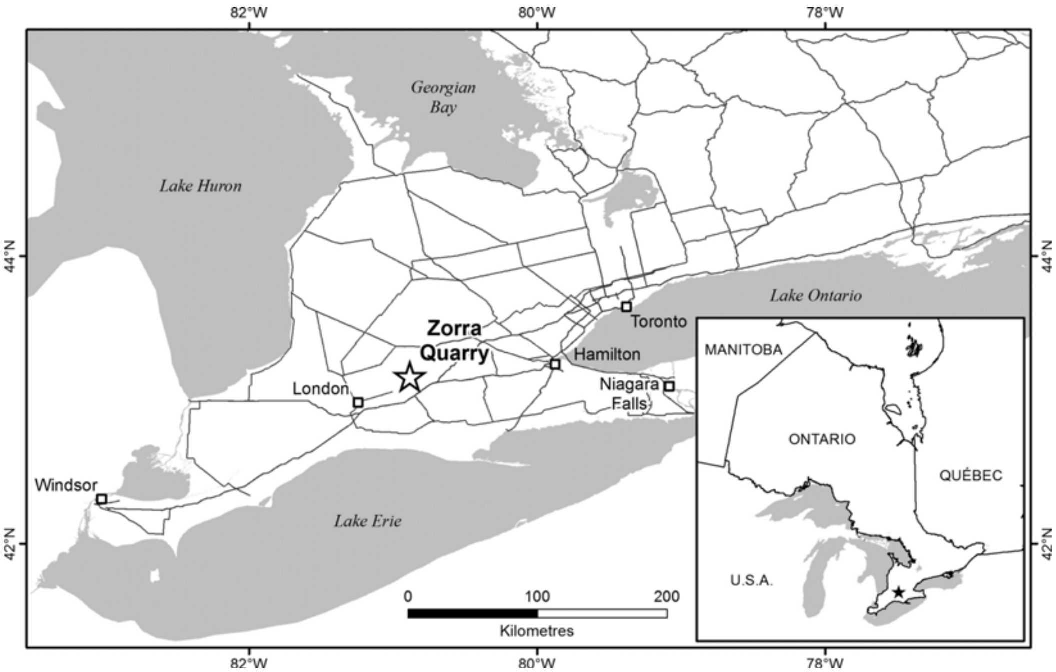
The quarry is situated adjacent to an important interlobate zone that formed during the initial breakup of the Laurentide Ice Sheet (LIS) approximately 15 ^{14}C ka BP as thinning ice conditions resulted in lobate ice flow out of the Great Lakes basins. Undoubtedly, this area would have experienced similar interlobate conditions during the growth of the LIS resulting in conditions favourable for preservation of fossiliferous, nonglacial deposits of Middle Wisconsin or older age. Areally extensive, ice-marginal lakes would have occupied this interlobate zone during the onset of the Late Wisconsin glaciation, their deposits burying these organic-rich, nonglacial records and protecting them from subsequent erosion by advancing glaciers. In fact, a significant number of subtill organic sites have been recently discovered within this interlobate zone due to an increase in deep drilling carried out as part of government-funded groundwater initiatives (Bajc et al. 2009).

Drift thickness in the immediate vicinity of the Zorra quarry ranges between 20 and 30 m, with measured thickness at the quarry site of approximately 25 m. Clayey silt Tavistock Till is the surficial till unit mapped within this area (Cowan 1975). It was deposited by the Huron Lobe during the Port Bruce Phase and is generally less than a few metres thick close to the study site. Thicknesses approaching 8–10 m have, however, been encountered in cored boreholes drilled in adjacent townships as part of the OGS three-dimensional mapping project (Bajc and Dodge 2011). A fluted till plain is observed on aerial photos adjacent to the quarry site (Fig. 2). The ice lobe(s) responsible for the formation of these streamlined bedforms remains contentious, as indicated by the works of Cowan (1975), Westgate and Dreimanis (1967), Piotrowski (1987), and (Bajc and Dodge 2011).

Areally extensive windows of Nissouri Phase Catfish Creek Till, the deposit of the main Late Wisconsin (OIS2), have been recognized and mapped in the vicinity of the interlobate zone (Karrow 1993; Cowan 1975), and confirmed by recent drilling (Bajc and Dodge 2011). This unit generally accounts for a significant proportion of the stratigraphic sequence observed within this region with thicknesses ranging between 7 and 25 m in the vicinity of the quarry. Both early and late lobate phases of Catfish Creek Till have been recognized in southwestern Ontario and bracket the main deposits laid down by regional, southerly flowing ice (Hicock 1992; Bajc and Dodge 2011; Dreimanis et al. 2014). The observed fluting mentioned earlier in the text may therefore be associated with the late lobate flow of Catfish Creek ice out of the Lake Erie basin.

Pre-Nissouri Phase sediments have been previously recognized in southwestern Ontario and consist of both glacial and nonglacial deposits. Notable subtill organic occurrences include the Guelph, Innerkip, Waterloo, Haight, Clarksburg, and Port Talbot sites, all of which were initially presumed to be of Middle Wisconsin age (OIS3). Some speculation on the age of the Port Talbot, Innerkip, and Waterloo sites has arisen with new coring and paleoecological analyses (Pilny and Morgan 1987; Dreimanis 1992;

Fig. 1. Location of the Zorra quarry fossil site in southwestern Ontario.



Karrow 2004). There are suggestions that there may be a warm or interglacial (OIS5) component to these sites. Approximately 10 new radiocarbon dated subtill organic sites have been discovered in the last decade within the interlobate zone as part of government-funded drilling programs. In all cases, pollen and plant macrofossil studies indicate cool interstadial environments for these sites. Results of accelerator mass spectrometry (AMS) radiocarbon dating indicate a Middle Wisconsin age for most of the sites (50.5–23.5 ^{14}C ka BP) (Bajc et al. 2009).

Pre-Late Wisconsin tills are positively identified only where they occur beneath weathering zones or organic-bearing, nonglacial deposits. Units previously identified and formally named in southwestern Ontario include the Bradtville Drift (Dreimanis 1964) on the north shore of Lake Erie near Port Talbot and Canning Till (Karrow 1963) whose type-section is located on the Nith River west of the City of Brantford. Equivalent-aged deposits have been encountered in many boreholes throughout the interlobate zone (Bajc and Shirota 2007; Bajc and Dodge 2011; Burt 2012). In most cases, the tills are stone-poor, have a red–mauve to grey colour, and are silt-rich. The red and mauve colouration is presumed to reflect an Erie–Ontario lobe source area (i.e., ice flow towards the west), with the Queenston Formation contributing to the red pigmentation. Buff to grey-coloured, stony, silty to sandy tills of similar character to typical Catfish Creek Till often underlie these deposits and rest directly on bedrock. The ages of these pre-Late Wisconsin tills remain unclear. An Early Wisconsin or Illinoian age is suggested for these units.

Site geology

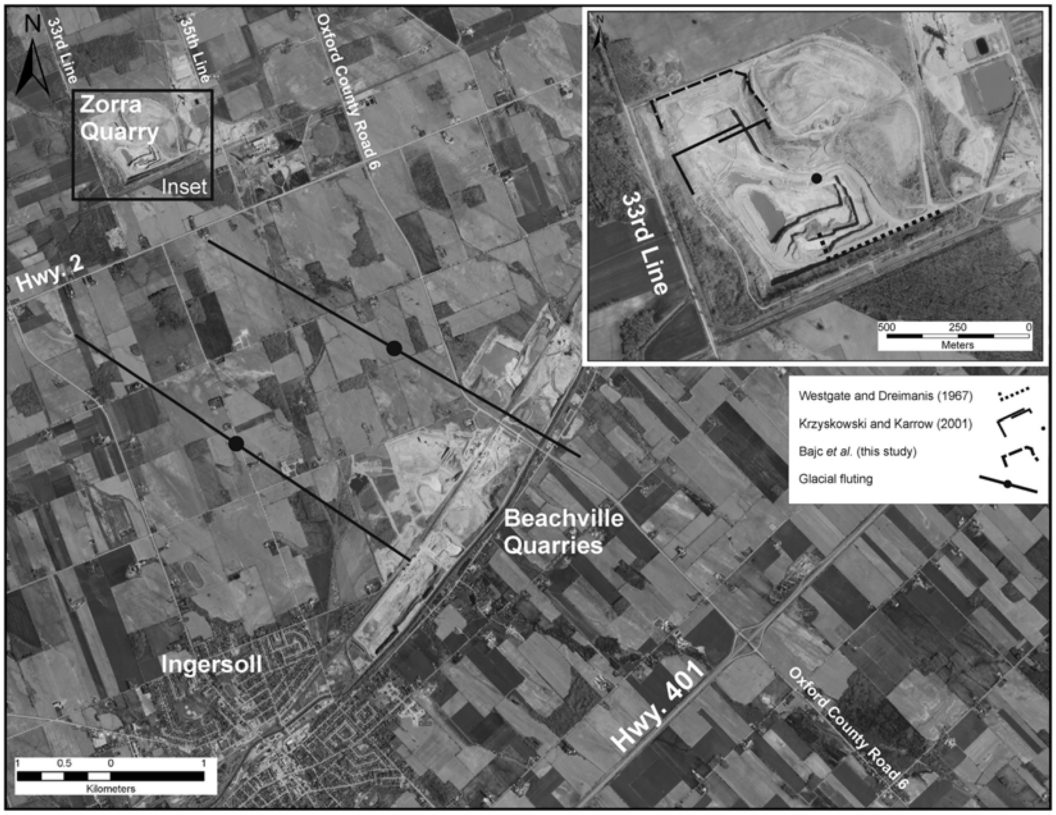
Exposures at the Zorra quarry were initially described by Westgate and Dreimanis (1967) and later by Krzyszkowski and Karrow (2001). The quarry exposures were revisited in 2006 as part of an OGS three-dimensional mapping project for aquifer and aquitard characterization and were monitored annually between 2006 and 2009.

Previous investigations

Westgate and Dreimanis (1967) and Krzyszkowski and Karrow (2001) both describe a complex stratigraphic record consisting of multiple tills of varying provenance with intervening stratified deposits. The locations of sections described in their papers are illustrated in Fig. 2. Westgate and Dreimanis (1967) identified nine distinct till units, which they correlated to previously recognized units in the Nith–Hamilton area (Karrow 1963) and the north-central Lake Erie basin (Dreimanis et al. 1966). They attributed the lower two till units (Tills A and B) to the Canning Till of Karrow (1963) and the Upper and Lower Bradtville drifts of Dreimanis et al. (1966). Both of these units were interpreted to be deposited by the Erie ice lobe during the Early Wisconsin (Brimley Phase). Of particular note was the discovery of inclusions and beds of partly leached and gleyed, silt and clay containing pollen, fine plant detritus, and molluscs both within and directly below Till unit A. A cool interstadial climate was inferred from the pollen assemblage. Till units C and D were correlated to glaciolacustrine units identified in north-central Lake Erie and which occur between Port Talbot I and II and between Port Talbot II and Plum Point nonglacial beds. A Middle Wisconsin age (Farmdale Phase) was assigned to these units. Till units E and F were correlated to the main and late phases of Catfish Creek Drift deposition, unit G to Port Stanley Drift and units H and I to Tavistock Till.

