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Surficial geology of Cockburn Island, Ontario

P.J. Barnett

2024

Canada

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Abstract

Cockburn Island landscape is somewhat unique in the northern Lake Huron-Georgian Bay basin, in that, it's overall topography and relief is dependant primarily on glacial sediments that can exceed thicknesses of 85 m (275 feet), rather than the bedrock surface. Cockburn Island is underlain by gently dipping carbonate and clastic rocks of Middle Silurian age that outcrop in a belt that rings the northern half of the island. The crest of the Niagara Escarpment crosses the northern part of the Island. In places the bedrock surface has been affected by karst processes particularly in areas above the level of the Nipissing transgression where the land surface has been exposed for approximately 11,500 years. Karst features and alvars appear to be best developed in rocks of the Amabel Formation along the crest of the Niagara Escarpment.

Evidence of the direction of glacier flow that affected Cockburn Island is primary from the orientation of streamlined forms, in particular drumlins. Three distinct sets of drumlins have been recognized. The drumlin orientation does not necessarily reflect flow during two or multiple glacial advances. The variation in orientation of the long axis of the drumlins, the south-southwest flow around the eastern shore of the island, southern flow in the central part of the island and the south-eastward flow the western shore, may reflect ice flowing around the island along the inter-island channels at a greater speed than that flowing over the higher areas of the island.

Drumlins are commonly associated with till. Till is widespread across the island and occurs commonly as poorly-drained till plains, littered with boulder (lags). In addition, to till and its associated landforms, other surface landforms and sediments include a large hill of sand and gravel covered with till (McCaigs Hill), and two long ridges of gravel of probable ice-contact origin.

Emphasis in this report has been placed on the Post-glacial shoreline features of Glacial Lake Algonquin and subsequent glacial and post-glacial lakes that greatly affected the landscape of Cockburn Island. The record of ancestral lake levels in the Lake Huron basin on Cockburn Island appears complete including the highest level of glacial Lake Algonquin (Main) through a series of falling glacial lake and post-glacial lake levels. These ancestral lake levels have created a spectacular record of abandoned shore bluffs, beach ridges and bars.

Extensive areas of surface sand and gravel deposited in ice marginal or subglacial settings and the karst terrain along the crest of the Niagara Escarpment are the main areas of groundwater recharge on Cockburn Island.

INTRODUCTION

Purpose

This report presents information on the distribution and characteristics of the surface sediments and landforms that occur on Cockburn Island. The information contained herein will be useful as a basis for future soil mapping, vegetation studies, environmental and ecological investigations. Particular attention was paid to the excellent series of abandoned shorelines that occur on Cockburn Island.

Location, Access and Topography

Cockburn Island is an island located between Lake Huron and the North Channel of Georgian Bay (**Fig. 1**). It is about 3 km west of Manitoulin Island, separated from it by the Mississagi Channel and it is located approximately 2.5 km east of Drummond Island, Michigan, USA, separated from it by the False Detour Channel.

Figure 1: Location Map of Cockburn Island within the northern basin of Lake Huron (source: Google Maps).

Cockburn Island is approximately 171 km^2 in area and the total relief of the island about 136 m (**Fig. 2**). Two broad, prominent NW-SE trending ridges rise above the surrounding landscape of the island (**Fig. 2**). Local relief along the two ridges is approximately 20 m along the southernmost ridge and 55 m along the northernmost ridge. Both of these ridges appear to be composed entirely of glacial sediments. The island has few permanent residents but rises to about 200 residents in the summer and fall. Access to the island is either by water or air. There is one private airfield on the island.

Present Survey

The field work for this survey was carried out in June 2017, November 2019 and in June 2022. Field observations were made of natural exposures, artificial excavations, test pits and primarily hand auger samples. This was accomplished by vehicle traverse of all accessible roads and trails, supplemented by foot traverses. These observations were supplemented by the study of remotely sensed data including conventional air photographs (1:70 000 scale), two sets of digital ortho-photographs (leaf on, United States Geological Survey Earth Explorer and leaf off, Ontario Ministry of Natural Resources and Forestry COOP imagery) and a Digital Elevation Model (DEM) created by the Ontario Ministry of Natural Resources and Forestry. In some of the more remote areas of the island, map unit boundaries become more subjective where they are based solely on the interpretation of remotely sensed data with little or no ground checking.

Information was collected on landforms and sediment types, their properties and distribution. A total of 367 field observations were collected throughout the island. This information was integrated with the interpretation of remotely sensed data, including conventional air photographs, two sets of digital ortho-photographs (leaf on and leaf off) and a Digital Elevation Model to create the surficial geology map of Cockburn Island. Additional information presented on the map and included in the report has come from other, previously published, maps, reports or interpreted from digital files. For example, outcrop locations from Wolf (2006) in addition to those identified by the author from digital air photographs are displayed on the map. Also drumlin locations and orientations of Chapman and Putnam (1984) were compiled with drumlins interpreted from bathymetry images created from LiDAR data by Fisheries and Oceans Canada (2020a, b).

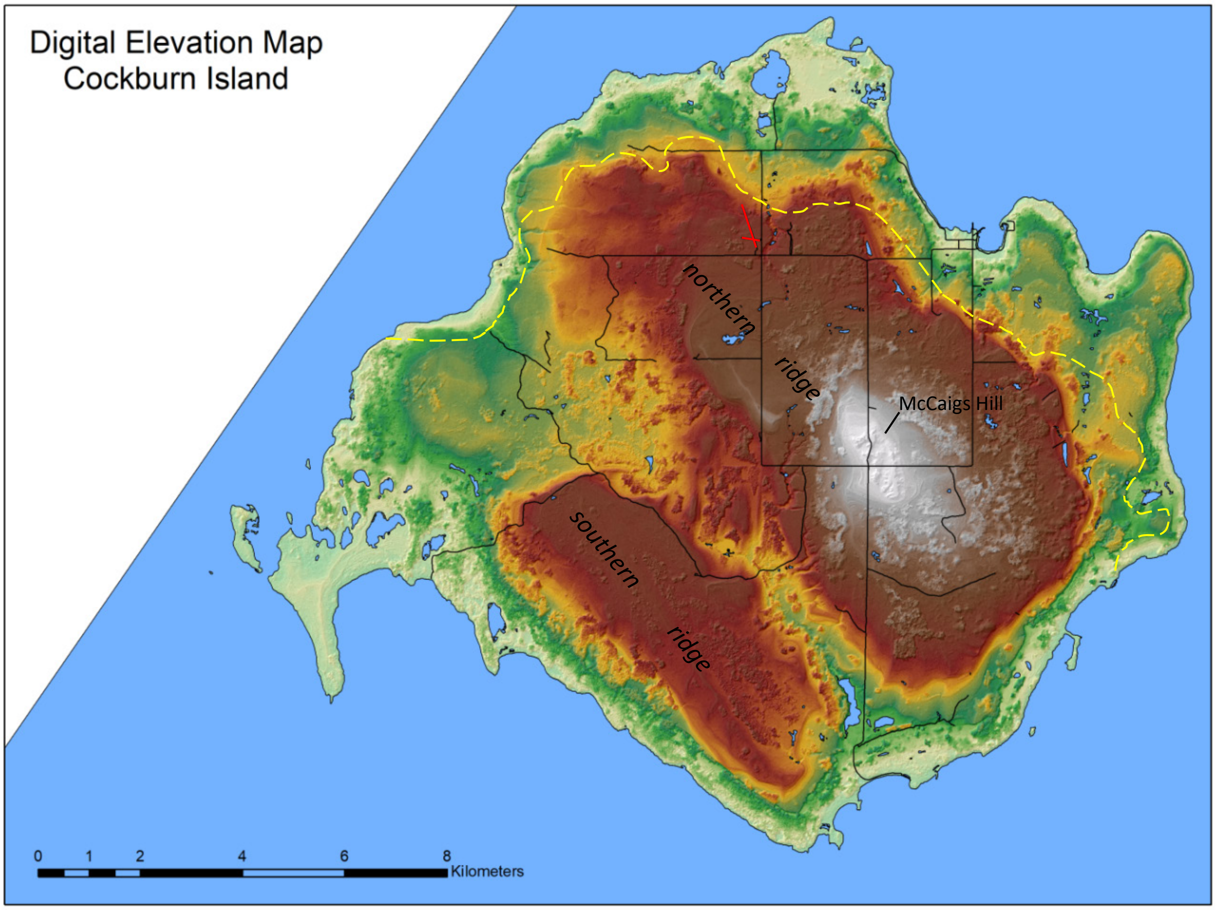

Figure 2: Digital Elevation Map (topographic map) of Cockburn Island. Colour ramp for map: Light Green (~172 masl) to White (~313 masl); yellow dashed line is approximate position of the Niagara Escarpment (from Wolf 2006), roads in black, airfield in red. (Ontario Ministry of Natural Resources and Forestry 2017).

Acknowledgments

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The author would like to thank former colleagues from the Ontario Ministry of Natural Resources and Forestry and the Ministry of Northern Development and Mines for their assistance in acquiring some of the remote sensing data used in this study. John Dodge helped create the polygon coverage and geodatabases and Matt Pyne created the map layout. The author also appreciates Dr. D.R. Sharpe and the other staff of the Geological Survey of Canada with their review and assistance in publishing this Open File. Every possible effort was made to ensure the accuracy of the information presented on the accompanying map and Open File. However, the author does not assume liability for errors that may occur. Users should verify critical information in the field.

Previous Work

Very little previous work has been undertaken on the mapping of the surficial geology of Cockburn Island. R.R. Wolf (2006) mapped the bedrock geology of the island with earlier maps made by Williams (1919), Kelley (1949), and Liberty (mapped in 1954 to 1957, published in 1972). Chapman and Putnam (1966, 1984) made a very generalized map of Cockburn Island, mentioned the similarities between St Joseph and Cockburn islands and stated that the islands "consists of morainic hills near the centres which stood as islands above glacial Lake Algonquin and which are given prominence by high bluffs which encircle them. … Below the bluffs there are broad boulder terraces, gravel beaches, and plains of deeper sands. A group of drumlins with boulder surfaces add variety to both islands." (Chapman and Putnam 1984, p.116).

Most attention paid to the glacial sediments of the island has been concentrated on the record of Glacial Lake Algonquin shorelines which was a large ice-contact glacier-fed lake that occupied parts of the Huron, Michigan and Superior great lake basins. The abandoned shorelines on Cockburn Island have been noted by Leverett (1914), Chapman and Putnam (1966) and Drzyzga (2007). Glacial Lake Algonquin existed, in one form or another, from about 13,000 until about 11,400 cal yr B.P. (Harrison 1972, Karrow et al. 1975, Karrow 2004). The level of the lake generally fell in stages during this interval of time (Harrison 1972, Finamore 1985, Karrow 2004). Drzyzga and others (2012, p.360) suggested that "observations of strandline sets of stratified shoreline features support the theory that lake levels fell in discrete stages (Lawson 1891, Leverett and Taylor 1915, Stanley 1936, Deane 1950, Hough 1958)".

