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FOR LOW & INTERMEDIATE LEVEL WASTE

Neotectonic Features and Landforms Assessment

March 2011

Prepared by: S. Slattery

NWMO DGR-TR-2011-19

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EXECUTIVE SUMMARY

This report presents the findings of a neotectonic investigation completed as a part of site characterization activities for Ontario Power Generation's proposed Deep Geological Repository (DGR) project at the Bruce nuclear site in the Municipality of Kincardine, Ontario. The purpose of this investigation was to use desktop and field based methods to look for evidence of paleoseismicity within Quaternary sedimentary deposits in the Bruce nuclear site region. For the purpose of this investigation, a study area was defined and subdivided into two study zones based on proximity to the Bruce nuclear site. The inner study zone, referred to as Zone A, represents a 5 km zone around the Bruce nuclear site whereas the outer study zone, Zone B, is represented by a 50 km zone around the Bruce nuclear site.

The paleoseismic investigation was completed in three phases. During the initial phase of the investigation, a literature review was completed to obtain and analyze pertinent data within and adjacent to the outer study zones. Data sources reviewed and analyzed during this phase of the investigation included literature sources from refereed and non-refereed journals, published geological maps and reports, private sector reports, aggregate resource inventory reports, soils maps, etc. released by government agencies.

The second phase of the investigation, the interpretation of monochrome air photographs (~1:40,000 scale) viewed in stereo was completed to assess the occurrence of neotectonic features and/or landforms (i.e., bedrock stress release features, offset beach ridges, clastic dykes, etc.) in the inner and outer study zones. Further inspection for these features and/or landforms was completed through the analysis of a 10 m grid-spaced digital elevation model (DEM) accented with hillshaded relief. Additional landform assessment was completed in Zone A through the use of high resolution light detection and ranging (LiDAR) imagery. Features and/or landforms interpreted to reflect a possible paleoseismic origin identified in the inner and outer study zones were further assessed during the third phase, the field-based component, of the investigation.

During the third and final phase of the investigation, potential neotectonic features and/or landforms identified during the preliminary phase of the investigation were examined in detail through field-based inspection. The physical examination of these features was completed through the examination of natural and man-made exposures (i.e., road-cuts, exposures in river valleys, aggregate operations, etc.). During this phase of the investigation emphasis was placed on the analysis of vertical sediment profiles within the inner study area. Liquefaction features resulting from seismic activity as recent as 500 to 1,000 years ago are rarely visible for examination at the ground surface (in plan view) despite the use of aerial photographs and satellite imagery.

Several conclusions can be made based on the data obtained from the above mentioned phases of the paleoseismic investigation, as described below.

1. The Bruce nuclear site is located in a tectonically stable zone with no active fault zones.
2. Offset landforms resulting from neotectonic activity were not observed in the study area. Beach ridges which appeared "offset" when viewed on air photographs in stereo are explained by anthropomorphic processes such as road building and residential development, scattered vegetation growth and subsequent dune (eolian) development. Collectively, these processes have altered the original morphology of the examined ridges creating an offset-like appearance.

3. Offset-like trends observed in the Nipissing-aged lake bluff observed in LiDAR imagery near the community of Inverhuron (southwest of the Bruce nuclear site) are likely related to preferential erosion of the Nipissing bluff and are not associated with neotectonic activity. Offset-like trends in adjacent beach reaches (less than 100 m west of the noted offset-like trend) were not evident in LiDAR imagery or noted during field-based examination.

4. Perpendicular to pseudo-trellis patterns on ground surface within the study area are the result of anthropomorphic processes and do not reflect neotectonic activity (i.e., the lateral spreading or the natural venting of sediments).

5. Contorted beds of rhythmically bedded very fine to fine-grained sands, silts and clays found with St. Joseph Till are associated with an ice-marginal readvance of the Huron-lobe during Port Bruce time. During this readvance glacial Lake Saugeen was overridden and glaciolacustrine sediments were incorporated through subsole drag processes thereby explaining the deformed nature of these sediments.

6. Observed liquefaction features that are bound stratigraphically by undeformed stratigraphic intervals (often used as criteria for neotectonic activity) demonstrate evidence of lateral movement and orientation indicating current movement and subsequent drag processes. These observations indicate a syndepositional origin formed through current shear on liquefied sand and are not the result of past neotectonic activity.