Three quarries in the Beachville–Zorra area were subsequently visited in 1995 and reported in Krzyszkowski and Karrow (2001) (Fig. 2). New exposures created by quarry expansion were described using an improved understanding of glacial sedimentology to help refine the stratigraphic sequence previously defined

Fig. 2. Orthoimagery of the Zorra quarry site showing the locations of sections described in this study and by previous workers. Sections in the Beachville quarries were included in the studies of Dilabio (1971) and Krzyszkowski and Karrow (2001). Flutings in the surface till plain are highlighted.



by Westgate and Dreimanis (1967). Krzyszkowski and Karrow (2001) identified a nine-till sequence consisting of four older till layers, which correlate to Tills A and B of Westgate and Dreimanis (1967), two middle till layers with intervening stratified deposits assigned to Catfish Creek Drift, and three upper tills with interbedded glaciofluvial and glaciolacustrine deposits correlated to Port Stanley and Tavistock tills. Compositional and structural (fabric and striation) information was collected at multiple locations to gain an improved understanding of the affinity of the various units. Of particular note was the absence of any subtill organic remains in the exposures available at the time of their study.

Current investigation

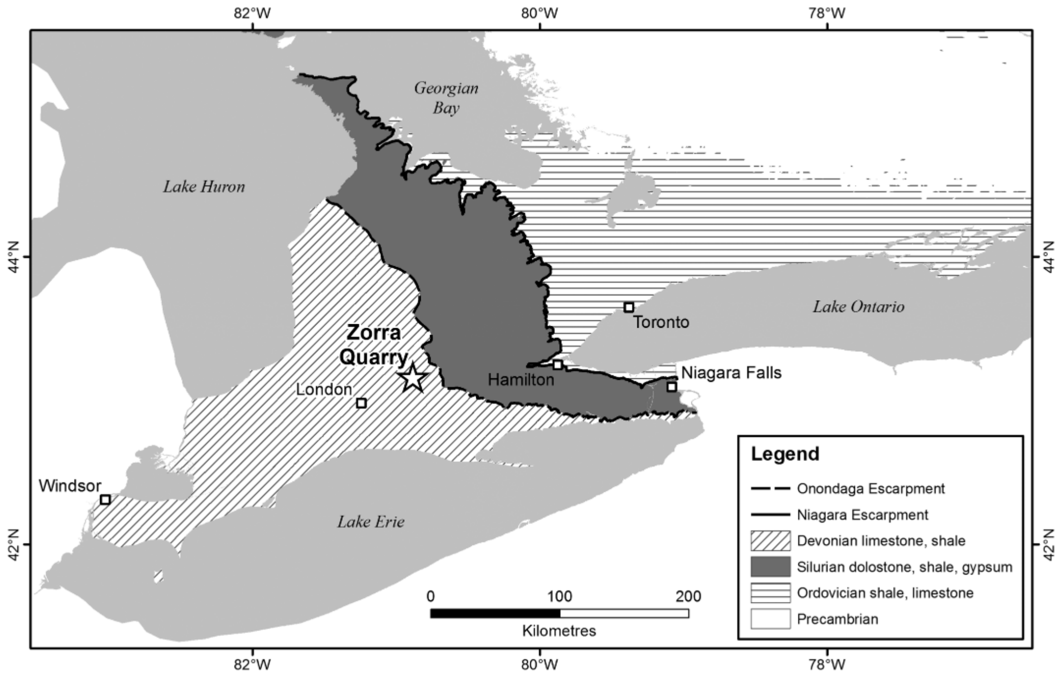
The Zorra quarry was visited on several occasions in 2006 then revisited at least once annually between 2007 and 2009. The active quarry face at the time of this investigation was at the north end of the excavation and was oriented east-northeast (Fig. 2). The face has been moving northward at a rate of about 5–10 m/year. Continuous, fresh exposures occur on the north and east faces and measure approximately 270–280 m in length (Figs. 4, 5). Exposures previously described are either grown over and slumped or covered by waste material. Significant changes in the composition of the sediments exposed along the north face have occurred between 2006 and 2009 as the quarry face was pushed back. It is estimated that the north face has moved back by about 40–50 m during this interval. The eastern exposure has remained unchanged, although its condition has deteriorated slightly due to slumping.

The Zorra sedimentary sequence described here is subdivided into six lithostratigraphic units (Fig. 6). These consist, from oldest to youngest of the following: (1) local, stony, silty to sandy till and associated stratified deposits resting directly on bedrock; (2) reddish brown to mauve–grey, gritty, pebbly silt till with interbeds and lenses of glaciofluvial pebble gravel; (3) greenish grey to orangy-brown, slightly pebbly, clayey silt and silt with fine organic staining, plant remains, molluscs and other macrofossils; (4) light, reddish brown grading upwards into buff–grey, stony, sandy silt till with large (tens of metres) lenses and channels infilled with glaciofluvial sand and gravel and lesser silt; (5) glaciolacustrine silt and very fine sand, in places containing abundant ice-rafted debris and locally containing lenses and interbeds of glaciofluvial sand and gravel; and (6) mottled orangy-brown to brown gritty and pebbly sandy silt till.

Unit 1 (pre-Late Wisconsin Till A)

The lowest unit exposed in the Zorra quarry ranges from 0 to 1.0 m in thickness and correlates with Till A of Westgate and

Fig. 3. Simplified bedrock geology of southern Ontario highlighting the location of Ordovician, Silurian, and Devonian units and major escarpments (derived from Armstrong and Dodge 2007).



Dreimanis (1967). It consists of a light buff–brown to buff–grey, stony, silty sand till (47% sand, 45% silt, 8% clay; Table 1) that pinches and swells and, in places, grades laterally into poorly sorted, bedded to massive, angular pebble to cobble gravel (Fig. 7a). This unit has been observed to interbed with the lower part of the overlying unit (unit 2), suggesting that they may be either genetically related or glaciotectonized along their contact. The heavy mineral signature of unit 1 is, however, quite distinct (higher epidote, olivine and tremolite–actinolite and lower total garnet and enstatite–ferrosilite) from that of the overlying unit, favouring a separate origin (Fig. 6). Matrix carbonate content is 65%, with a calcite to dolomite ratio of 3.0 (Table 1); an observation that is in line with the underlying bedrock unit consisting of high purity limestone. Striae were not observed on the bedrock surface below this unit; however, Westgate and Dreimanis (1967) found striae oriented just east of south and suggested an Erie lobe source for the till. A reevaluation of the striation record is warranted to further assess provenance of this unit. Organic remains were not observed either below or within this unit as reported by Westgate and Dreimanis (1967). The original exposures were not available for further investigation, as they were either heavily overgrown and slumped or fully excavated.

Unit 2 (pre-Late Wisconsin Till B)

Unit 1 is abruptly overlain by up to 3.0 m of a reddish grey to maroon, stone-poor, sandy silt till (35% sand, 58% silt, and 7% clay; Fig. 6; Table 1) in places containing lenses and relatively continuous interbeds (tens of metres) of pebble gravel and pebbly medium to coarse sand. Imbricated pebbles in the gravelly horizons indicate paleoflow to the west-northwest. The diamicton is generally massive, dense, matrix-supported, and contains <10% clasts in the pebble fraction (Figs. 7a, 7b, 8a). Granules and small pebbles of red shale, presumably derived from the Queenston Formation below the Niagara Escarpment to the east, are commonly observed within this unit. Striae, oriented at 275°–300° azimuth (Az) have been observed on the bedrock surface where unit 1 is absent and a flat-topped, bullet-shaped boulder within the till was striated towards 245° Az (west-southwest). The till contains significantly lower matrix carbonate (25%) than the underlying unit 1 till and a calcite to dolomite ratio of 1.1 (Table 1). A heavy mineral assemblage consisting of elevated garnet and enstatite–ferrosilite (hypersthene) and depressed epidote and olivine supports an Erie–Ontario source lobe for this till unit (Dreimanis et al. 1957). This unit correlates to Till B as described by Westgate and Dreimanis (1967) and Canning Till of Krzyszkowski and Karrow (2001).

Unit 3 (organic channel-fill deposits)

Unit 3 occurs as a scoured channel-fill set into pre-Late Wisconsin Till B (unit 2). The channel-fill trends northwesterly and attains a thickness of up to 2.85 m on the east-face exposure and slightly greater than 1.4 m on the north face (Figs. 4, 8a, 8b). An apparent channel width of 12–15 m was observed on both the east and north faces of the quarry exposure. The channel has a discontinuous cobble to small boulder lag at its base and is infilled with mottled, black–brown, greenish brown, grey, orangy-brown, and buff–brown gritty, slightly pebbly, clayey silt and silt with small wood fragments, seeds, terrestrial and aquatic molluscs, many of which are well preserved, and various other macrofossils. The complex mosaic of colours (Fig. 8c) is reminiscent of gleyed soil formation punctuated by intermittent periods of exposure, resulting in short-lived oxidation events.

Organics are both randomly distributed and concentrated within thin (1–5 mm) seams of black sediment that follow horizontal

Fig. 4. Stratigraphic sequence exposed in the east face of the Zorra quarry in 2006. Drift sequence is 26 m thick.