GEOLOGICAL SETTING

Bedrock Geology

Cockburn Island is underlain by gently dipping carbonate (dominantly dolostone) and clastic rocks of Middle Silurian age that outcrop in a belt that rings the northern half of the island (**Fig. 3**). The Niagara Escarpment crosses the northern part of the Cockburn Island (**Fig.4**). Its crest coincides roughly with the boundary between Map Unit 13 and Map Unit 16, (Wolf 2006; *see* **Fig. 3**).

In places the bedrock surface has been affected by karst processes (solution weathering) particularly in areas above the level of the Nipissing transgression where the land surface has been exposed for approximately 11,500 years. "The Niagara Escarpment portion of Manitoulin Island and the central and northern Bruce Peninsula constitutes one of the most regionally extensive and significant dolostone karst plains in North America" (Brunton 2013, p 37-5). Cockburn Island dolostone karst plains would be an extension of this area. Karst processes appear to be better developed in rocks of the Amabel Formation (Unit 16, **Fig. 3**). On the exposed or thinly covered bedrock plains, alvars have developed and occur at several locations on Cockburn Island (Map Unit 1a, *see* Surficial Geology Map of Cockburn Island, **Fig. 15, oversized figure**). One example is displayed in Photo 2 where the road north from Sand Bay (15^{th} Sideroad) intersects the road to the First Nation Reserve (12^{th} Concession Road). Here grikes, solution weathered joints, in the carbonate bedrock and clints, the intervening blocks, are well developed (karst features; **Fig.5**). The grikes appeared to extend to depths of about 2 m at this site. Elsewhere on the Island, glacial and non-glacial sediments of various thicknesses cover the bedrock surface. The cover of glacial sediment likely exceeds 85 m (275 feet) in the central part of the Island beneath McCaigs Hill, based on borehole records drilled to bedrock (*see* Wolf 2006).

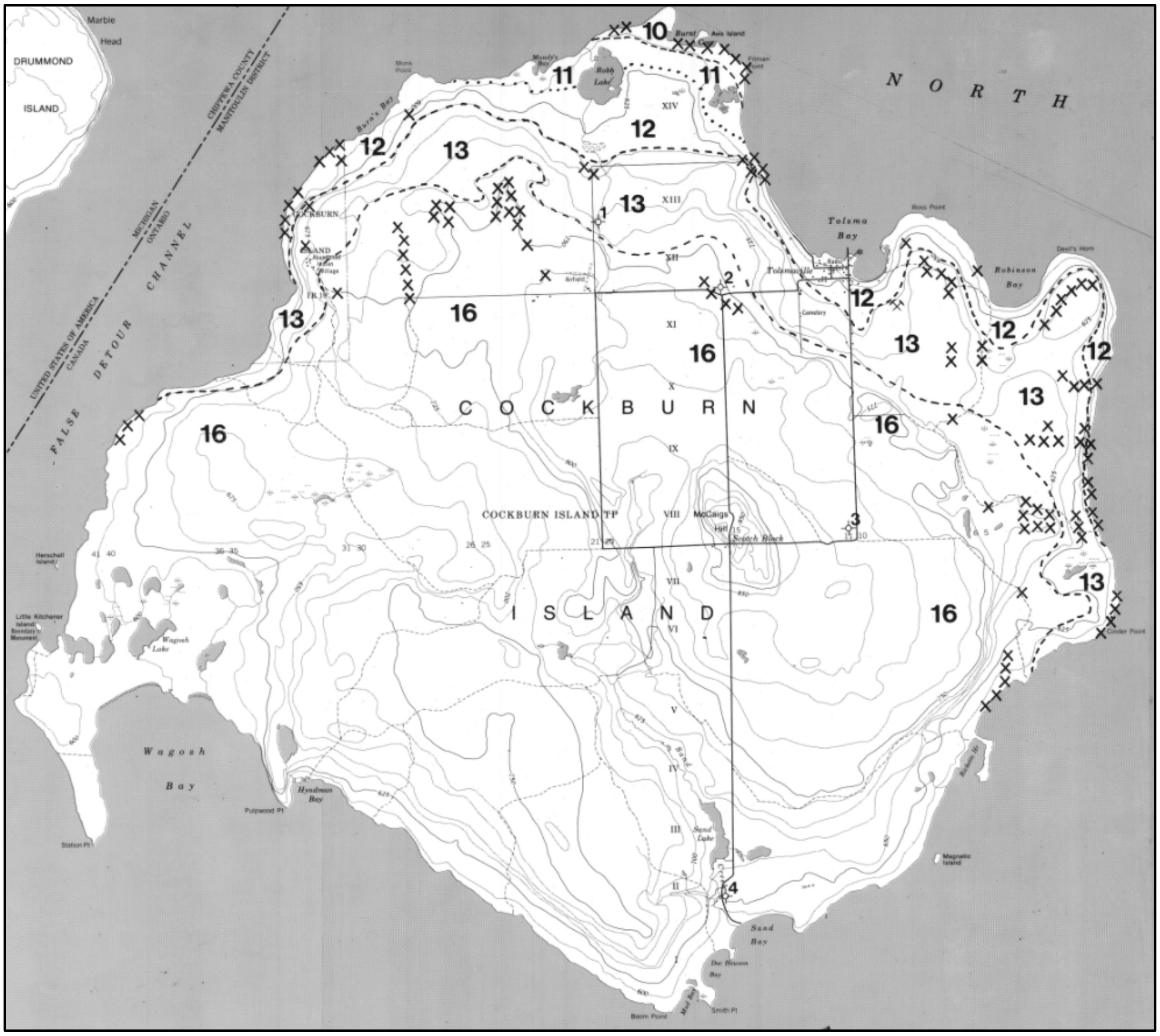

Figure 3: Bedrock geology of Cockburn Island (Wolf 2006). Legend: 10-Dyers Bay Fm, 11-Wingfield Fm, 12 St. Edmunds Fm, 13-Fossil Hill Fm. and units 14- to 16-Amabel Fm.

Figure 4: Small waterfall flowing over the stepped surface (bedding) developed in the Fossil Hill Formation along the face of the Niagara Escarpment on Cockburn Island. Photograph by P.J. Barnett. NRCan photo 2023-295

Figure 5: An alvar exhibiting grike and clint features of a karst landscape. Photograph by P.J. Barnett. NRCan photo 2023-296

The Cockburn Island Landscape

Cockburn Island is somewhat unique in the northern Lake Huron-Georgian Bay basin, in that, it's overall topography and relief is dependant mainly on glacial sediments rather than the bedrock surface. It is very similar to St. Joseph Island to the west where the central core of that island is composed of glacial sediments (Karrow 1991). Most islands, like Manitoulin Island, have their topographic high areas underlain by bedrock. In general, surface sediments on Cockburn Island include till that occurs mainly as till plains that are commonly poorly-drained and littered with boulders (lags) or as drumlins and till forms the surface sediment on McCaigs Hill. Gravel of probable ice-contact origin occurs in two large hills or ridges on the island. Additional landforms include features of ancestral levels of Lake Huron; abandoned shore bluffs, gravel and sand beach ridges and sand and clay plains. Sand dunes have developed where sands have been disturbed by wind and wetlands have developed in local topographic low areas.

That is not where the similarities between Cockburn Island and St Joseph Island end. The "Mountain", the central and highest point on St. Joseph Island is capped by till that overlies thick sand deposits (Karrow 1991). This relationship can also be observed at McCaigs Hill on Cockburn Island. In addition, both hills have been altered extensively by wave and current action of glacial and postglacial lakes resulting in well-developed shoreline features and deposits that ring the central hills of St Joseph and Cockburn Island. The uppermost elevations of both islands were not inundated by post-glacial lakes during and following deglaciation. As a result, Cockburn Island contains an almost complete set of glacial Lake Algonquin shorelines which have developed, for the most part, in glacial and non-glacial sediments; not influenced by the bedrock surface. However, "the widespread submergence of the island by glacial and postglacial lakes tend to smooth and conceal [the original] glacial topography" (Karrow 1991, p.17) making deciphering the original glacial landforms and history difficult.

Regional evidence of glacier flow patterns

The surface of Drummond Island, located immediately west of Cockburn Island, contains numerous glacial streamline landforms, in particular, drumlins. The orientation of the drumlins varies across the island with a general south to south-southwest trend of their long axis in the area north of the Niagara Escarpment (averaging 195° N. AZ., ranging between 180° and 206°, n=23), and shifting to a slightly more southerly orientation south of the Niagara Escarpment (averaging 188° N. Az., ranging between 170° and 203°, n=27). In the very south-western part of the Drummond Island, the streamline forms are oriented similar to the forms north of the Niagara Escarpment or are oriented slightly to the south-southwest. This change in orientation westward is even more pronounced on the very eastern tip of the Upper Peninsula mainland to the east of Drummond Island in the area east of Saint Vital Point (averaging 222° N. Az., ranging between 209° and 246°, n=6). The pattern suggests a fanning out of the glacier flow as it entered the Lake Huron basin.

Saint Vital Point is a ridge that extends out into Lake Huron and appears to mark the location of a former ice margin of the Laurentide Ice Sheet. This former ice margin, or moraine, can be traced north-westward where it has been previously named the Kinross moraine by Leverett (1929). It separates two distinct drumlin fields: the drumlins of Drummond Island to the north and east of the moraine and the Les Cheneaux Islands drumlins, southwest of and beyond the moraine. Les Cheneaux Islands drumlins are oriented to the southeast, 125° to 130° N. Az. near Cedarville, Michigan (Russell 1905). This moraine is an end moraine of the Algoma lobe generally sourced from the north or northeast (Karrow 1987, 1991). The area beyond the moraine to the west and south was last affected by the Superior lobe (Karrow 1987, 1991). The drumlins of Les Cheneaux Islands are composed of till that is "rather compact and clayey and has a reddish color" (Leverett 1929, p.47).

The Kinross moraine may be the correlative of the Watton moraine that was described by Peterson (1986) that was built at the maximum extent of his “advance III”. The moraine is inferred to extend east across the area south of the Huron Mountains and then southeast towards the north end of Green Bay where it bends northward. It is then mapped to the east across the Upper Peninsula of Michigan, however Peterson continues it northward (Peterson 1986, his Figure 1). It is possible however, that the ice margin continued along the Kinross moraine and eastward into Lake Huron at Saint Vidal Point and extends south of Drummond Island.