7. Cyclic repetitions of liquefaction structures were not observed within the study area. Although cyclicity of these structures is, however, by itself, not diagnostic of a neotectonic origin it is expected by many researchers in seismic zones due to reoccurring seismic activity.

8. Lateral continuity of liquefaction features was not identified within the study area on a regional basis. Deformation structures and their regional abundance are prerequisites for regarding them as neotectonically induced.

9. The absence of liquefaction-induced venting features and water escape flow paths in examined sediment-outcrop sections, and the dominance of plastic deformation, indicates a regime in which vented liquefaction features (neotectonically induced) could not develop.

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1. INTRODUCTION

This report presents the findings of a neotectonic investigation completed as a part of site characterization activities for Ontario Power Generation's proposed Deep Geological Repository (DGR) project at the Bruce nuclear site in the Municipality of Kincardine, Ontario. The purpose of this investigation was to use desktop and field based methods to look for evidence of paleoseismicity within Quaternary sedimentary deposits in the Bruce nuclear site region.

1.1 Background

In many tectonic settings where seismic activity has exceeded a moment magnitude (M) of 5.5, seismic activity tends to reoccur at the same localities throughout time (Obermeier 1996a, 1996b, Obermeier and Pond 1999). However, in many of these settings evaluating the severity of the hazard such as earthquake magnitude and ground shaking intensity is difficult due to a paucity of suitable study sites (i.e., visible faulting), the absence of historic data and the duration of the event (Obermeier 1999).

In order to better our understanding of the severity of seismic related hazards in these areas, analysis of seismically induced liquefaction features or paleoliquefaction studies have become a standard means of estimating the severity of past seismic events (e.g., Obermeier 1999). Such investigations have aided in determining the timing of past seismic events and provided estimates of magnitude for Holocene-age earthquakes in the central and eastern United States (Obermeier 1996a, 1996b, Obermeier and Pond 1999). The results of these investigations through the recognition and analysis of seismically induced features (described below) have allowed researchers to provide a more precise assessment of the occurrence of potentially hazardous events in the near geologic future.

Seismically induced features such as sand volcanoes, sand boils, lateral spreads, etc., indicate M of approximately 5.5, thereby providing an initial estimate of seismic intensity (Obermeier 1996a, 1996b, 1999). More importantly, the recognition of these features suggests that seismic activity was severe enough to cause damage to man-made structures. Similarly, the presence of clastic intrusions (dikes and sills) in sediments of glacial and non-glacial origin is often related to the effects of seismically induced liquefaction (Obermeier 1996a, 1996b, Obermeier and Pond 1999). Such intrusions develop when water and sediment (typically sand) flow from depth into fissures along the base of an overlying fine-grained sediment cap such as glaciolacustrine silts and clays (Obermeier 1999). According to Obermeier (1999), paleoliquefaction features resulting from seismic activity within the last 500 years are rarely visible at the ground surface even when aerial photographs or satellite imagery are used. Therefore, emphasis should be placed on the recognition of seismically induced soft-sediment deformation features in vertical sediment profiles during paleoliquefaction investigations.

Evidence of paleoseismicity in the form of soft-sediment deformation that results in the formation of contorted beds of silts and clays, load casts, flame structures, ball-and-pillow structures etc. are formed through the lateral and vertical disruption of sediments and subsequent liquefaction processes. However, these features commonly develop in the absence of seismic activity and are readily produced by sediment loading in glacial and non-glacial settings (e.g., deltas, fluctuating ice-margins, sediment loading produced via lobe switching in subaqueous fans, channel avulsion etc., Russell and Arnott 2003, Miall 1985, 1988). In many cases a seismic origin is difficult if not impossible to verify in the absence of field-based sedimentological analysis.