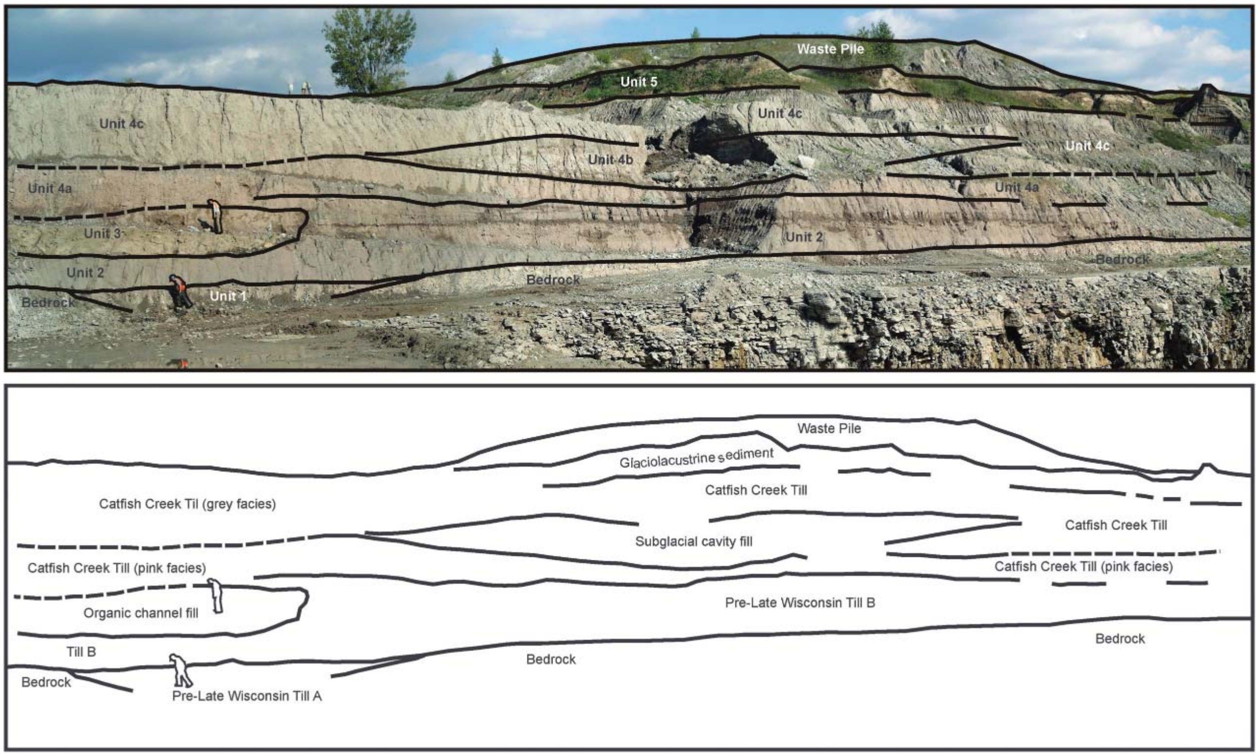


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Fig. 5. Stratigraphic sequence exposed in the north face of the Zorra quarry in 2009. Drift sequence is approximately 25 m thick.

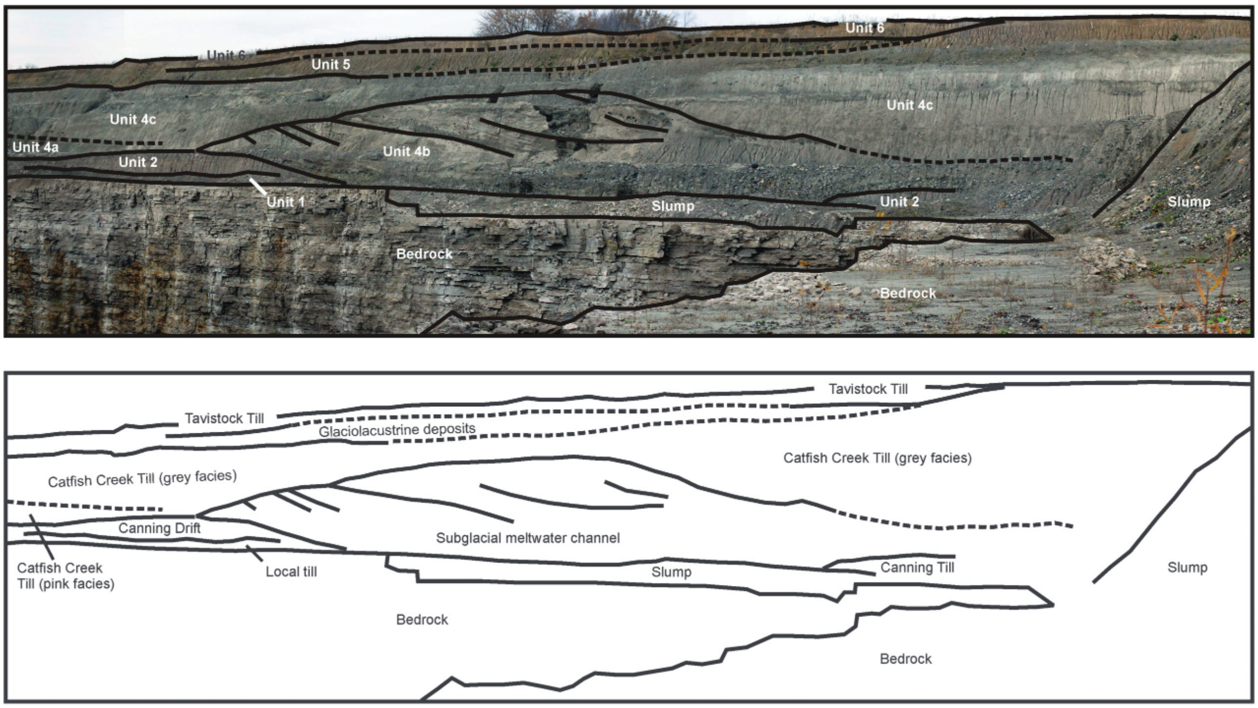


Fig. 6. Graphic log of sediment sequence exposed on the east face of the Zorra quarry in 2006. Grain-size information acquired using a Microtrac particle size analyzer. Carbonate data obtained using the Chittick method (Dreimanis 1962). The heavy mineral data are derived by energy-dispersive X-ray analysis on a scanning electron microscope of over 2000 fine sand (0.125–0.25 mm) grains per sample. asl, above sea level; Ca:Do, calcite:dolomite; CPx, clinopyroxene.

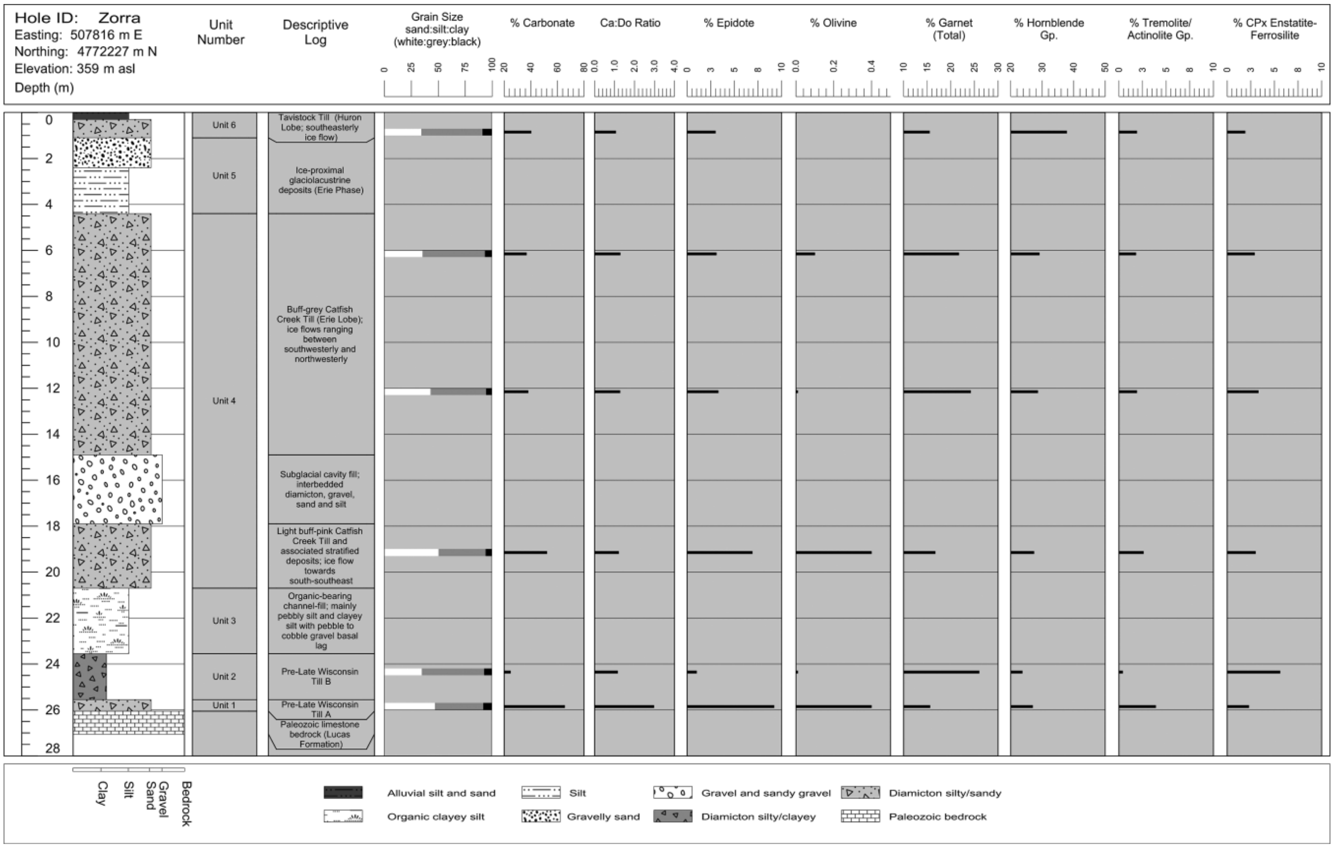
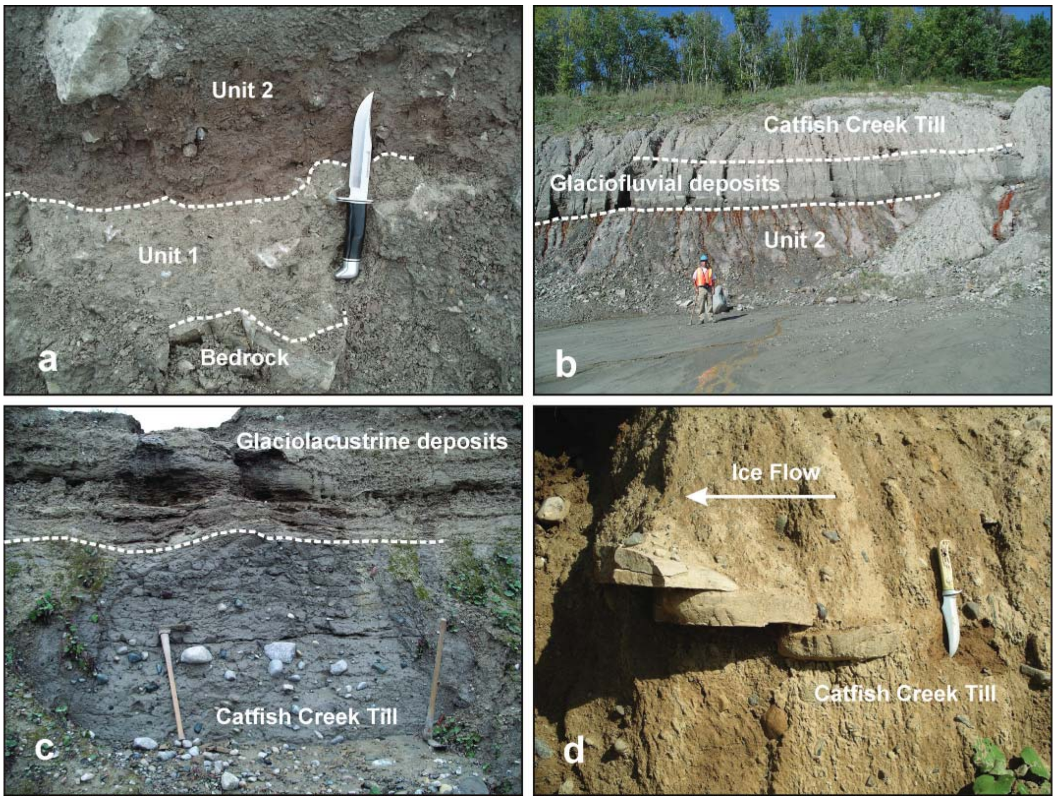


Table 1. Summary grain size and carbonate data.