The streamline forms of Drummond Island extend into and below Lake Huron for a distance of a few km up to 10 km south of the present shoreline. High resolution multi-beam bathymetry surveys done off-shore near Scammond Cove (Riley et al. 2014, Binder et al. 2014, 2018) display the occurrence of two sets of drumlins; a set of large drumlins, presumed older, oriented toward the southwest (averaging 201° N. AZ., ranging between 195° and 204°, n=9) and a finer set of drumlins, likely younger, oriented slightly east of south (averaging 174° N. AZ., ranging between 165° and 181°, n=13).

Peterson (1986) suggested that the ice position of the Watton moraine may have an age of about 11,000 years B.P. (~13,000 cal. yr. B.P.) and Karrow (1991) working on St Joseph Island concluded that deglaciation of the region occurred between the Onaway Advance (~13,000 cal. yr. B.P., equivalent of Advance III of Peterson 1986) and the Marquette Advance (~11,500 cal. yr. B.P.). Cockburn Island was likely deglaciated during the same interval of time.

Prior to this survey, only a set of north-south oriented drumlins (averaging 183° N. AZ., ranging between 181° and 184°, n=4) had been reported on Cockburn Island (Chapman and Putnam 1984). However, in the southwest part of the island near Wagosh Lake, based on air photo interpretation, there appears to be another set of drumlins that are oriented to the south-southeast (averaging 163° N. AZ., ranging between 163° and 175°, n=3). These two sets of drumlins are separated by a ridge of gravel that extends north-westward from Sand Bay (southern ridge, **Fig. 2**).

The striation record on Drummond Island indicates ice flow toward the southwest and west-southwest; different than the ice flow directions indicated by the streamline forms. The striations likely represent older ice advances in the area. The older set of drumlins oriented to the southwest that occur off-shore of Drummond Island may have formed during the time of the striations. On Cockburn Island, no striation data has been recorded, however they are more likely to be preserved on outcrops of bedrock below the level of the Nipissing Great Lakes (Barnett 2016).

Summary of glacial and post-glacial lake history in the Huron and Georgian Bay basins[1]

As the Laurentide Ice Sheet margin receded, Glacial Lake Algonquin, a large ice-contact glacier-fed lake, occupied parts of the Huron, Michigan, Superior and Georgian Bay basins. It existed, in one form or another, from about 13,000 cal. yr. until about 11,400 cal. yr. B.P. (Harrison 1972, Karrow et al. 1975, Karrow 2004, Rabett et al. 2019). The level of the lake generally fell in stages during this interval of time (Harrison 1970, 1972, Finamore 1985, Karrow 2004). Drzyzga and others (2012, p.360) suggested that “observations of strandline sets of stratified shoreline features support the theory that lake levels fell in discrete stages (Lawson 1891, Leverett and Taylor 1915, Stanley 1936, Deane 1950, Hough 1958)”.

[1] Parts of this summary was taken from a previous report written by the author “Barnett, P.J., 2016. Post glacial shoreline features of Misery Bay Provincial Park, Manitoulin Island, unpublished report submitted January, 2016 for Ontario Parks, Northeast Zone Office, Sudbury, Ontario.”

The abandoned shorelines of Cockburn Island have been noted by Leverett (1914), Chapman and Putnam (1966) and Drzyzga (2007). The following stages have been recognized with their suggested outlets (Rabett et al. 2019) given in brackets: the highest or Main phase of glacial Lake Algonquin; an Upper Group of shorelines, Ardtrea (Fenelon Falls) and Upper and Lower Orillia (Port Huron?) that were initially mapped by Deane (1950) in the Barrie area of Ontario; and a Lower Group of shorelines consisting of the Wyebridge (South River), Penetang (Genesee), Cedar Point (Fossmill), Payette (Sobie-Guilmette) phases followed by the Sheguiandah (Mink Lake) and Korah (Windigo Lake) phases that drained through various channels in the North Bay area. The Payette lake phase has been assigned an age of c. 10, 480 cal B.P. based on AMS 14C dating and cryptotephra chronology (Rabett et al. 2019).

Following the Lower Group phases of glacial Lake Algonquin, about 9, 500 and 8, 400 cal. yr. B.P. (Rabett et al. 2019) water levels in the Huron basin fell below present-day level of Lake Huron and eventually reached an elevation of approximately 122 m below Lake Huron level (Hough 1958). This occurred as a result of the Laurentide Ice Sheet margin receding north of the Continental Divide and its meltwater by-passing the Upper Great Lake basins combined with dry, early Holocene climate (Edwards et al. 1996, Booth et al. 2002, 2005, McCarthy et al. 2015) creating a situation in that a low supply of water was delivered into the Huron and Georgian Bay basins. Low stands of Lake Stanley (Huron) and Lake Hough (Georgian Bay) formed that were closed basin lakes; no rivers draining them towards the sea. Water levels fell, probably 25 to 30 m below the level of the controlling sill, the North Bay outlet (Lewis et al. 2008a, b). These events are supported by the occurrence of tree stumps in growth position now occurring below the present day level of Lake Huron and Georgian Bay (Blasco 2001). In situ tree stumps have been recorded at several localities around Lake Huron and Michigan (Chrzastowski et al. 1991, 1992, 1994, Lewis and Anderson 1989, Hunter et al. 2006, Karrow et al. 2007). In addition, topographic highs within the Huron basin, like the Alpena-Amberley ridge, provided hospitable environments and migration pathways for caribou and also provided areas for setting up blinds and drive lines for hunting caribou (Lemke 2015, McCarthy et al. 2015, O'Shea 2015, and Sonnenberg 2015).

With the continuing glacial isostatic adjustment, the outlet at North Bay began to rise relative to other parts of the basin. Water levels within the Huron and Georgian Bay basins began to rise from the low-stand levels from about 8,300 and continued to 5,760 cal. yr. B.P. River valleys that were eroded down to the low water levels became flooded and infilled with sediment during the transgression (Karrow et al. 2007). Water level continued its slow rise until the Nipissing Great Lakes formed about 4 m above the current level of Lake Huron at Port Huron, Ontario (Baedke et al. 2004). This lake drained through three outlets; North Bay, Des Plains River at Chicago and at Port Huron. The Nipissing beaches "are among the strongest and most spectacular shoreline features of any age in the Great Lakes region" (Hough 1958, p.249-250). They appear "remarkably fresh and undissected, but are built on dissected topography in many places" (Hough 1958, p.250).

Eventually, the North Bay outlet was abandoned as a result of differential uplift and waters from this lake drained southward. The Nipissing Great Lakes level ended when down cutting occurred within the Port Huron outlet and the Algoma phase began (Hough 1958). There were four periods of relatively long-lived post-glacial high water levels in the Michigan and Huron basins. The first related to the post-glacial Nipissing Great Lakes (6,000 to 3,700 cal. yr. B.P.) and in particular, the peak Nipissing phase (4,500 cal. yr. BP), followed by the Algoma phase (2,300 to 3,300 cal. yr. B.P.) and two unnamed high phases (1,100 to 2,000 cal. yr. B.P. and 0 to 800 cal. yr. B.P.; Thompson et al. 2004). During the first of the two unnamed phases water level in the Huron basin was actually higher than during the preceding Algoma phase.

SUMMARY OF FINDINGS

Sub-till Sediments

The oldest sediments observed to date consist of stratified sand and sandy gravel deposits that occur beneath till at McCaigs Hill. This hill is a prominent flat-topped hill and the highest point of the island (**Fig. 2**). Based on observations of nearby road cut exposures, up to 5 m of till cover the hill's surface and the remainder of the hill is composed of sand that appears to coarsen with depth. Where the till layer is absent, boulders occur in the upper layers of sand and at the surface. McCaigs Hill is interpreted to be an ice marginal feature, likely a subaqueous fan that was subsequently overridden by a minor fluctuation of the glacier. Subsequent action of waves and currents of the various phases of glacial Lake Algonquin severely altered the slopes of this original landform. Beyond McCaigs Hill to the northwest, a boulder gravel ridge extends north-westward from the base of the hill towards the airport and may have formed along the same ice margin (northern ridge, **Fig. 2**). In this area the original landform appears to have been totally planed off by waves of ancestral lakes.

Another ridge of gravel extending from near Sand Bay to the west-northwest may also have formed along a former ice margin (southern ridge, **Fig. 2**). It may have originally been a series of coalescing subaqueous fans. A small feeder system (esker) was observed at the northern end of the ridge. Sediments deposited in subaqueous fans tend to coarsen downward from silts and sands near surface to boulder gravel at depth or in their cores (Shaw 1985). The original landform, however, has been totally altered by waves and currents of falling glacial Lake Algonquin phases. Beach ridges are now superimposed on the surface of the feature that appears to be composed of boulder gravel. The upper fine sediment components have likely been removed leaving their gravelly core exposed on surface. The removed fines appear to have been transported and deposited as lake-basin sediments in adjacent low areas, like the valley of Sand Creek; later to be eroded by streams, transported and re-deposited.

Till

As mentioned previously, till overlies the ice-contact stratified sediments of McCaigs Hill. It is brown, massive, very sandy silt containing granules, pebbles, cobbles and boulders (till). Several boulders were strewn across the surface of the plateau. One bullet-shaped boulder was striated on the top. Bullet-shaped boulders are indicative of the lodgement process of deposition or being deposited from the base of an actively flowing glacier. The direction of the striations on the top of boulder were 195° N. Az. and similar to nearby drumlin orientation in the central part of the island (**Fig. 6**, *see* **Fig. 15, oversized figure**).

The matrix of the till observed elsewhere on the island ranges from silty, very fine to fine sand to clayey silt. It occurs beneath poorly-drained and boulder strewn plains below the northern and eastern flanks of McCaigs Hill. The till plains occur lateral and adjacent to the aprons of sand and gravels (glaciolacustrine beach and near shore deposits) and sand plains (glaciolacustrine coarse-grained basin deposits) that encompass McCaigs Hill. The generally poorly drained plains are underlain by thin sand deposits resting on till or till and extend laterally to the top of the shore bluffs formed by either Glacial Lake Penetang or Cedar Point or the Nipissing Great Lakes that ring the entire island (*see* **Fig. 12**). Exceptions to this are the area of the western extension of McCaigs Hill and the southern ridge extending from Sand Bay to the west-northwest (**Fig. 2**). At one site south of McCaigs Hill, an occurrence of red, massive, clayey silt till containing granules, pebbles, cobbles and boulders was encountered. Numerous Jasper conglomerate boulders were in the vicinity. The reddish colour and the Jasper conglomerate boulders suggest a possible source of this till to the northwest.

Drumlins were identified on air photographs in the extreme southwest corner of the Island that are oriented northwest to southeast. However, to date, the sediment composing them has yet to be observed by the author.

North-south oriented drumlins locate to the west-southwest of McCaigs Hill have been reported by Chapman and Putnam (1966. 1984) but unfortunately the sediment making up these landforms has also not been described except that they are reported to be covered by boulder lags.