In eastern Canada, the residuals of high-horizontal stresses in bedrock were first noted in bedrock excavations at the base of a Quarry in Ontario (White et al. 1973, Lo 1978, Adams 1982). Since then, additional features such as elongated compressional ridges or pop-up structures (White et al. 1973, White and Russell 1982, Gorrell 1988), faulted and striated bedrock surfaces (Gorrell 1988, Barnett and Kelly 1987) have been attributed to bedrock unloading (stress release). Although several explanations are offered by (Fakundiny et al. 1978) to explain the occurrence of stress-release features, only two main theories are generally accepted by researchers. These include: 1) a response to glacial unloading (Adams 1988), and 2) regional tectonic forces (White and Russell 1982).

1.2 Study Area Location

The Bruce nuclear site is within National Topographic System (NTS) Map Sheet 41 A/5 and is bound to the south by Inverhuron Provincial Park, to the west by Lake Huron and to the north and east by the boundaries of private lands (Figure 1.1). The Bruce nuclear site is located in the Municipality of Kincardine approximately 7 km northwest of the community of Tiverton, 21 km northwest of Kincardine and 31 km southwest of Port Elgin.

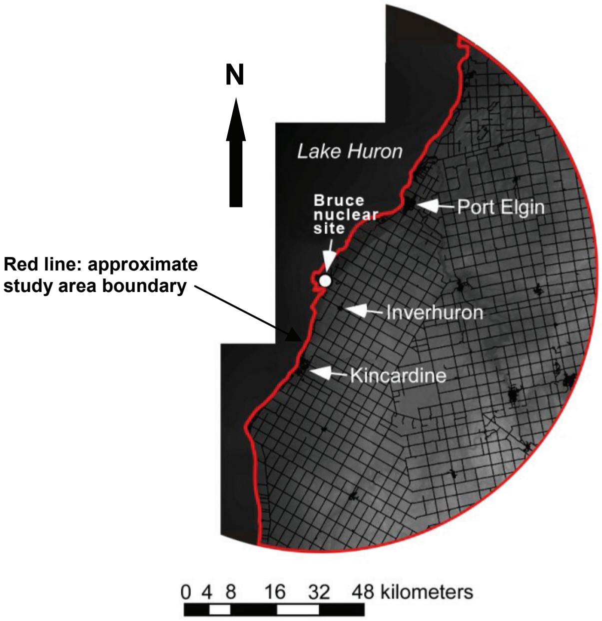


Figure 1.1: Digital Elevation Model of the Study Area

1.3 Methodology

For the purpose of this investigation, the study area was subdivided into two buffer zones based on proximity to the Bruce nuclear site. The inner study zone, referred to as Zone A, forms a 5 km buffer around the Bruce nuclear site whereas the outer study zone, Zone B, forms a 50 km buffer around the study site (Figure 1.2). In order to identify seismically induced features in Quaternary sediments and/or landforms within these zones a phased approach was completed. Each phase of the investigation is described below.

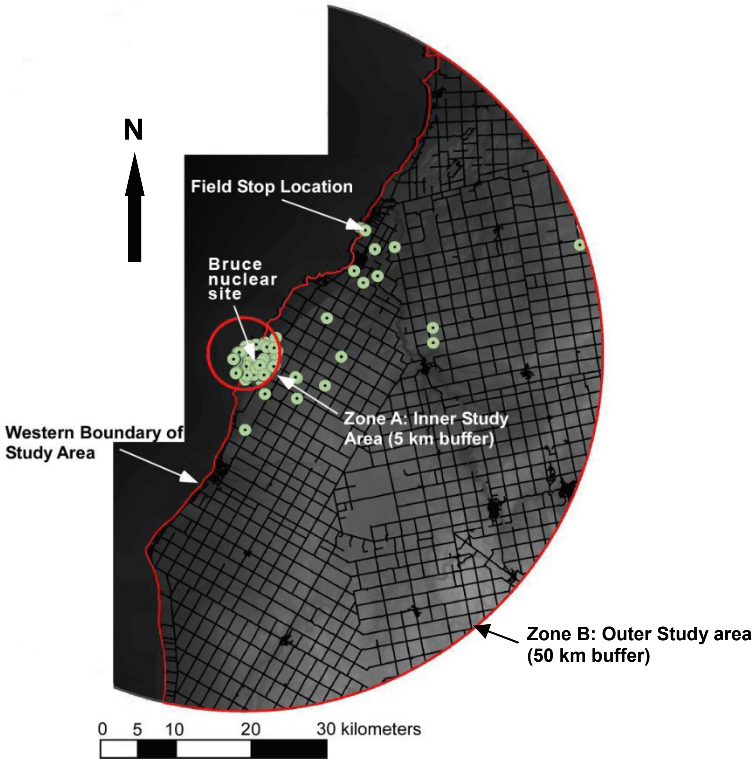


Figure 1.2: Digital Elevation Model of the Study Area – Inner Zone A and Outer Zone B