	Clay (%)		Silt (%)		Sand (%)		Total carbonate (%)		Calcite/dolomite ratio	
Till	Cowan (1975)	This study	Cowan (1975)	This study	Cowan (1975)	This study	Cowan (1975)	This study	Cowan (1975)	This study
Tavistock Till	16.5	8.8	44.9	56.9	37.9	34.3	40.8	40.3	0.9	1.3
	7–36	–	32–59	–	17–57	–	30–53	–	0.4–1.7	–
Catfish Creek Till	12.6	5.7	47.8	51.3	39.6	43.0	44.6	42.3	0.7	1.3
	7–25	5–6	38–56	44–58	27–54	36–50	36–53	37–52	0.3–1.2	1.2–1.3
Canning Till	25.3	7.1	50.3	58.1	24.3	34.8	37.9	24.8	1.2	1.2
	23–28	–	46–54	–	23–26	–	34–42	–	1.0–1.6	–
Till A	–	7.8	–	45.2	–	47.0	–	65.5	–	3.0

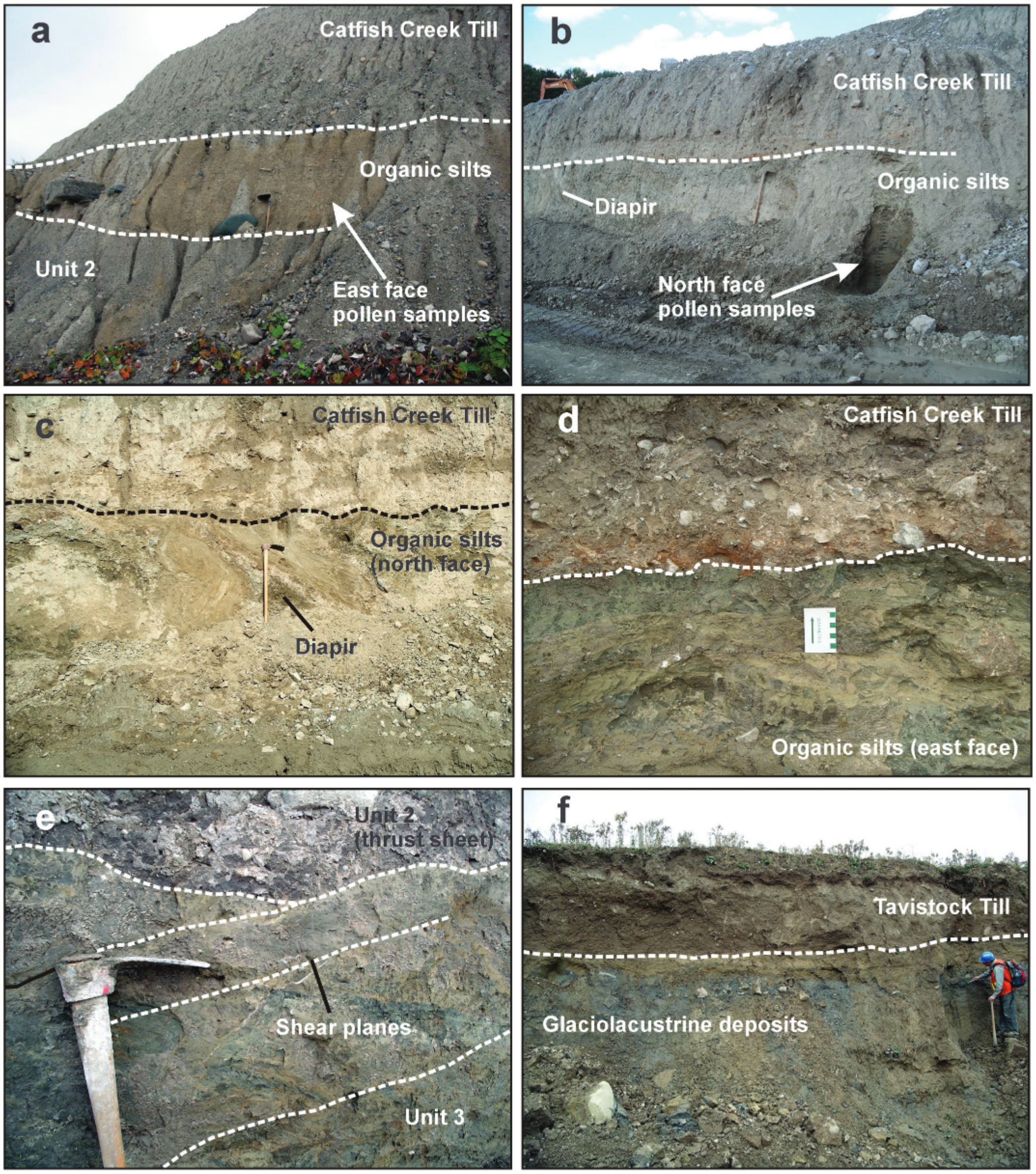
Note: Data reported in Cowan (1975) are from regional Quaternary mapping in the Woodstock 1 : 50 000 scale National Topographic System (NTS) map area. Cells with multiple entries indicate mean and range of data.

Fig. 7. Photographs of important sedimentary units exposed in the Zorra quarry. (a) Pre-Late Wisconsin Till (unit 2) overlying stony, buff-coloured till (unit 1) resting on bedrock; (b) exposure of glaciofluvial sand and gravel sandwiched between Catfish Creek Till (unit 4) and pre-Late Wisconsin Till (unit 2); (c) subglacial facies of Catfish Creek Till overlain by Erie Phase glaciolacustrine deposits; (d) exposure of uppermost part of Catfish Creek Till displaying a Paleozoic carbonate clast sheared and displaced by westward-flowing ice.



bedding planes. The richest material occurs along the north face in what appears to be relatively undisturbed, horizontally bedded and laminated slack water deposits. Farther to the west, this unit is loaded and displays vertically oriented flame structures up to 1.5 m in height (Fig. 8b). On the east face, the channel fill appears to be glaciotectonically deformed, with possible thrusting and stacking of the unit along shallowly dipping shear planes that rise to the south (Fig. 8c). In fact, along the southern channel margin of the east face, the underlying Till B (unit 2) has been partially thrust over the channel-fill deposits. Pebble and small cobble, sandy gravel, and diamicton are also injected into tension fractures along the top of the channel-fill sediment at this location in what appears to have been a soft, possibly water-saturated, unit.

Fig. 8. Photographs of important sedimentary units exposed in the Zorra quarry. (a) East-face exposure of pre-Late Wisconsin Till (unit 2) overlain by buff–brown fossiliferous silt then Catfish Creek Till; (b) north-face exposure of fossiliferous silt overlain by Catfish Creek Till; (c) close-up of diapir shown in (b); (d) Catfish Creek Till overlying organic silts in the east-face exposure; (e) fossiliferous silt and clayey silt displaying low-angle shear planes and overlying unit 2 diamicton thrust into place by glaciotectonic processes; (f) north-face exposure of Tavistock Till overlying ice-proximal deposits of Erie Phase glaciolacustrine silt, clay, and very fine sand.



Rounded to subrounded clasts of carbonate and crystalline lithologies are commonly observed within the channel-fill deposits. Unusual, angular pebbles of chert, presumably derived from the Bois Blanc Formation to the east are also abundant. Upon initial inspection, the channel-fill sequence appears to resemble a diamicton, possibly deposited as a slump deposit or debris flow. Alternatively, it may represent a pond deposit laid down in an abandoned channel with intermittent influx of ice-rafted debris carried in by river ice. The geometry of the unit coupled with the presence of a basal lag favours a floodplain or alluvial fill origin for the sedimentary sequence.

Up to 2 m of well-bedded sandy, pebble gravel occupying the same stratigraphic position was observed between units 2 and 4 along the extreme northwest corner of the quarry exposure. Here, cross-bedded and horizontally bedded to gently inclined sheets of pebble gravel and sand indicating paleoflow towards the south are found between pre-Late Wisconsin Till B and Catfish Creek Till (Fig. 7b). No organic remains were observed within this stratified deposit, and a glaciofluvial origin associated with Catfish Creek Till is suspected.

Unit 4 (Catfish Creek Drift)

A thick unit of silty sand diamicton and related stratified deposits unconformably overlies the organic channel-fill sequence (unit 4, Figs. 4 and 6). In places, this unit cuts down through all of the older stratigraphy and rests directly on bedrock. It ranges from approximately 15 to 22 m in thickness and contains variable proportions of stratified sediments. Significant changes in these proportions were observed in the north quarry exposure over the 3 year period that observations were collected. In both the east and north faces, the lower part of this unit consists of a light, pinkish grey – brown, stony, sandy silt diamicton containing up to 35% subangular clasts, many of which are faceted and striated (unit 4a, Fig. 4). The reddish hue of this sediment is attributed to the overriding and incorporation of underlying, reddish coloured, pre-Late Wisconsin Till B (unit 2). A striated boulder pavement at the base of this unit along the east face indicates ice flow ranging from 150° to 155° Az. Striated boulders from the same stratigraphic position along the north face indicate ice flow towards the south (180° Az). The heavy mineral fraction contains relatively higher concentrations of northern provenance minerals including olivine and epidote (Fig. 6).

A lenticular unit of bedded sand, gravel and diamicton, 40–50 m wide and 3 m deep, occurs along the east face of the quarry above the pinkish diamicton (unit 4b, Fig. 4) and extends northwestward where it is well represented along the north face. In the east face, this unit contains highly deformed and faulted beds of sand and gravel, loose, sandy diamicton likely deposited as subglacial debris flows and silt and silty very fine sand that occurs as stringers, drapes, and coatings on large clasts. A single, 2.5 m long, bullet-shaped limestone boulder, oriented north–south, and striated at 160° Az was observed near the top of this unit. Deformed, vertical sand dikes cut across horizontally bedded units supporting a subglacial environment of deposition. On the north face, the width and thickness of this subglacial channel-fill deposit increased substantially as the face was pushed back between 2006 and 2009. Large, steeply inclined bedforms up to 12 m in height and with apparent dips to both the east and the northwest were observed within the channel sequence, which extended across two-thirds of the north face in 2009 (unit 4b, Fig. 5). The base of the channel consists of cobble to small boulder gravel that progressively deepened as the exposure moved northward, eventually cutting down through pre-Late Wisconsin tills A and B to the bedrock surface. The origin of this stratified unit is likely related to a localized subglacial meltwater discharge event.