As mentioned above, prior to this survey, only one set of drumlins, oriented north-south (averaging 183° N. AZ., ranging between 181° and 184°, n=4) had been reported on Cockburn Island (Chapman and Putnam 1984). However, in the southwest part of the island near Wagosh Lake based on air photo interpretation there appears to be drumlins that are oriented to the south-southeast (averaging 163° N. AZ., ranging between 163° and 175°, n=3) . These two sets of drumlins are separated by a ridge of gravel that extends north-westward from Sand Bay (south ridge, **Fig. 2**).

Both these two sets of streamline forms (drumlins) extend into and below Lake Huron for a distance of a few km up to 7 km south of the present shoreline (**Fig.6**). They are visible on bathymetry images created from LiDAR data by Fisheries and Oceans Canada (2020a, b). The one set of drumlins in the off-shore is oriented south-southeast (averaging 172° N. AZ., ranging between 162° and 177°, n=11); similar to the south-southeast set of drumlins on-shore. The north-south oriented drumlin set appears to extend beneath the ridge of gravel to about a kilometer off-shore (oriented between about 177° and 183° N. AZ. n=4). An additional set of streamline forms (drumlins) is visible in the off-shore at the south-eastern end of the Cockburn Island (Fisheries and Oceans Canada 2020a, b). This set is oriented south-southwest (averaging 199° N. AZ., ranging between 190° and 213°, n=19).

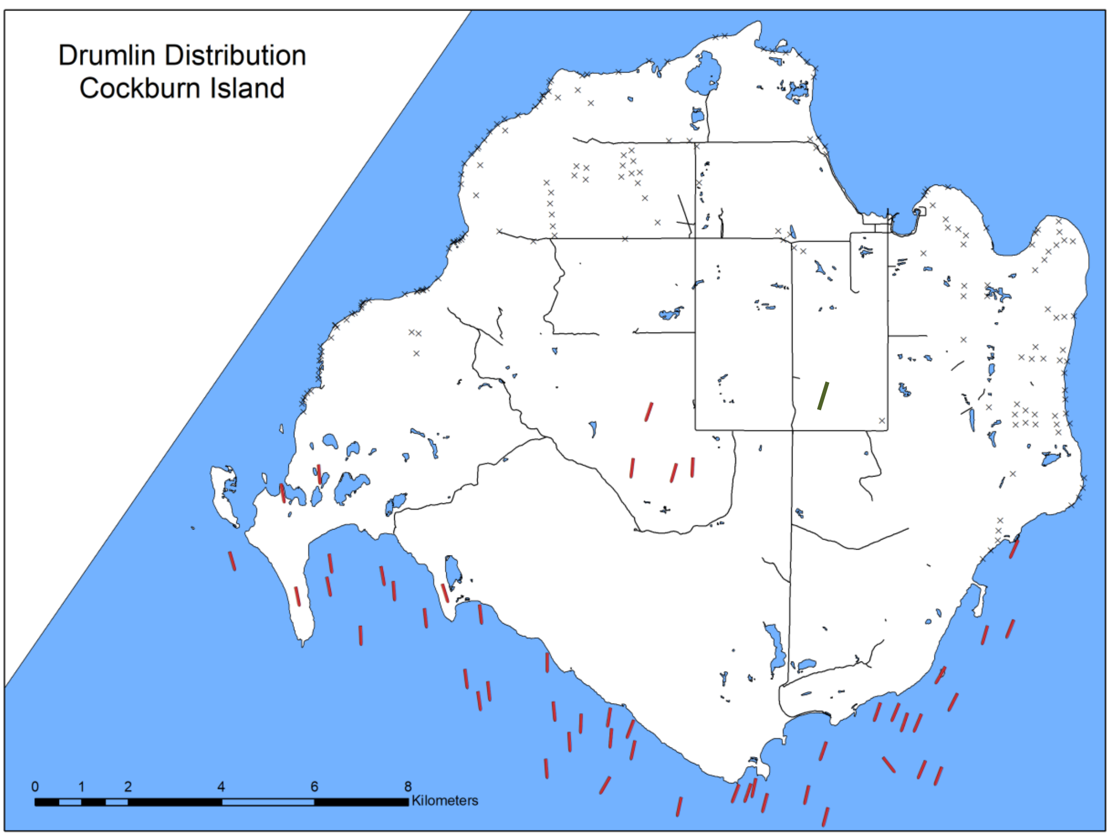

Figure 6: Distribution and orientation of drumlins (red lines) and the bullet-shaped boulder (green line) on Cockburn Island.

The drumlin orientation (**Fig. 6**) does not necessarily reflect flow during two or more glacial advances. The variation in orientation of the long axis of the drumlins, the south-southwest flow around the eastern shore of the island and the south-eastward flow along the western shore, may reflect ice flowing around the island along the inter-island channels at a greater speed than that flowing over the higher areas of the island; flow expansion into the Lake Huron basin and divergent flow when exiting the inter-island channels.

Glaciolacustrine (Glacial Lake) Deposits and Features

The very top of McCaig Hill was not inundated by post-glacial lakes and stood as an island in glacial Lake Main Algonquin during deglaciation. The flanks of the hill are highly notched (**Fig. 7**), terrraced and ringed by linear ridges of sand and gravel (**Fig. 8**). Gullying is also pronounced around the upper slopes of the hill above the limit of glacial lake inundation (**Fig. 9**). The island grew in area as the subsequent lower levels of glacial Lake Algonquin phases occurred. A series of paleogeographic maps have been created to illustrate the growth of the island at various stages of glacial Lake Algonquin and to delineate the various beach ridges and features that occur on Cockburn Island (*see* **Fig. 12a-f**). Paleoeographic maps were created for the Main Phase of glacial Lake Algonquin; Upper Group of shorelines, Ardtrea and Upper and Lower Orillia and the Lower Group shorelines consisting of the Wyebridge, Penetang, Cedar Point, Payette phases. Paleogeographic maps for the subsequent lower phases, Shequiandah and Korah phases were not created but shoreline features of these lakes may occur in the northern part of the island between the altitudes of the Payette Phase of glacial Lake Algonquin and Nipissing Great Lakes shoreline features.

Beach ridges and shore bluffs of glacial Lake Algonquin phases display well on the hillshaded COOP DEM (OMNRF 2017). **Figure 9** is an example of a hillshaded DEM of the southern part of McCaigs Hill. It displays the flat till covered surface of McCaigs Hill, the extensive gullying along the hills flanks and the steep shore bluff (Photo 3) that marks the limit of glacial Lake Main Algonquin on Cockburn Island. Extensive shoreline features can be seen below the main shore bluff of glacial Lake Algonquin on this image (**Fig. 9**).

Figure 10 is an annotated version of **Figure 9**. The shoreline features of the Main phase and Upper Group shorelines of glacial Lake Algonquin are marked and a cross-section of the southern slope of McCaigs Hill occurs as the inset on Figure 6. Shoreline elevations of glacial Lake Main Algonquin, Ardtrea, Upper Orillia and Lower Orillia phases are identified. On the cross-section it can be seen that as has been suggested previously in the literature that distinct drops in water level occurred between each named lake phase (Lawson 1891, Leverett and Taylor 1915, Stanley 1936, Deane 1950, Hough 1958, Drzyzga et al. 2012; marked by arrows on insert **Fig. 10**). However, it can also be noted on the profile that during several of the Upper Group phases, multiple beach ridges formed in response to glacial isostatic adjustment.

Extensive deposits of sand and gravel were deposited within the series of beach ridges and inter-ridge swales that surround McCaigs Hill. Extensive shoreline features and deposits also occur on and surrounding the other ice-marginal ridges that occur on the island. The upper fine sediment components of these ridges likely have been removed by waves and currents within glacial Lake Algonquin leaving their gravelly core exposed on surface. The fines that may have been removed appear to have been transported and deposited as lake-basin sediments in sand plains and terraces deposited in the adjacent low areas, for example, the valley of Sand Creek; later to be eroded by streams, transported and re-deposited.

Figure 7: Abandoned shore bluff and beach bar of glacial Lake Main Algonquin along the south side of McCaigs Hill. Beach bar surface is beneath the thin blanket of snow. Photograph by P.J. Barnett. NRCan photo 2023-297

Figure 8: Four gravel beach bars of glacial Lake Algonquin phases crossing Sand Bay Road (15th Sideroad) south of McCaigs Hill. Photograph by P.J. Barnett. NRCan photo 2023-298

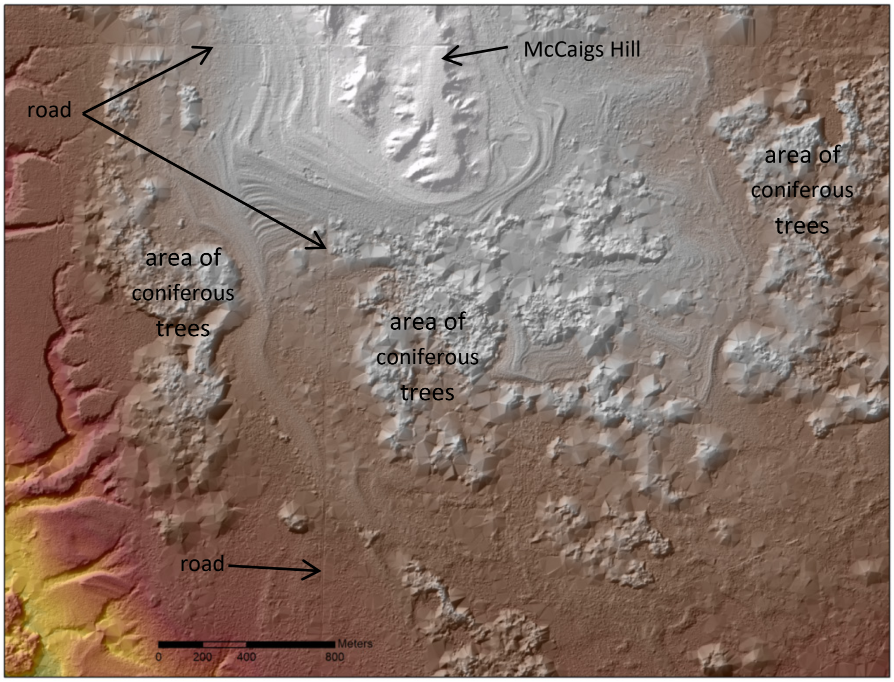

Figure 9: COOP DEM (OMNRF 2017) for the southern part of McCaigs Hill, Cockburn Island. The DEM was created from leaf-off digital ortho-photographs making ground surface features visible not only within cleared fields but also beneath deciduous forests. Data in areas of coniferous forests is essentially the elevation of the tree tops not the ground surface. Roads are also visible on the imagery.

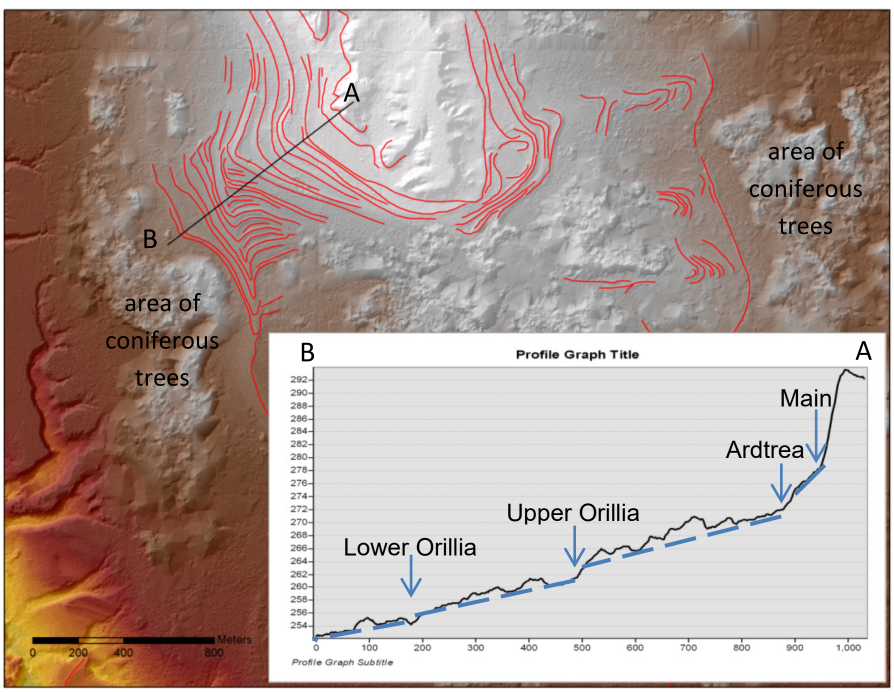

Figure 10: Main and Upper Group shorelines (red lines) of glacial Lake Algonquin, at the southern end of McCaigs Hill, Cockburn Island, Ontario. Arrows on inset denote discrete drops in lake level as outlets for the lakes changed. Blue dashed lines show the former foreshore slope and gradual lake level response (drop) to glacial isostatic adjustment.

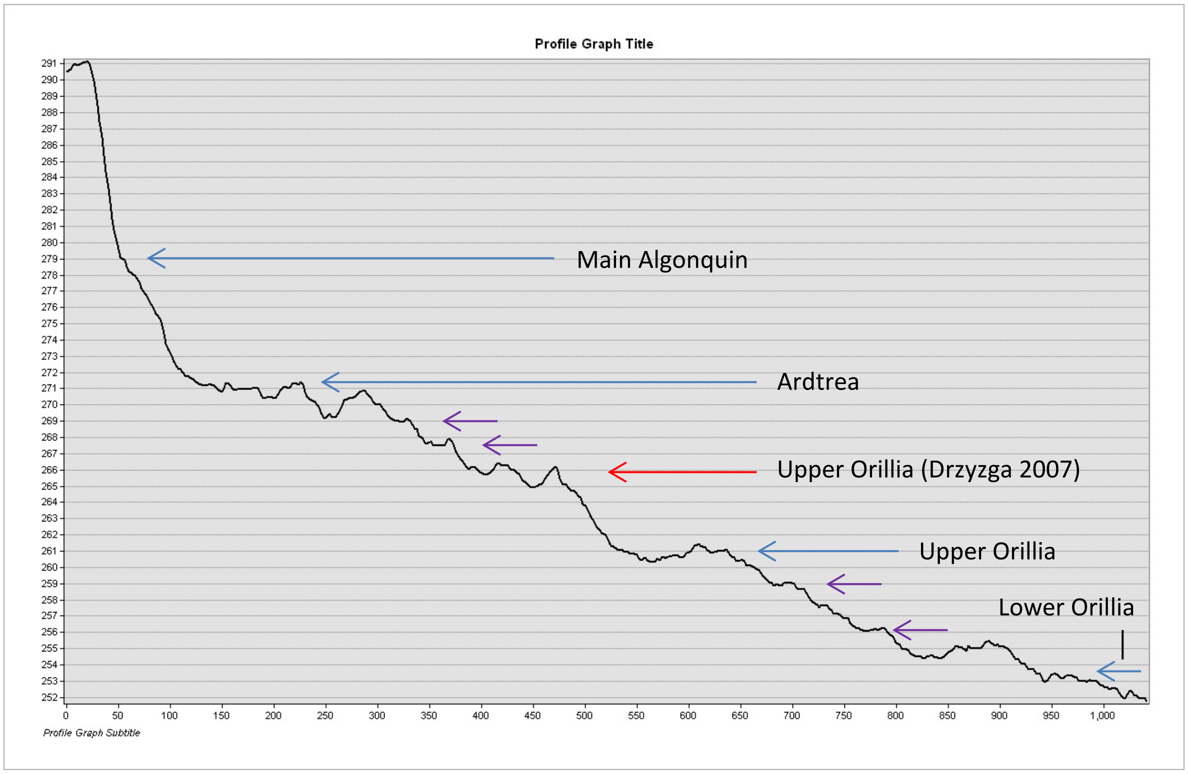

Figure 11: Profile of Main and Upper Group shorelines of glacial Lake Algonquin, at the south-western end of McCaigs Hill. Arrows mark former lake levels. Arrows mark former water levels.

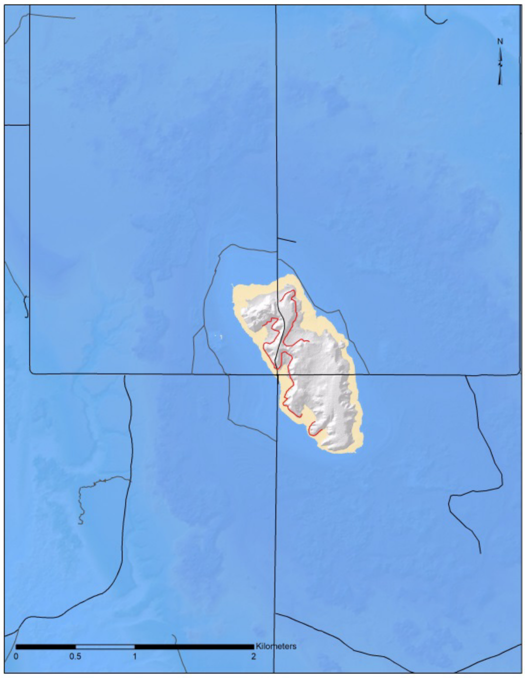

Figure 12a: Glacial Lake Main Algonquin.[2]

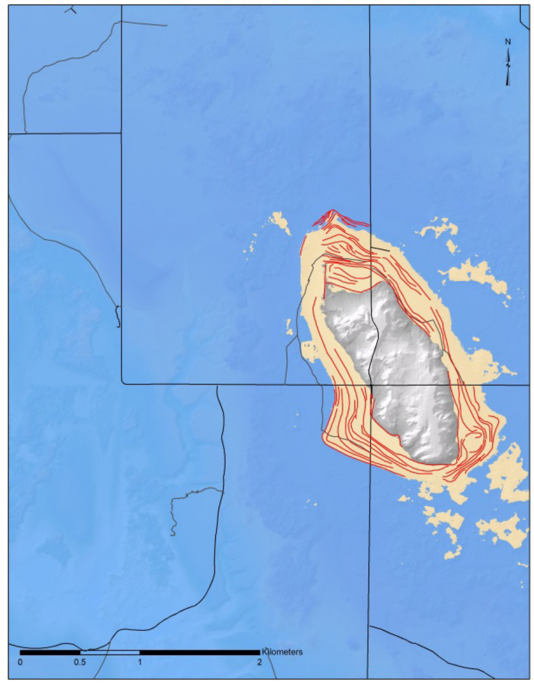

Figure 12b: Glacial Lake Ardtrea.

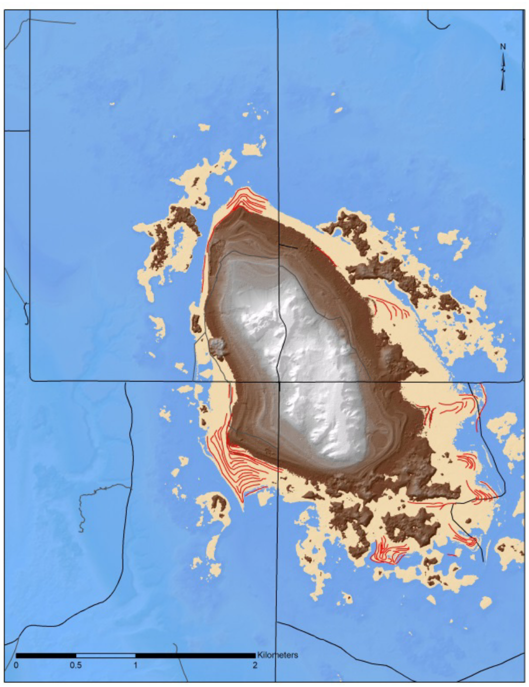

Figure 12c: Glacial Lake Upper Orillia.

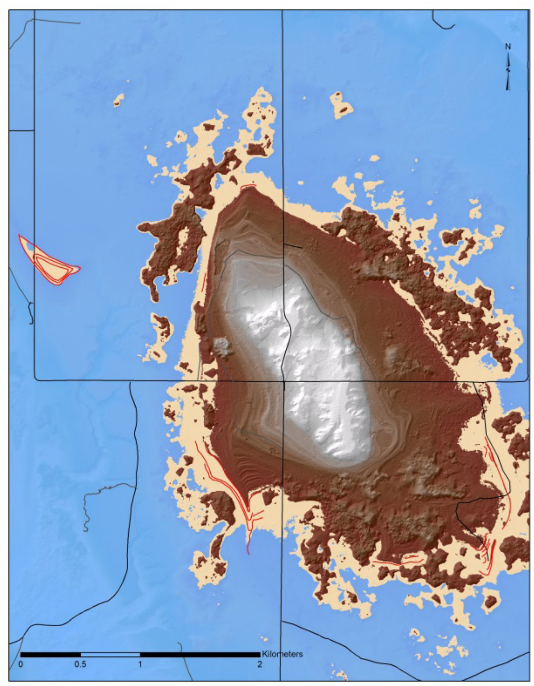

Figure 12d: Glacial Lake Lower Orillia.

[2] Legend: Blue, lake water deeper than 3m; Tan, water depths < 3m, White to brown, land area; red lines, mapped beach ridges in the area depicted.