Up to 10.5 m of buff–grey, stony, sandy silt till averaging 40% sand, 54% silt, and 6% clay conformably overlies these stratified deposits across the north and east faces of the quarry (unit 4c, Figs. 4 and 7c). The average carbonate content derived from two samples in this unit is 37%, with a calcite to dolomite ratio of 1.3 (Table 1). The diamicton is matrix-supported and contains up to 15% subangular clasts, many of which are faceted and striated. Boulder pavements are common within this till and indicate ice flows towards the west-southwest at the base, west-northwest in the middle, and west-southwest at the top (Fig. 7d). This massive till is dense, blocky, and contains subhorizontal shear planes that are sometimes accentuated by fissility. The upper surface of the unit appears to be fluted as well suggesting a subglacial origin for the till. Along the western part of the north-face exposure, the upper part of this diamicton unit is interbedded with glaciolacustrine deposits of silt and very fine sand, suggesting deposition as subaquatic debris flows in a standing water body.

Collectively, this unit correlates to the main Nissouri Phase deposits identified across much of southwestern Ontario and formally referred to as Catfish Creek Drift (de Vries and Dreimanis 1960). The base of this unit appears to represent the main regional ice flow event associated with Catfish Creek Drift when the ice margin was located south of Lake Erie approximately 22 ^{14}C ka BP. A shift to more lobate flow originating from the Erie–Ontario lake basins is suggested not only by the boulder pavements but by the heavy mineral assemblages. Similar, although more complex shifts in ice flow, were documented by Westgate and Dreimanis (1967) and Krzyszkowski and Karrow (2001).

Unit 5 (glaciolacustrine deposits)

Up to 2.5 m of well-laminated, steel grey to buff–brown silt and very fine sand with occasional dropclasts in the pebble to small boulder size range overlies Catfish Creek Drift throughout the quarry exposures (Figs. 7c, 8d). At the east end of the north face, these deposits pinch out against a topographic high in the underlying Catfish Creek Till. In places, lenses and beds of sandy gravel and pebble–cobble gravel were observed below, within, and above the fine-grained deposits. Thin units of rhythmically laminated silt with clay caps were observed in a few places. The glaciolacustrine deposits conformably drape over the underlying till as well as over the glaciofluvial lenses. Black shale pebbles and small cobbles presumably derived from the Kettle Point Formation were observed within some of the gravelly units, suggesting a possible Huron lobe source for the deposits. This unit is assigned to the Erie Phase; a period of ice withdrawal that saw widespread deposition of glaciolacustrine deposits following deposition of Catfish Creek Drift (Karrow et al. 2000).

Unit 6 (Tavistock Till)

Glaciolacustrine deposits of unit 5 are unconformably overlain by up to 2 m of a brown, stone-poor, gritty, pebbly, clayey silt diamicton (unit 6, Figs. 6 and 8f). The diamicton is massive, dense, blocky, and moderately weathered, in places displaying a subhorizontal fissility. A sharp, planar lower contact is observed across much of the north-face exposure. Similar diamicton was not observed along the east face, although exposures of the upper sediment were limited. A number of black and grey shale clasts were found within this unit. Of note was the discovery of a single spiriferid brachiopod within the till that clearly suggests a source to the west in the Devonian Hamilton Group. This unit is correlated to the Port Bruce Phase Tavistock Till, which forms the surface till over a broad area northwest of the interlobate zone (Cowan 1975). Port Stanley Till, the Erie Lobe equivalent to the Tavistock Till, was not observed in the exposures studied as part of this investigation but was noted in the earlier works of Westgate and Dreimanis (1967) and Krzyszkowski and Karrow (2001).

Radiocarbon dating

Samples of wood were collected from both the north and east channel-fill sequences for radiocarbon dating by accelerator mass spectrometry (AMS). At the east face, wood samples were collected

Table 2. Reported AMS radiocarbon ages from the Zorra quarry exposures.

Sample	Laboratory No.	Pretreatment	Reported age (^{14}C years BP)	Material dated
Zorra north	TO-13125	AAA	45 160 ± 1260	Wood fragments
Zorra east	TO-13126	AAA	42 900 ± 1050	Wood fragments
Zorra north	TO-13125 R	Standard cellulose	47 220 ± 1050	Wood fragments
Zorra east	TO-13126 R	Standard cellulose	50 520 ± 1570	Wood fragments
Zorra east	TO-13126RR	Aggressive cellulose	47 640 ± 680	Wood fragments
Zorra east	NZA-30833	Standard cellulose	>47 000	Wood fragment
Zorra south	A3030	AAA	44 900 ± 1500	Wood fragment

from a clean exposure 150–200 cm from the base of the 280 cm thick channel-fill sequence. At the north exposure, bulk sediment samples were collected from four stratigraphic levels within the channel-fill sequence. Stratigraphic level C, which represents a sample depth of 80–110 cm from the base of the 140 cm thick channel-fill sequence, was, by far, the richest and yielded the most wood for dating. The wood was isolated from the bulk sediment samples by wet sieving and subsequent picking under a binocular microscope.

Wood fragments collected from the north- and east-face exposures were competent, well preserved, and generally <1 cm in length. Multiple wood fragments were submitted for radiocarbon dating to Isotrace Laboratory, University of Toronto. Due to the limited size of the samples submitted, only a standard acid–alkali–acid (AAA) pretreatment was performed on the samples initially. This pretreatment removes most, but not all of the potentially modern humic and fulvic acids that can migrate into the sample by groundwater flow. The reported ages of 45.2 and 42.9 ^{14}C ka BP for the north and east exposures, respectively, are therefore considered minimum ages for the sample (Table 2).

A second set of samples from the same stratigraphic positions were resubmitted to Isotrace Laboratory for a standard cellulose extraction, which is reported to remove a higher proportion of possible modern contaminants. The reported ages of 50.5 and 47.2 ^{14}C ka BP for the north and east exposures, respectively, are slightly older than those reported by the standard AAA pretreatment, possibly suggesting the removal of some modern humic or fulvic acids. It should be noted, however, that new material (i.e., different pieces of wood) was submitted for dating in the second batch, and the new dates may simply reflect the variability in ages of detrital wood within the channel-fill deposits.

Seeing that the second date from the east exposure was at or above the upper limit of AMS dating, a split of the same sample was redated following a more aggressive hot acid chlorite bleach to isolate a “cleaner” cellulose fraction. The reported age of 47.6 ^{14}C ka BP was slightly younger than the original cellulose age of 50.5 ^{14}C ka BP and is therefore considered a true finite age (Roelf Beukens, Isotrace Laboratory, personal communication, 2008).

A single wood fragment was collected from the east face in the fall of 2009 and submitted to Rafter GNS Science in New Zealand for AMS dating. A standard cellulose extraction was performed on the sample and a radiocarbon age of >47.0 ^{14}C ka BP was reported for the sample. In 2013, a wood sample collected from the original southern exposure studied by Westgate and Dreimanis (1967) was submitted for AMS dating to the Illinois State Geological Survey. A standard AAA pretreatment was performed on the sample, and a radiocarbon age of 44.9 ^{14}C ka BP was reported. Although stratigraphically of different ages, dating does not distinguish this occurrence from the main organic channel fill of this study. They are simply of similar age.

Paleoecology

Field and laboratory methods

In the summer and fall of 2006, bulk sediment samples of the organic channel-fill sequences were collected from both the north and east exposures at the Zorra quarry. The north-face exposure contained the richest material, showed the least deformation by subsequent overriding ice, and was therefore sampled most extensively. Samples from four stratigraphic levels, totalling over 125 kg of material, were collected from the north face, with the majority of the material being collected from the upper part of the channel fill where the highest concentration of macrofossils was observed. At the east exposure, 14 kg of sediment was collected from multiple rich zones with no particular stratigraphic context. Molluscs exposed on weathered surfaces of the channel fill were generally collected during each site visit to bolster the species list. Bulk sediment samples were wet sieved in the laboratory on stainless steel US standard sieve mesh No. 10 (2 mm), No. 30 (0.59 mm), No. 60 (0.25 mm), and No. 120 (0.125 mm). The dried +10, +30, and +60 mesh fractions were picked and sorted using a binocular microscope to isolate seeds, leaves, mosses, molluscs, ostracodes, insect fragments, bones, and teeth.

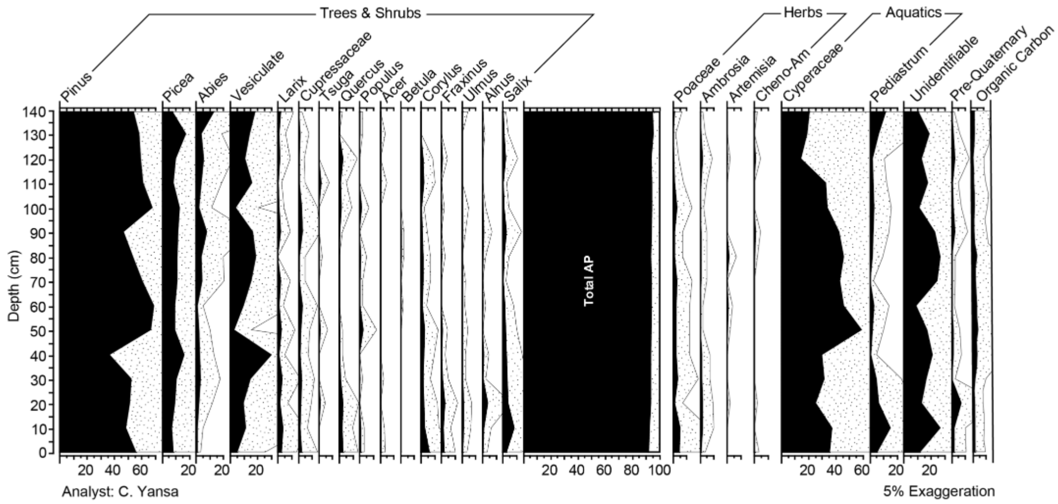
Sediment samples were also collected for pollen analysis during the summer and fall of 2006. Samples were collected from freshly exposed and cleaned faces (bottom to top) at a 5 cm interval. A total of 28 samples spanning 1.4 m and 57 samples spanning 2.8 m were collected from the north and east faces, respectively. Samples were also submitted to the Geoscience Laboratories of the Ministry of Northern Development and Mines for loss on ignition to determine organic carbon content.