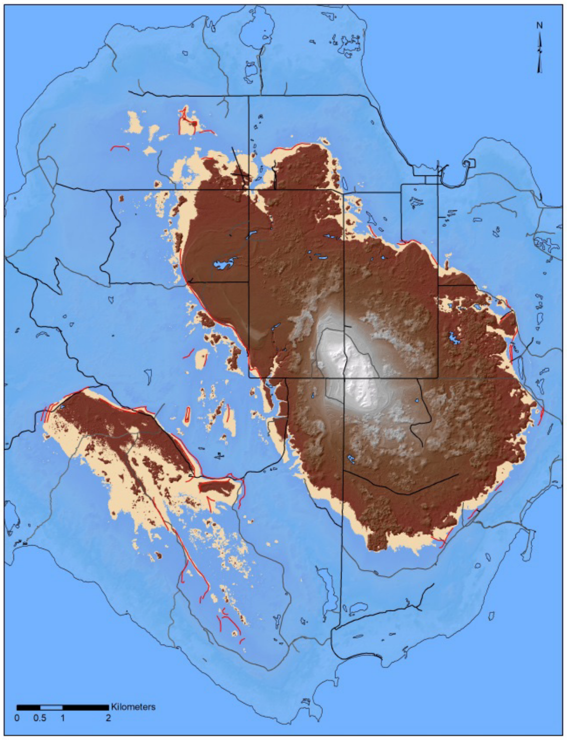

Figure 12e: Glacial Lake Penetang.

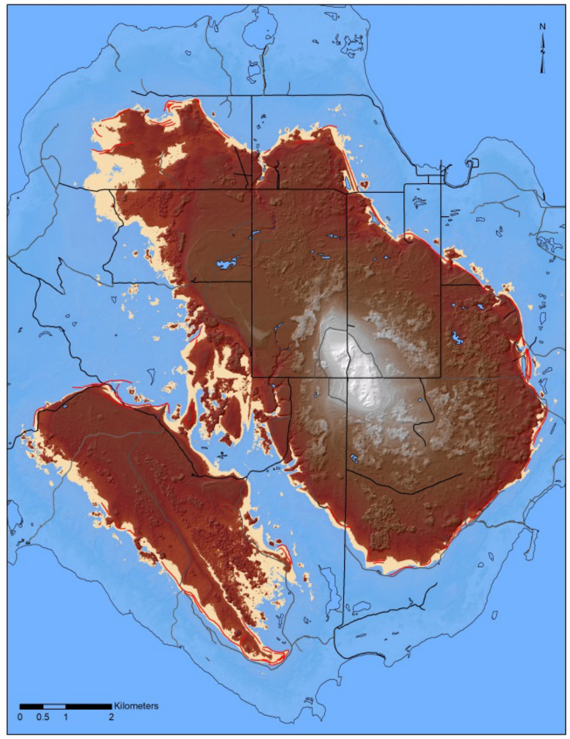

Figure 12f: Glacial Lake Cedar Point.

Glacial Lake Main Algonquin

The highest shoreline features on Cockburn Island occur at altitudes between 279 and 280 m rising to about 284 m along the northern edge of McCaigs Hill; primarily an abandoned shore bluff accompanied by a corresponding beach berm. The shore bluff is steep and prominent in the landscape. It rises between 10 and 15 m above the surrounding land surface. It encircles an island that is roughly oriented north-northwest and is about 1.5 km long and 0.5 km wide (**Fig. 11** and **12a**).

Above the bluff, till is the dominant surface material. It overlies a thick deposit of sand and gravel; probably ice-contact glaciofluvial/glaciolacustrine fan origin. The till layer was deposited below actively flowing glacier ice (subglacial) as lodgement till based on the presence of rare bullet-shaped boulders on the surface. No evidence of submergence was observed on the top of the hill.

The shore bluff is steep and well-formed because the till layer, that can exceed 5 m in thickness, creates a resistant cap above the sand and gravel core. The shore bluff slopes, however, have subsequently been gullied (box gullies) because of the relation of the different layers composing the hill.

The level of the ice-contact glacier-feed lake defined primarily by the shore bluff is likely glacial Lake Main Algonquin, the highest glacial lake that occurred within the Lake Huron basin. Drzyzga (2007) measured the altitude of this shore bluff at several locations and suggested that it occurs at an altitude of 280 +/- 0.48 m using a Differential Global Positioning System (GPS) for shoreline position and elevation. The altitudes determined by the current study, are similar to that of Drzyzga (2007) and his conclusion that the lake bluff at the base of McCaigs Hill was formed during glacial Lake Main Algonquin.

Glacial Lake Main Algonquin level has been surveyed on St Joseph Island by Leverett (1914) and Karrow (1991). Leverett (1914) measured the shore bluff to occur at an altitude of 285 m (934.56 feet) and lower features he associated with Main Algonquin at an altitude of 283 m (930.86 feet). Karrow (1991) recorded values of 280 m on the southern part of the "Mountain" up to 285 m in the north. These altitudinal values, although associated with what appears to be the highest abandoned shore bluff on St Joseph Island, are at lower altitudes than the level of glacial Lake Main Algonquin predicted from charts of Lewis and Anderson (2017) that would suggest Main Algonquin features would occur nearer to altitudes of about 290 m and at Sault Ste. Marie; at about 310 m. Cowan (1985) identified Main Algonquin shoreline features at Sault Ste. Marie at an altitude of 309 m. Leverett's (1914) and Karrow's (1991) measured altitudes for the shore bluff are closer to the predicted values of the subsequent Lake Algonquin level of Ardtrea (~280 m).

The base of the glacial Lake Main Algonquin shore bluff from the work of Drzyzga (2007) and the present study on Cockburn Island places the base of the Main Algonquin shore bluff at an altitude of approximately 280 m. The tilt of the Main Algonquin shoreline features on St. Joseph Island is about 1m/km to the northeast (Karrow 1991).

Assuming that the abandoned shoreline features are rising in altitude by 1m/km, the shoreline features on St Joseph Island that are at least 10 km north of the features on Cockburn Island (projected to the line of maximum isostatic recovery), then Main Algonquin level features should occur about 10 m higher than the same lake features on Cockburn (~290 m).

A preliminary analysis of a DEM of St Joseph Island by the author indicates that the base of several isolated escarpments occur at about 290 m where they were preserved from erosion by the next youngest glacial Lake level, Ardtrea. The author suggests that based on the above information, it is possible that the level assigned to glacial Lake Main Algonquin by Leverett (1914) and Karrow (1991) is actually the Ardtrea level and that the isostatic rebound curves of Lewis and Anderson (2017) are a reasonable predictor of glacial Lake Algonquin levels.

Upper Group Lakes

Ardtrea

The record of glacial Lake Ardtrea is well defined on Cockburn Island (**Fig. 10, 11, 12b**). It is marked by a shore bluff up to about 8 m high eroded into McCaigs Hill at an altitude of about 271 m in the south. It rises to altitudes of 272 to 273 m on the northern edge of the hill as a result of glacial isostatic adjustment. A series of storm berms or beach ridges have developed lake-ward of the shore bluff. The base of the individual storm berms decrease in altitude the farther away from the shore bluff they occur. At least six storm berms occur along the south flank of McCaigs Hill. The bases of the berms occur at altitudes of 270.3, 270, 269, 267.6, 266 and 265 m. Storm berm heights range from about 0.3 to up to 2 m high.

Drzyzga (2007) assigned the beach berm that occurs at 266 m to Upper Orillia, the next lowest phase of glacial Lake Algonquin. This berm occurs below a low (about 1.5 m high) shore bluff (**Fig. 11**) that may indicate a certain amount of erosion and possible down-cutting at the lake's outlet, it does not fall into the altitudinal spacing of either the pre-rebound shoreline altitudes of named lake levels (Scheatzl et al. 2002) or the predicted altitudes on Cockburn Island (Lewis and Anderson 2019). It is for this reason that both the 266 m and 265 m berms are included here as shoreline features of glacial Lake Ardtrea in this report.

The shoreline features associated with glacial Lake Ardtrea record a 6 m relative drop in water level of this lake during its existence. Assuming an initial rebound rate of 7.5 cm/year for the first 2000 years following local deglaciation (Passe 1997) then glacial Lake Ardtrea may have existed for about 80 years.

Below the altitude of 265 m and beyond the outermost ridge, a shore bluff occurs that is about 3.5 m high. The base of the bluff is at an altitude of about 261 m or very near to the projected water level of Upper Orillia (262 m, from Lewis and Anderson 2019).

Upper Orillia

The Upper Orillia shoreline is defined by a 3.5 m high shore bluff that can be traced around McCaigs Hill (**Fig. 12c**). At least seven storm berms or small breaks in slope occur along the south flank of McCaigs Hill. The bases of the berms or the breaks in slope occur at altitudes of 261.5, 261.3, 261, 259, 257.7, 256.9 and 256 m. Storm berm heights range from about 0.3 to up to 1 m high. There is a 5 m relative drop in water level of this lake during its existence. Following the same reasoning as above for glacial Lake Ardtrea, glacial Lake Upper Orillia may have existed for approximately 65 years.

Lower Orillia

Glacial Lake Lower Orillia is the last and lowest level of the Upper Group of glacial Lake Algonquin (Deane 1950). In the central part of Cockburn Island, its shoreline features occur at an altitude of 253 m (**Fig. 10, 11, 12d**). They ring McCaigs Hill and in addition occur around a small island of newly exposed land approximately 1 km west of McCaigs Hill. During this and during subsequent levels of glacial Lake Algonquin, at least to the Cedar Point level, multiple islands occurred.

Lower Group Lakes

The Lower Group of glacial Lake Algonquin phases consist of Wyebridge, Penetang, Cedar Point, Payette, Shequiandah and Korah that drained through various outlet channels in the North Bay area. Shoreline features of all these levels occur on Cockburn Island with some better developed than others as a result of wave and current action, fetch, substrate and time.

Wyebridge

Glacial Lake Wyebridge is the highest of the Lower Group beaches. Shoreline features range from altitudes of 237 m in the southern end of the island to about 246 m in the northern part of Cockburn Island. There was basically one main island during this lake phase as the higher parts of the northern ridge emerged. Wave and current action occurred around the island; northwest of McCaigs Hill where the top of the north ridge was being eroded and planed off and sands were also being eroded and deposited within the valley of Sand Creek to the south and northwest to the area surrounding the airport (**Fig. 2**). Several small areas of land emerged along the southern ridge during this lake phase.

Penetang

Shoreline features of glacial Lake Penetang rise from approximately 227 m in altitude in the southern part of Cockburn Island to about 235 m in the northern part of the island. Two main islands began to emerge above the waters of this lake; a large island centered on the northern ridge and a small island developed at the northern edge of the southern ridge (**Fig. 12e**). Waves and currents in this lake were impacting the remainder of the southern ridge and the western side of the northern ridge. Planning or erosion of the upper sediments of the southern ridge began during this stage and likely fines eroded from the ridge were re-deposited in the adjacent low areas.