Pollen and plant macrofossils

Pollen preservation is extremely poor at the site. Exploratory pollen analysis of representative samples revealed that preservation was dismal at the east section; hence, just data from the north section are presented. Pollen grains from the north section are still poorly preserved, but some are identifiable. Pollen concentration is low in these clastic-dominated samples; hence, the sediment volume processed was doubled to 2 cm^3 per sample interval. Preparation, counting, and identification of 16 selected pollen samples (5–10 cm interval spacing) from the north section followed standard procedures outlined in McAndrews et al. (1973), Faegri and Iverson (1975), and Bates et al. (1978). Pollen concentrates (after chemical preparation) were very small due to the extremely low organic content of the samples, and so for half of the samples all materials from the vials were used to prepare microscope slides and counted, and for the rest, at least seven slides were counted per sample. The target for the pollen sum of trees, shrubs, and upland herbs (excluding Cyperaceae, members of the sedge family) was 400 grains per sample, but for some of the samples where all of the concentrate was counted, the sums ranged from 298 to 377, but still adequate for a pollen study.

Sediment (100 cm^3) from each of the samples collected for pollen analysis from the north section was sieved, but all of these were barren of organic remains except for the occasional tiny fragments of worn wood. The plant macrofossil data presented here come from the large bulk samples collected from the north and east faces. These plant fossils are in poor condition and are reported as total counts, except for moss leaves and stems, which are represented as common, few, and rare, as per standard practice. Most of the few conifer

Fig. 9. Pollen profile from the north exposure of fossiliferous sediments, Zorra quarry.



needles recovered were broken. Macrofossil counts and pollen percentages were entered and plotted in Tilia 1.7.16, and the resulting diagrams modified in Adobe Illustrator 10. No pollen or plant macrofossil zones were identified because of the strong taphonomic signals in both records, which probably account for changes in taxa abundance over time, rather than vegetation responses to climate change. Pollen and plant macrofossil interpretations are based on the plant taxonomy and habitat information in Ritchie (1987) and Scoggan (1978).

The exceedingly poor preservation of the pollen and plant macrofossils from this site can be partly attributed to oxidation. The plant and other fossils were probably deposited in a channel fill, and thus likely exposed to air for much of the time following deposition and prior to burial, which resulted in bacterial and fungal decay of the organic remains to varying degrees. The seeds that survived also bear evidence of wear that could suggest fluvial transport. Wood fragments are common in the macrofossil samples, but these are hardier than seeds and needles. The wood pieces are too small to identify to taxa, but appear to be those of conifer(s) rather than of deciduous hardwoods.

Another contributing factor to the very poor preservation of plant fossils at the Zorra site is the silty nature of the sediments, which are derived from the silt-rich tills in the area. Silt is notoriously poor for preserving pollen because the arrangement of silt grains allows for voids to fill with air, which oxidizes the pollen (discussed in Cushing 1967). Also rapid clastic sedimentation at the site diluted the pollen, and explains the low pollen abundance.

The pollen data are displayed in Fig. 9 and plant macrofossil counts shown in Table 3. The pollen grains are mainly crumpled and deteriorated, hence the very high counts of indeterminable grains (9.2%–26.8%, calculated outside the pollen sum). The best preserved are conifer grains, which are well known to contain the most sporopollenin (a protein polymer that comprises the exine of pollen grains) and hence are most resistant to decay (Birks and Birks 1980). Therefore, the high percents of *Pinus* (pine, 36.2%–68.9%), moderate abundance of *Picea* (spruce, 7.2%–17.5%), and low–moderate concentrations of *Abies* (fir, 0.7%–12.9%) should be interpreted cautiously, as these grains are better preserved than the others. But even these are mainly represented as torn-off single bladders, some of which are identifiable, but others are not and hence counted as vesiculate (so could be either *Pinus*, *Picea*, and (or) *Abies*). Some of the intact *Pinus* grains were identified as those of the *Pinus banksiana* – *P. resinosa* type, and given the ecology are likely those of *P. banksiana* (jack pine), which of the two has a more northern distribution today. Small numbers of the *Picea* grains could be sorted to type, with both *P. glauca* (white spruce) and *P. mariana* (black spruce) being represented, with greater abundance of the latter. Rare and fragmentary spruce needles were recovered, confirming the local presence of this taxon, but were in too poor of condition for species identification via dissection to examine resin ducts (as per Jackson and Weng 1999). Some of the *Pinus* and *Picea* pollen are also of long-distance origin, but, as Warner et al. (1984) stated, these grains cannot be distinguished from those that came from local pine and spruce trees. However, the pollen percents for both taxa are definitely high enough to confirm the dominance of these trees in the southern Ontario landscape during the Middle Wisconsin. A study of modern pollen deposition compared with the composition of local vegetation reveals that *Pinus* overproduces pollen by 20%, whereas *Picea* pollen is produced in proportion to the abundance of spruce trees in the environment (Webb and McAndrews 1976). So with this in mind, the vegetation at the Zorra site would be a pine–spruce, boreal (taiga)-type forest, rather than a pine forest.

Very low (0.5%–1.5%) pollen percents of *Tsuga* may indicate a few local eastern–Canadian hemlock trees, and (or) the long-distance dispersal of pollen from the south. Also, some of these conifers as well as the other pollen taxa of southern affinity may be recycled, coming from older Quaternary-age (e.g., Sangamon) deposits (discussed in Warner et al. 1984). This interpretation is supported by some pre-Quaternary palynomorphs (0.4%–2.6%) identified at the Zorra site, that came from tills, and ultimately derived from eroded Paleozoic rock, but likely this represents a small component of the pollen spectra.

Those pollen grains known to contain the least amount of sporopollenin, such as *Larix* (tamarack), *Populus* (poplar), and Cupressaceae (white cedar – juniper) (Birks and Birks 1980), are thus underrepresented in the Zorra pollen record. Undoubtedly, the first two taxa were present, given that one needle of *Larix* was recovered along with a few seeds of *Populus* (which cannot be identified to species), but are probably those of *Populus tremuloides*

Table 3. Plant macrofossils recovered from the north- and east-face sections of the Zorra fossil site.

	Tree				Shoreline herb or emergent										Aquatic				Unknowns and mosses		
										Carex											Unknown moss (stem fragment)
Section	Picea sp. (needle)	Larix sp. (needle)	Populus tremuloides (bract)	Populus sp.	Potentilla cf. P. norvegica	Polygonum sp.	Ranunculus sp.	Asteraceae	Cirsium sp.	sp. 1	sp. 2	sp. 3	sp. 4	Scirpus cf. S. validus	Potamogeton filiformis	Najas flexilis	Hippuris vulgaris	cf. Equisetum sp. (stem fragment)	Unknown seed	Drepanocladus sp. (stem fragment)	sp. 1	sp. 2
North D (top)	–	–	–	–	3	–	–	–	–	1	–	–	–	1	5	–	–	–	1	C	–	–
North C-01	0.1	–	–	–	1.5	–	–	–	–	–	–	–	–	–	6	–	–	–	1	C	–	–
North C-02	–	–	–	–	6.5	–	–	2	–	–	–	–	–	1	6.5	–	–	–	0.5	F	R	R
North C-03	–	–	–	–	1.5	–	–	–	–	–	2.5	–	–	1.5	5.5	–	–	1	1	F	–	F
North C-04	–	–	–	–	1	–	–	–	–	–	–	–	–	–	2	–	–	–	1	C	F	–
North C-05	–	–	–	–	0.5	–	–	–	–	–	–	–	–	–	3	–	–	–	–	F	–	–
North C-06	–	–	–	–	2	–	–	–	–	–	1	–	–	–	4	–	–	–	–	F	–	–
North C-07	–	–	–	–	2.5	–	–	–	–	–	1	–	–	–	3.5	–	–	–	–	F	–	R
North C-08	–	–	–	–	1	–	–	1	–	–	–	–	–	1.5	4	–	–	–	2	–	–	R
North C-09	1	–	–	–	3.5	1	–	–	1	1.5	–	–	–	3.5	6	–	1	–	–	F	–	R
North C-10	0.5	–	–	–	7.5	–	–	1	–	1	–	–	–	1.5	3	–	–	–	1	C	R	–
North B	–	–	–	–	–	–	–	–	–	1	–	–	–	2	2.5	–	–	–	2	R	R	–
North A (base)	–	–	1	2	3	–	–	–	–	2	2	1	–	–	6	1	–	–	–	C	R	–
East-1	1	1	–	–	0.25	–	–	–	–	–	–	1	–	–	1	0.25	–	–	1	C	–	–
East-2	0.2	–	–	1	2	1	0.5	1	–	2	–	–	0.5	–	4	–	–	–	1.5	C	R	R

Note: Data are counts, except for moss stem fragments (C, common; F, few; R, rare). All are seeds unless otherwise noted.

(trembling aspen – aspen poplar), seeing that one bract of this species was found. Very low abundance and poor preservation of the pollen of thermophilous deciduous hardwood trees and shrubs indicate long-distance transport and (or) their local presence in low numbers (0.4%–2.8% per taxon). These taxa include Quercus (oak), Acer (maple), Betula (tree birch), Corylus (hazel), Fraxinus nigra (black ash), Ulmus (elm), and the shrubs Alnus (mainly those of A. viridis, green alder, with some A. incana, speckled alder) and Salix (willow). Of these, most likely Quercus rubra (northern red oak) and (or) Q. macrocarpa (bur oak), Corylus, Alnus, and Salix were present. Taxa not plotted in Fig. 9, because of their rarity (<0.5%), include Ostrya–Carpinus (hop hornbeam – hornbeam), Juglans (walnut), Fagus (beech), Carya (hickory), and Shepherdia canadensis (Canada buffaloberry), the latter a shrub that currently inhabits the boreal forest. Again, these pollen grains may be of local or long-distance origin.

The nonarboreal (herb) pollen was a very minor component of the local flora at Zorra quarry. It included Poaceae (grass), Ambrosia (ragweed), Artemisia (wormwood–sage), Cheno–Am (Chenopodiaceae–Amaranthaceae families), which are shown in Fig. 9, as well as rarer amounts of Tubliflorae (subfamily of Asteraceae), Thalictrum (meadow rue), Brassicaceae (mustard family), Ranunculus (buttercup), and Caryophyllaceae (pink family). Identified seeds confirm the local presence of Potentilla cf. P. norvegica (rough cinquefoil, which was most abundant of the shoreline herbs), Ranunculus, Polygonum (knotweed), and Asteraceae, some of which were identified as Cirsium (thistle).

The relatively abundant aquatic pollen and seeds indicate the local presence of water, thereby lending support to the sedimentological interpretation of the organic-bearing unit as a channel fill that for a time contained a pond. This interpretation is based on the high abundance of Cyperaceae pollen (14.3%–58.8%, calculated outside of the pollen sum), and seeds of this sedge family, including those of Scirpus cf. S. validus (softstem – great bulrush) and at least four species of Carex (sedge). Species identification of Carex is not feasible given the 100+ sedge species that exist in the region today. These Cyperaceae plants occupied the shoreline along with the herbs (including Equisetum, horsetail) and some of the trees described earlier in the text. Shallow waters of this pond or wetland were inhabited by Pediastrum (algae colonies), and the submerged aquatic plants Najas flexilis (naiad), Hippuris vulgaris (mare's tail), and Potamogeton filiformis (slender pondweed), the latter being most abundant. There are also limited amounts of the stem fragments and leaves of three moss species, one identified as Drepanocladus, a fen-type of moss that favours calcareous waters. Not plotted in the pollen diagram are rare spores of Osmunda regalis (royal fern), Sphagnum (moss), and Selaginella selaginoides (clubmoss).