Cedar Point

During the Cedar Point phase of glacial Lake Algonquin most of the southern ridge had emerged and nearly joined the exposed northern ridge (**Fig. 12f**). Abandoned shoreline features of this phase occur at altitudes between 220 m and 228 m from south to north across Cockburn Island. It formed a 6 m high shore bluff at the southeast end of the southern ridge and can be seen as prominent beach ridges, bay-mouth bars and spits, particularly along the eastern side of the island.

Payette

The Payette shoreline occurs between altitudes of 202 m and 212 m across the island; rising in altitude to the north. The northern and southern ridges had become one large island during this phase. Broad, shallow near shore zones developed over the bedrock plateau in the north-eastern part of the Island and on the western side of the island where deposits of sand are common.

Additional Phases

Shoreline features of the lower phases of glacial Lake Algonquin, for example Shequiandah and Korah, were not recognized with confidence during this survey. For the most part, shorelines of both these lakes likely occurred below the level of the Nipissing Great Lakes and were likely destroyed by the Nipissing transgression. There are possibly a couple of Shequiandah shoreline features in the northern part of the island occurring at an altitude above the Nipissing Great Lake shoreline features due to differential glacial isostatic adjustment. These possible Shequiandah shore features occur at an altitude of about 200 m.

A well-developed shore bluff along the southern ridge occurs at an altitude of approximately 210 m. It marks a former water level midway between the Cedar Point and Payette phases.

Glaciolacustrine beach and near-shore deposits

The location and characteristics of the form of the glaciolacustrine beach and near-shore deposits have been discussed above and delineated on the surficial geology map (**Fig. 15, oversized figure**). Beach deposits consist of sorted, stratified, coarse grained sediments including open-work boulder gravel to pebble gravel, sandy gravel to gravelly sand and coarse to very coarse sand. Beach deposits were observed up to 5 m in thickness.

Glaciolacustrine coarse-grained basin deposits

Glaciolacustrine coarse-grained basin deposits occur adjacent to the beach and near-shore deposits immediately off-shore where gravelly sands, sands and minor amounts of silt are deposited. The sands typically range from medium to coarse to very fine to fine sand. Commonly massive at the depths observed in auger holes (0.5 m) as a result of soil forming processes but can become laminated and bedded with greater depth. A typical soil profile consist, from top to bottom, of about 10 cm of black organic rich very fine to fine sand (H, humus layer), 4 cm of light grey fine sand (Ae, zone of eluviation), 70 cm of orange brown fine to very fine sand (B, zone of iron and clay enrichment) and 10 cm of grey interlaminated fine sand and clayey-silt (C, parent material of the soil).

Glaciolacustrine fine-grained basin deposits

Glaciolacustrine fine-grained basin deposits are deposited further out into the lake basin and usually in deeper water. Silt and clay, commonly rhythmically bedded or laminated are deposited with some interbeds or laminations of very fine to fine sand. This type of sediment was only mapped in the western part of the island where rhythmically bedded sand, silt and clay extend to the Nipissing Great Lakes shore bluff where they have been eroded and removed. However, these fine grained basin sediments were also observed beneath sand that reached thicknesses of over 1 m throughout the map area.

Low-water lakes and subaerial exposure

Water levels in the Lake Huron and Georgian Bay basins continued to fall and in the Huron basin fell below present-day level of Lake Huron and eventually reached an elevation of approximately 122 m below Lake Huron level (Hough 1958). This occurred as a result of the Laurentide Ice Sheet margin receding north of the Continental Divide and its meltwater by-passing the Upper Great Lake basins combined with dry, early Holocene climate (Edwards et al. 1996, Booth et al. 2002, 2005, McCarthy et al. 2015) creating a situation in that a low supply of water was delivered into the Huron and Georgian Bay basins. Low stands of Lake Stanley (Huron) and Lake Hough (Georgian Bay) formed that were closed basin lakes; no rivers draining them towards the sea. Water levels possibly fell, 25 to 30 m below the level of the controlling sill, the North Bay outlet (Lewis et al. 2008a, b), about 9, 500 and 8, 400 cal. yr. B.P. (Rabett et al. 2019). During these events, Cockburn Island was part of a much larger land mass and was subject to subareal weathering and erosion. The large areas of surface sand were exposed to the wind and areas of sand dunes (Map Unit 10, **Fig. 15, oversized figure**) likely developed at this time and/or during the subsequent Nipissing transgression.

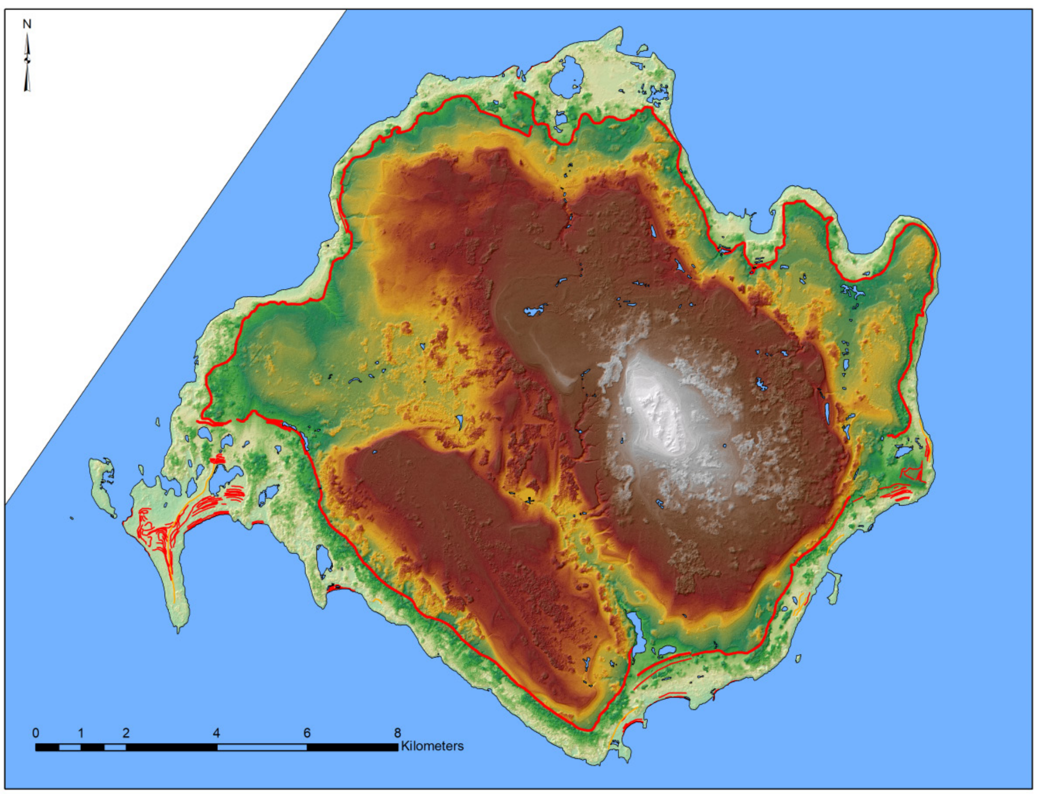

Figure 13: Area flooded by post-glacial lakes including the Nipissing Great Lakes, Algoma and several unnamed lakes, Cockburn Island, Ontario. Thick red line marks the approximate position of the Nipissing Great Lakes main shore-bluff. Thin red lines represent post-glacial shoreline features.

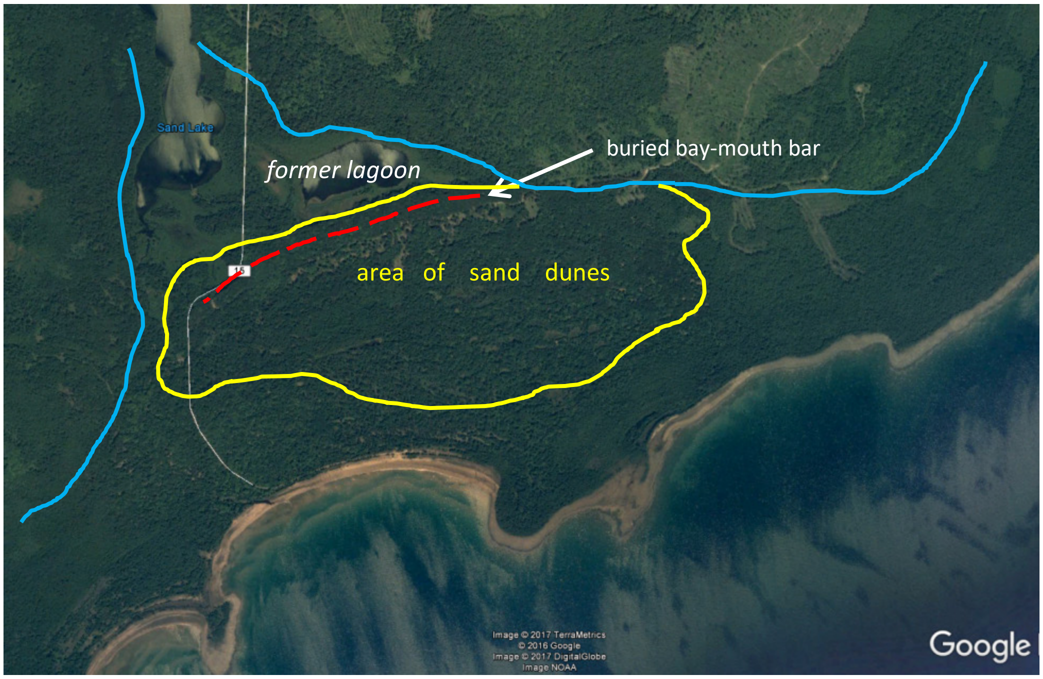

Figure 14: Landforms of the Sand Lake area, Cockburn Island. Former Nipissing Great Lakes shore bluffs (blue line), lagoon area, buried bay-mouth bar (red dash line) and an area of sand dunes that formed as post-glacial water levels fell (yellow line).

Lacustrine (Post-glacial Lake) Deposits and Features

Following the low-stands in the Huron and Georgian Bay basins and with continuing glacial isostatic adjustment, the outlet at North Bay continued to rise relative to other parts of the basin. Water level in the basins began its slow rise, the Nipissing transgression, from about 8,300 and continued to 5,760 cal. yr. B.P. until the Nipissing Great Lakes formed about 4 m above the current level of Lake Huron at Port Huron, Ontario (Baedke *et al.* 2004). This lake drained through three outlets; North Bay, Des Plains River at Chicago and at Port Huron. **Figure 13** is a paleogeographic map of the Nipissing Great Lakes level in relation to Cockburn Island. This lake formed a major shore bluff that encircles the entire Island (**Fig. 13**).