In overview, although the exact taxonomic composition of the vegetation of the Zorra quarry site cannot be ascertained due to taphonomy, the record does suggest a local paleovegetation most comparable to a boreal-type pine–spruce forest with temperatures definitely cooler than present in the study area. The absence of arctic tundra plants is notable. There was definitely a local pond or wetland at the site inhabited by shoreline herbs, shrubs, and trees, including the boreal taxa Larix, Picea mariana, Abies, and Populus tremuloides, as well as Alnus, Salix, and possibly the others listed earlier. Abies pollen values are high enough to indicate the local presence of this taxon, significant as it occupies the southern part of the boreal forest today, and indicates that the climate of the site during this time was cooler than modern, but not severely subarctic or arctic. Most of the pollen from deciduous hardwood trees was probably from trees distant to the south, except for Quercus and possibly a few other taxa that may have occurred in low numbers, which also supports the interpretation of the vegetation most like that of the southern boreal forest. Pinus, assumed to be P. banksiana, was the most common tree in the upland landscape even after accounting for this taxon being a notorious overproducer of pollen (Faegri and Iverson 1975; Birks and Birks 1980). This pine abundance may indicate that the regional climate was mainly dry in spite of the presence of a local, shallow wetland with abundant sedges, bulrushes, and pondweeds and hydric- and mesic-adapted trees. The low pollen values for Abies, Alnus, Tsuga, Picea glauca, and Betula may indicate that soils were too dry for their widespread abundance, except along the edges of waterbodies. Alternatively, the high pine abundance may simply indicate the presence of sandy soil in the area, as jack pines today inhabit areas with well-drained, coarse-textured substrates in the mesic boreal forest (taiga), and not a dry climate signal. The other conifers probably occupied the finer grained soils in the area that retained more moisture, with tamarack and black spruce inhabiting the moistest (hydric) locales.

Molluscs

An assemblage dominated by terrestrial molluscs and a less diverse aquatic molluscan assemblage was recovered from the north- and east-face exposures (Table 4). Most of the aquatic specimens were highly fragmented as a result of the disaggregation–washing process as well as by crushing due to overriding glaciers preventing definitive identification of many fragments to the species level.

The terrestrial mollusc assemblage consists of eight species belonging to six genera. Specimens from the family Succineidae were most frequently recovered; however, identification to even the genus level is impossible without information regarding soft-body genitalic anatomy. As such, these shells can only be referred to by family. Likewise, the presence of an agriolimacid slug in the genus Deroceras is indicated by the presence of internal shell plates; unfortunately, these do not allow for species level identification. However, the modern range of the native Deroceras laeve extends well into the boreal zone (Oughton 1948), and the recovered material is almost certainly of this species.

The observed fauna is indicative of boreal forest (taiga) or tundra conditions. All species recorded from these deposits currently occur in open, cold shoreline turf along the Gulf of St. Lawrence in the Côte-Nord region of Quebec, especially in the limestone-dominated districts associated with the Mingan Archipelago. However, many of these species (e.g., Columella columella, Pupilla hudsonianum, Vertigo aff. genesii, Vertigo modesta, Vertigo oughtoni) disappear within a few kilometres of the shore. Some reemerge in the mixed taiga–tundra landscape of the central Laurentian Shield and extend north into the tundra of Baffin Island (e.g., Columella columella, Vertigo modesta, Vertigo oughtoni; Oughton 1948; Nekola and Coles 2010). Of particular interest is the lack of Beringian species commonly seen in modern taiga–tundra sites west of Hudson's Bay and in late-glacial sites from Ohio and west in the North American midwest (e.g., Vertigo hannai; Hubricht 1985; Pigati et al. 2010).

The aquatic mollusc assemblage consists of two species of gastropod and at least two species of pelecypods. The pulmonate gastropods Gyraulus parvus and Helisoma anceps indicate the presence of shallow water habitats with dense, submerged vegetation and large areas of swamps, marshes, and wet mud flats. Similar environments are suggested by the pisidiids, Pisidium casertanum and P. ventricosum (Clarke 1981). No climatic inferences are possible based on the aquatic assemblages recovered.

Ostracodes

Ostracode valves were recovered primarily from the 0.59–0.25 mm fraction of the sieved bulk sediment samples. The concave portions of most valves contain very fine sand cemented with iron-stained carbonate. Seventeen species belonging to eight genera were recovered from the north- and east-face exposures (Table 5). Candona candida, Limnocythere itasca, Cypridopsis vidua, and Ilyocypris bradyi, species commonly found in a wide range of habitats including lakes, ponds, and streams (Delorme 1989; Curry et al. 2012), were the most abundant ostracodes recovered.

Table 4. List of aquatic and terrestrial mollusc species recovered from the north- and east-face exposures of the Zorra quarry.

	Aquatic							Terrestrial								
Exposure	Gyraulus parvus?	Helisoma anceps?	Pisidium casertanum?	Pisidium ventricosum	Pisidium spp.	Pisidium fragments	Unidentified aquatic fragments	Columella columella	Deroceras sp.	Discus cronkhitei	Pupilla hudsonianum	Succineidae spp.	Vertigo aff. genesii	Vertigo modesta	Vertigo oughtoni	Immature Vertigo and (or) Columella individuals
North D (top)	–	1	–	–	1	P	P	1	4	–	1	50	1	3	12	28
North C	2	–	–	2	10	P	P	10	32	–	10	423	7		86	198
North B	–	1	–	3	3	P	P	–	2	–	–	61	–	–	9	14
North A (base)	1	2	1	6	3	P	P	5	4	–	3	118	3	–	24	43
East	–	1	–	–	–	P	P	12	11	1	4	264	4	1	103	123
Till A	–	–	–	–	–	–	–	–	–	–	–	10	4	–	–	–

Note: P indicates present.

Table 5. List of ostracode species recovered from the north- and east-face exposures of the Zorra quarry.

Exposure	Candona candida	C. inopinata	C. ohioensis	Fabaeformiscandona caudata	F. rawsoni	Cyclocypris ampla	C. laevis	Cypridopsis vidua	Cytherissa lacustris	Ilyocypris biplicata	I. bradyi	Limnocythere itasca	L. sharpei	L. posterolimba	L. robusta	L. pseudoreticulata	Physocypria globula	Total
East	12	–	–	2	3	–	–	1	–	–	2	1	1	–	–	1	–	23
North D (top)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0
North C-01	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	1
North C-02	–	1	1	1	–	–	1	–	–	–	–	–	–	–	–	–	–	4
North C-03	1	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	2
North C-04	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	2
North C-05	9	–	1	3	2	1	–	11	–	1	3	10	6	–	1	–	–	48
North C-06	12	–	–	–	4	–	4	1	–	–	10	10	1	2	–	–	–	44
North C-07	3	–	–	–	–	–	2	1	–	–	3	3	–	–	–	–	–	12
North C-08	–	–	–	–	–	–	–		–	–	–	3	–	–	–	–	–	3
North C-09	2	–	–	–	–	–	1	5	–	–	1	2	1	–	1	–	1	14
North C-10	1	–	–	–	–	–	–	3	1	–	–	4	–	–	–	–	–	9
North C-11	4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4
North B	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0
North A (base)	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1

Several species in the collective assemblages prefer water bodies with variable hydrology in terms of water depth and total dissolved solids, particularly *Fabaeformiscandona rawsoni*, *Limnocythere sharpei*, *L. posterolimba*, and to a lesser degree, *L. itasca*. These species would be expected to occur in water bodies seasonally impacted by evaporation in excess of precipitation. Other species from the Zorra site today prefer low salinity and stable hydrologic conditions (i.e., sites less impacted by seasonal evaporation), but they are much less common (e.g., *Candona ohioensis*, *C. inopinata*, and *Cytherissa lacustris*). The poor temporal resolution of the samples and relatively low numbers of specimens precludes robust interpretation of hydrological changes indicated by ostracode autecology. Of note is the presence of *Limnocythere robusta*, a species known only from the fossil record (Delorme 1971).

Vertebrates

Of 19 samples examined, 15 produced fragmentary vertebrate remains. All 15 samples contained fragments of rodent incisors, which are generally unidentifiable. Several groups of North American rodents have grooved incisors (e.g., bog lemmings and zapodid jumping mice), but all of these fossil fragments consisted of plain, ungrooved incisors, perhaps representing microtines. Only two nonincisor specimens are complete enough for identification. The first is Royal Ontario Museum (ROM) 63324, an upper M2 of a meadow vole, *Microtus pennsylvanicus*. The upper M2 in this species has four closed triangles plus a diagnostic small rounded posterior loop that is not present in other microtines. The meadow vole is a common and widespread North American vole, living in a wide variety of habitats, but preferring wet meadows and open grassland (Forsyth 1985). The second specimen, ROM 63325, is the tip of a right lower incisor of a *Sorex* shrew, preserving only the tip and the first (of three) posterior cusplets. Today, *Sorex* shrews generally have only two posterior cusplets, but some develop an accessory cusplet closer to the tip. This most anterior of the posterior cusplets is lacking in almost all North American *Sorex* species surveyed (a total of 14 species present in the ROM Mammalogy collection), but occasionally is partially developed in *S. cinereus* and to a lesser extent in some *S. arcticus*. No good match could be found amongst the available comparative material, because in the fossil this accessory cusp is rather large and well developed. However, several *S. cinereus* examined (3 of 20 Yukon specimens, 2 of 19 Saskatchewan specimens, 1 of 11 Nunavut specimens, and 0 of 23 Sudbury specimens) had this cusp partially developed, in the same location and angled in the same way. Perhaps this cusp was better developed in the past, but today this polymorphism is in the process of being lost. Because this fossil is slightly larger than the recent comparative of *S. cinereus*, and has the well-developed accessory cusp, an identification of *Sorex* cf. *S. cinereus* is suggested. Today, the masked shrew *S. cinereus* lives in a wide variety of habitats, including moist or dry woods, fields, bogs, and marshes (Forsyth 1985). Together these two mammals suggest a moist, grassy meadow or woodland habitat.

Discussion

The reported ages of 50.5–42.9 ^{14}C ka BP place the Zorra fossiliferous horizon within the Port Talbot Phase and correlative with Member C of the Tyrconnell Formation whose stratotype section occurs along the north shore of Lake Erie and for which radiocarbon ages of between 48.0 and 43.0 ^{14}C ka BP are common (Karrow et al. 2000). The discovery of a large number of Middle Wisconsin deposits across a vast region of southern Ontario, extending from Lake Erie in the south to Georgian Bay on Lake Huron to the north, advocates for a period of significant ice withdrawal between 50 and 40 ^{14}C ka BP. Organic deposits resting on a deeply buried paleosurface along the trend of the Laurentian buried bedrock valley, east of the Niagara Escarpment, have similar ages and occur at or below the current level of Lake Huron (Bajc et al. 2014). Peat beds of equivalent age similarly occur below the level of Lake Erie at Port Talbot. If similar basin and outlet configurations existed in the Lake Huron and Erie basins during the Middle Wisconsin, as did following the last deglaciation, then significant retreat of the LIS must have occurred to drop base levels below their present elevation. Recent studies in the Finger Lakes and Genesee River areas of west-central New York State indicate that the Lake Ontario basin was still occupied by glacial ice shortly after 35.0 ^{14}C ka BP (Young and Burr 2006; Karig and Miller 2013). This is in line with the early work of Karrow (1967) who identified diamicton units in the Scarborough bluff exposures (Seminary and Meadowcliffe tills), which he assigned to the Middle Wisconsin (Karrow 1984). In central Indiana, Wood et al. (2010) present evidence in Porter Cave for Middle Wisconsin occupation of the Mill Creek Valley by the LIS during this time interval as well. In the Laurentian Valley area of Ontario, drowning of the deeply buried paleosurface likely began prior to 50 ^{14}C ka BP and continued until after 37.5 ^{14}C ka BP (youngest date obtained from the regional unconformity) as the Georgian Bay and Ontario ice lobes advanced into their respective basins damming a large proglacial lake within the Laurentian trough and Ontario basins (Bajc et al. 2014). Collectively, there appears to be a growing consensus for persistent ice within the Great Lakes basins during at least part of the Middle Wisconsin.

The ages of the diamictons underlying the organic channel-fill sequence at Zorra (units 1 and 2) remain uncertain. Organic matter recovered from stratified deposits both underlying and contained within unit 1 (Till A) and reported on in Westgate and Dreimanis (1967) were not observed as part of this study. However, a sample of wood collected from this occurrence in the mid-1970s and recently dated as part of this study returned a radiocarbon age of 44.9 ^{14}C ka BP. Contamination by modern carbon resulting in a finite age is suspected. Alternatively, the stratigraphic relationships observed during the initial studies may be more complex than reported. Westgate and Dreimanis (1967) assigned till units A and B (units 1 and 2 of our study) to the Early Wisconsin and suggested a correlation with the Upper and Lower Bradtville drifts. These units have since been reinterpreted to be of Illinoian age (Dreimanis 1992), further complicating the correlation. Interglacial deposits have not been found in association with the older tills at Zorra as they have in the Lake Erie basin to the south. We therefore cautiously assign both units 1 and 2 to either an Early Wisconsin or Illinoian age. Kzyskowski and Karrow (2001) followed a similar reasoning in their discussion of the older tills.

The pollen and plant macrofossils analyzed in this study indicate a pine–spruce forest, like that found in the southern boreal forest today, and hence a climate cooler than present, given that the natural vegetation of the area today is a deciduous forest. But the vegetation was definitely not a cold subarctic or arctic one. There are two possible interpretations for moisture levels: (i) there was less precipitation during this interval; or (ii) the upland soils were largely sandy, supporting jack pine, whereas oaks would occupy these well-drained areas today. However, a review of other pollen records in the region (discussed in the following text) provides more support for a climate interpretation, one of widespread dryness.

Clearly, the pollen and plant macrofossil data reconstruct local wetlands containing sedges, bulrushes, and some shallow-water aquatic plants. The aquatic molluscs and ostracodes similarly indicate the presence of shallow water habitats with dense submerged vegetation and the likelihood of permanent lakes within the catchment of the fluvial system preserved here. The assemblages are consistent with water depths within the photic or littoral zone, but the presence of abundant benthic ostracodes (versus species that are nektonic–planktonic) suggests the fauna were reworked from shallow to somewhat deeper water environments. No climatic inferences are drawn from these aquatic fauna. Together, the recovery of fossils of *Sorex* shrew and meadow vole suggest the presence of moist, grassy meadows or woodland habitats. The terrestrial mollusc assemblage generally indicates a cold open environment like that now present in shoreline limestone turf along the Gulf of St. Lawrence.

The environmental interpretations presented here seem reasonable despite obvious taphonomic problems, including the partial oxidation and decay of the fossils (due to fluctuating moisture levels and the silty nature of the sediments), reworking of pollen from older interstadial–interglacial deposits, long-distance transport of pollen from coeval forests to the south, and high rates of clastic sedimentation that diluted pollen concentrations. The excellent preservation of some of the fossil molluscs present within the channel-fill deposit suggests that at least a proportion of the faunal and floral remains are locally derived. The sediment sequence preserved at the Zorra quarry most likely represents a short period of sedimentation, as there are no obvious faunal and floral changes that occur vertically through the sampled profile.

The paleobotanical record obtained from the current study is nearly identical to those of other sites in southern Ontario and Michigan of comparable Middle Wisconsin age (preliminary pollen work by Terasmae in Cowan 1975; Wright 1977; Karrow et al. 1982; Karrow and Warner 1984; Karrow et al. 2001). Coincidentally, many of these other studies also report very poor preservation of pollen and plant macrofossils, including some samples that are barren (e.g., Berti 1975; Karrow et al. 2001). These researchers are similarly cautious in their floristic interpretations.

Almost all of these prior studies of the paleobotany of Middle Wisconsin organic deposits interpret the same type of southern boreal forest dominated by *Pinus*–*Picea*, and a cooler and drier climate than today in spite of fairly high Cyperaceae pollen, often supported by seeds of *Carex* and *Scirpus*. For example, a pollen study of an intertill paleosol overlain by fossiliferous pond deposits at the Victoria Road site in Guelph, Ontario, which dates to >35.0 ^{14}C ka BP, was interpreted as jack pine forest or jack pine parkland in a southern boreal-type environment (Karrow et al. 1982). Likewise, pollen, plant macrofossils, insects, molluscs, and ostracodes from organic sediments dating to 40.8 ^{14}C ka BP under till at Waterloo, Ontario, record a similar vegetation, with the exception of higher *Picea* concentrations (Karrow and Warner 1984). However, these authors still interpreted more *Pinus* than *Picea* in the Waterloo landscape, attributing the greater spruce pollen abundance to local growth of *Picea* in a forested wetland, and insisted that the climate was still cooler and drier than modern. This interpretation is valid, but to note that *Picea* values are higher than *Pinus* at several Middle Wisconsin sites in Manistee County, Michigan, which along with slightly higher nonarboreal pollen values are interpreted as a more open boreal forest (Rieck et al. 1991). Karrow et al. (2001) notes in the fossil record from Woodbridge, Ontario, that the presence of *Najas flexilis*, which is also found at Zorra quarry, indicates a July mean temperature of 15 °C, again supporting a southern boreal forest interpretation.

However, there are a few other studies in southern Ontario that report arctic tundra plants, such as *Dryas* (white dryad) *Betula nana* (dwarf birch), and Ericaceae (heath), mixed with *Picea* and *Pinus* (e.g., Berti 1975; unit 7 in Karrow et al. 2001; Bajc et al. 2014). Berti (1975) reported an open forest–tundra environment with arctic plants and *Pinus* and *Picea* between 50 and 36 ^{14}C ka BP (Port Talbot II Interval). But Wright (1977) and Karrow and Warner (1984) questioned this arctic interpretation because of the high *Pinus* pollen values displayed in Berti's (1975) paper, and instead offered the scenario of mixed jack pine and spruce at tree line. The terrestrial mollusc assemblage reported here suggests a similar environment. Bajc et al. (2009) suggested that the mixture of arctic and boreal forest taxa in Ontario may be a result of long distance transport and reworking of older organic deposits, a scenario which is highly possible at these sites. However, there are other sites outside of the immediate study area that provide strong evidence for arctic tundra in certain places and at particular times during the Middle Wisconsin. Cong et al. (1996) provide good evidence for significant shifts in temperature during the Middle Wisconsin based on fossil beetle evidence from a site in Titusville, Pennsylvania. It is quite likely that southern Ontario experienced similar shifts in temperature during this time interval.

The study of pollen, plant macrofossils, and insects from a site in the Georgian Bay area near Clarksburg (Warner et al. 1988), the northernmost interstadial site in southern Ontario, reconstructed a tundra environment that was situated at or immediately north of tree line from >36.0 to 31.5 ^{14}C ka BP, based on an assemblage of *Picea* and *Pinus* pollen mixed with pollen and macrofossils from tundra plants. Wood from this site has been recently dated by accelerator mass spectrometry at 38.8 ^{14}C ka BP. Also, Winters et al. (1986) reported pollen from subtill organic deposits dated to 35.0 ^{14}C ka BP that indicated that first an open and later a closed boreal forest occupied northwestern Lower Michigan. Note that this record dates towards the latter part of the Middle Wisconsin, when the climate was on a cooling trend that culminated with marked expansion of the LIS during the early Late Wisconsin Glaciation (OIS2).

Karig and Miller (2013) similarly reported a tundra flora for two fossiliferous layers, one at 42.0 ^{14}C ka BP and the other between 37 and 34 ^{14}C ka BP, at the Sixmile Creek site near Ithaca, New York. These two units are interpreted as a vegetation response to a Middle Wisconsin glacial advance of the Ontario ice lobe into the Appalachian Plateau. An arctic flora in the Finger Lakes region of New York during the younger of the two intervals is supported by geomorphic evidence for the advance of the LIS 30 km south of the Lake Ontario shoreline at ca. 35.0 ^{14}C ka BP (Young and Burr 2006). The authors of these two papers suggest that a lobe of the LIS extended south into the Finger Lakes area during the latter part of the Middle Wisconsin when other areas to the northwest, such as in southwestern Ontario, were still ice-free. This interpretation of variation in climate, vegetation, and ice-sheet dynamics is supported by a pollen study on Cape Breton Island in Atlantic Canada. In this study, there were at least three episodes of a boreal forest that alternated with intervals of arctic tundra vegetation within a broader cooling trend that characterized the Middle Wisconsin (Fréchette and deVernal 2013). Some of the confusion in interpreting the type of environment of Middle Wisconsin sites stems from the poor chronological control, as these organic deposits are at the maximum limit of ^{14}C dating (Karrow 2004).

In summary, despite some taphonomic imprints on the fossil records from our study site and others in Ontario, as well as those from elsewhere in northeastern North America, it appears that some areas at certain times had tundra vegetation. But mainly a boreal forest dominated by *Pinus* and *Picea* (and in a few places possibly more *Picea* than *Pinus*) prevailed during the Middle Wisconsin. The climate was cooler and most likely drier than present regardless of whether tundra or boreal forest existed in a particular area. Finally, this cooling was confined to Canada and the northern United States, given that pollen and testate amoeba analysis of peat clasts in paleochannel deposits in coastal Georgia indicate a flora and climate like modern during the Middle Wisconsin (Booth et al. 2003).

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