Eventually, the North Bay outlet was abandoned as a result of differential uplift and waters from this lake drained southward. The Nipissing Great Lakes level ended when down cutting occurred within the Port Huron outlet and Lake Algoma began (Hough 1958). Four periods of relatively long-lived high water levels in the Michigan and Huron basins occurred during the post-glacial. The first related to the post-glacial Nipissing Great Lakes (6,000 to 3,700 cal. yr. B.P.) and in particular, the peak Nipissing phase (4,500 cal. yr. BP), followed by Lake Algoma (2,300 to 3,300 cal. yr. B.P.) and two unnamed high phases (1,100 to 2,000 cal. yr. B.P. and 0 to 800 cal. yr. B.P.; Thompson *et al.* 2004, Barnett 2016). During the first of the two unnamed phases water level in the Huron basin was higher than during the preceding Lake Algoma.

Sediments that were deposited on the plain below the Nipissing shore bluff consist predominantly of low ridges of gravel, gravelly sand and sand with minor silt and clay in intervening lows. Areas of boulder lags rest on remnant areas of till too small to map and outcrops of Paleozoic rocks occur along the current shoreline in the northern half of Cockburn Island (outcrop symbol, **Fig. 15, oversized figure**).

Sand Lake, along the south shore of Cockburn Island sits within a former lagoon of the Nipissing Great Lakes (6,000 to 4,500 years ago; **Fig. 14**). South of Sand Lake, an extensive field of sand dunes has formed burying the original bay-mouth bar of the Nipissing Great Lakes that occurs south of Sand Lake and the unnamed lake to the east (**Fig. 14**). The dunes can exceed heights of 8 m.

Little of the Nipissing and younger lake deposits and features have been studied on the ground due to problems of access. Shoreline features of Lake Algoma and the two younger unnamed lakes appear to be well preserved in the Wagosh Lake area based on the interpretation of traditional air and ortho-photographs and derived DEM (**Fig. 13**).

Eolian Deposits and Features

During the low-stand lakes between approximately 9, 500 and 8, 400 cal. yr. B.P. (Rabett et al. 2019), the surface of Cockburn Island was exposed to dry early Holocene climate, weathering and erosion. Fine-grained glaciolacustrine sediments that were deposited in the area northeast of Wagosh Lake were subjected to wind erosion resulting in the formation of an area of sand dunes 2.2 km wide and 5.5 km long above the Nipissing shoreline. Another small area of well-developed dunes formed above the Nipissing Great Lakes shoreline 2 km northeast of Ricketts Harbour. Here dunes composed of fine grained sand exceed 5 m in height.

In the valley of Sand Creek, glaciolacustrine sand, silt and clay deposits were eroded, gullied and then redistributed to the Sand Bay area where they were subjected to wind erosion and the field of dunes displayed on **Figure 14** were formed. This dune field post-dates the Nipissing Great Lakes as the dunes occur on the foreshore area and have buried the bay-mouth bar of this lake. Still younger dunes, in this case, cliff-top dunes, can be observed along the southwest shoreline of Station Point of Cockburn Island, on air photographs and remotely sensed images. Wind erosion, blow-outs and minor disturbances of sand along some current and abandoned beach ridges are currently active, for example, along the beach ridges at Wagosh Bay.

Wetland Deposits

Accumulation of organic matter has been fostered generally by the nearly level and poorly drained plains of Cockburn Island. Areas mapped as areas of wetlands may not contain organic-rich deposits that exceed one metre in thickness. Wetlands of Cockburn Island were observed and delineated remotely on air photographs or digital imagery. The majority of wetlands consist of marshes and swamps adjacent to the many small lakes on the island. Sediments likely contain a mixture of organic detritus (partially decayed) and mineral soil, minor peat, muck and marl deposits are possible as well.

Fluvial Deposits

Fluvial sediments are deposited on the flood plains and in channels of rivers and creeks. Stream deposits on Cockburn Island are of limited areal extent. Texture and variability of fluvial sediments depends largely on the materials that the river has been eroding and the environment of deposition. Only one area was mapped as a fluvial deposit consisting of sand, gravelly sand and minor silt deposited within a river or former river bed. It is located near the airport in an area of thick sand and gravelly sand deposits. Other occurrences of fluvial deposits were too small to delineate on a map at a scale of 1:50 000 (**Fig. 15, oversized figure**).

Groundwater

Surficial geology plays an important role in the behaviour and distribution of water. Two broad categories of ground water environments have been recognized; in exposed or thinly covered bedrock or in sediments (Sharpe 2022) and both occur on Cockburn Island.

In areas of exposed or thinly covered bedrock, water flows can run off directly to streams or flow primarily along joints and fractures in the rock that have enhance permeability, especially where augmented by Karst processes. In a belt that rings the northern half of the island, gently dipping carbonate (dominantly dolostone) occur at or near the surface (Map Units 1a,b, 2; *see* Surficial Geology Map of Cockburn Island, **Fig. 15, oversized figure**). At elevations above the Nipissing transgression, the carbonate bedrock has been subjected to Karst processes (solution weathering) enlarging joints and fractures enhancing permeability and creating spaces for groundwater storage. Karst processes appear to be better developed in rocks of the Amabel Formation (Unit 16, **Fig. 3**) along the crest of the Niagara Escarpment (Brunton 2013). In karst environments groundwater storage can be significant and exerts "a large influence on the amount, timing and distribution of groundwater recharge as well as the depths and distances of groundwater flow" (Sharpe 2022, p.22). Predicting the hydraulic conductivity and aquifer location is not easy. It does not appear to be controlled by one dominant geological feature, but by where water has had access to the bedrock for dissolution-enhancement since the rock's deposition (Priebe et al. 2019).

In sediments, water flows through pores or spaces between sediment particles and the thickness and texture of the surficial sediment controls the rate of infiltration (Sharpe 2022). Coarser sediments, such as sand and gravel, have a higher permeability than finer sediments such as clay. They also allow precipitation and snowmelt to infiltrate at a greater rate and for groundwater to be potentially stored. Tills, that can contain of a greater range of particle sizes and tends to be poorly sorted, have intermediate values of permeability.

McCaigs Hill is the highest point on Cockburn Island. It is composed primarily of sand and gravel but has a thin cap of till (up to 5m thick). The surface till layer allows for precipitation and snowmelt to run off and carve the gullies that have formed along the edges of McCaigs Hill. The permeability of the till also allows some infiltration and for water to flow through the till layer to recharge the thick sand and gravel aquifer below. The layer of till also provides some protection from surface contamination of the aquifer below. The sands and gravels beneath the till is an aquifer or a place that can store groundwater. The adjacent beach ridges and bars of sand and gravel is also an area where precipitation and snowmelt can infiltrate readily and be stored. The north and south ridges appear to be composed of sand and gravel at depth and are overlain by coarse-textured permeable beach sediments and are likely locations of groundwater storage.

The areas of till at or near the surface, like the one that surrounds McCaigs Hill, have low relief and commonly contains numerous, small wetlands that indicate a high water table at or near the surface. These till areas are regional discharge areas, often occurring down slope of sand and gravel aquifers, in particular, the till plain surrounding McCaigs Hill and the adjacent beach ridges aquifers.

High water tables also occur surrounding the dunes in the area of sand dunes northwest of the southern ridge. Although composed of permeable fine-grained sands they are likely underlain by less permeable sediments that is maintaining a high water table and maintaining the numerous wetlands in this area.

SUMMARY

Cockburn Island landscape is somewhat unique in the northern Lake Huron-Georgian Bay basin, in that, it's overall topography and relief is dependant primarily on glacial sediments rather than the bedrock surface. It is very similar to St. Joseph Island to the west where the central core of that island is composed of glacial sediments (Karrow 1991).

Cockburn Island is underlain by gently dipping carbonate and clastic rocks of Middle Silurian age that outcrop in a belt that rings the northern half of the island. The crest of the Niagara Escarpment crosses the northern part of the Island. In places the bedrock surface has been affected by karst processes particularly in areas above the level of the Nipissing transgression where the land surface has been exposed for approximately 11,500 years to subareal weathering processes. Karst appears to be best developed on bedrock plains in dolostones of the Amabel Formation above the Niagara Escarpment. Alvars have developed on the exposed bedrock plains and occur at several locations on Cockburn Island. In the southern part of the island the bedrock surface is obscured by glacial sediment that can exceed thicknesses of 85 m (275 feet) in the central part of the Island beneath McCaigs Hill (Wolf 2006).

Evidence of the direction of glacier flow that affected Cockburn Island is primary from the orientation of streamlined forms, in particular drumlins. Drumlins reported from the central part of the island are oriented north–south with ice flow to the south. However, drumlins oriented in the southwest corner of the island near Wagosh Lake are oriented south-southeast. There are also drumlins that extend below the level of Lake Huron. The drumlin orientation does not necessarily reflect flow during two or multiple glacial advances. The variation in orientation of the long axis of the drumlins, the south-southwest flow around the eastern shore of the island, southern flow in the central part of the island and the south-eastward flow the western shore, may reflect ice flowing around the island along the inter-island channels at a greater speed than that flowing over the higher areas of the island.

Drumlins are commonly associated with till. Till is widespread across the island and occurs commonly as poorly-drained till plains, littered with boulder (lags). In addition, to till and its associated landforms, other surface landforms and sediments include a large hill of sand and gravel covered with till (McCaigs Hill), and two long ridges of gravel of probable ice-contact origin. Glacial Lake Algonquin and subsequent glacial and post-glacial lakes greatly affected the landscape of Cockburn Island. The record of ancestral lake levels in the Lake Huron basin on Cockburn Island appears nearly complete including the highest level of glacial Lake Algonquin (Main) through a series of falling glacial lake and post-glacial lake levels. These ancestral lake levels have created abandoned shore bluffs, gravel and sand beach ridges and sand and clay plains. In addition, areas of sand dunes have developed where the sands on the sand plains have been re-disturbed by wind. Wetlands, containing peat and muck, have developed in localized topographic low areas. The distribution of sediment types are delineated on the accompanying surficial geology map of Cockburn Island (**Fig. 15, oversized figure**).

Two categories of groundwater environments of southern Ontario (Sharpe 2022) occur on Cockburn Island. Groundwater aquifers occur in exposed or thinly covered carbonate bedrock and groundwater aquifers can be found in the glacial and post-glacial sediments. Karst processes in areas of near-surface or exposed bedrock primarily along the Niagara Escarpment has widened joints and fractures creating passageways and storage areas for groundwater. Large ice-contact landforms, such as McCaigs Hill and the north and south ridges, combined with the extensive abandoned shoreline features, provide thick permeable porous bodies of sediment to store groundwater.

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