1.3.1 Phase I: Preliminary Investigation

A desktop investigation was completed as an initial means to obtain and analyze pertinent data within and adjacent to a 50 km buffer zone (Zone B) around the Bruce nuclear site (Figure 1.2). Data sources reviewed and analyzed during this phase of the investigation included literature sources from refereed and non-refereed journals, published geological maps and reports, private sector reports, aggregate resource inventory reports, soils maps, etc. released by government agencies and professional organizations including the Ontario Geological Survey (OGS), Geological Survey of Canada (GSC), Ontario Ministry of Natural Resources (MNR) and the Ontario Ministry of Agriculture and Food (OMAF).

1.3.2 Phase II: Preliminary Investigation

During this phase of the investigation, the interpretation of monochrome air photographs (~1:40,000 scale) viewed in stereo was completed to assess the occurrence of neotectonic features and/or landforms and bedrock stress release features (i.e., pop-ups, offset beach ridges, clastic dykes, etc.) in the inner and outer study zones (Zones A and B). Additional inspection for the presence of these features and/or landforms was completed through the analysis of a 10 m grid-spaced digital elevation model (DEM) accented with hillshaded relief. Further assessment was completed in Zone A through the use of high resolution light detection and ranging (LiDAR) imagery.

Features and/or landforms interpreted to reflect a possible paleoseismic origin identified in the inner and outer study zones were further assessed during the field-based component of the study (described below).

1.3.3 Phase III: Field-based Assessment

Potential neotectonic features and/or landforms identified during the preliminary phase of the investigation were highlighted and examined in detail during this phase of the investigation. The physical examination of these features was completed through the examination of natural and man-made exposures (i.e., road-cuts, exposures in river valleys, aggregate operations, etc.). During this phase of the investigation emphasis was placed on the analysis of vertical sediment profiles within the inner study. As demonstrated by Obermeier (1999), liquefaction features resulting from seismic activity as recent as 500 to 1,000 years ago are rarely visible for examination at the ground surface (in plan view) despite the use of aerial photographs and satellite imagery.

Following the completion of the field-based assessment, a total of 81 field-sites were examined in the inner study zone and 47 field-sites in the outer study zone. The locations of these sites are illustrated on Figure 1.2. Detailed descriptions of these sites are presented in Appendix A of this report.

1.4 Field-Based Assessment – Quality Assurance and Quality Control

In order to ensure that field-based observations and data collection methods were consistent and well documented prior to the course of the field-based investigation a sample data entry sheet was formulated. At each field-stop, data obtained from the stop was manually transferred to the data entry sheet. Site locations were obtained from a Garmin® handheld geographic positioning system (GPS) and recorded onto the data entry sheet. Location co-ordinates were then transferred manually to a field notebook and marked on the corresponding air photograph and NTS map sheet.

The data entry sheet consists of two parts. The first is designed to record a general site description whereas the second part allows for the documentation of general geological observations and detailed sedimentological and lithological descriptions of observed strata. An overview of the sample data entry sheet is provided below.

Part A. Site Description:

1. Site Number
2. Date (MM/DD/YYYY)
3. Person responsible for collecting sample (geologist, supervisor, manager, etc.)
4. Location (Universal Transverse Mercator [UTM] easting-northing co-ordinates, datum, Co-ordinate system and elevation, GPS Waypoint Number)
5. Location Method (GPS, Air photograph, NTS Map Sheet No.)
6. Site Photograph number (Also have GPS and camera clocks synchronized for Geo-referencing purposes)
7. NTS and Air photograph / Map Numbers
8. General Geographical Position (e.g., rolling, undulating, etc.)
9. Surrounding Vegetation (e.g., Pasture, Cultivated, Wetland, Forest - Deciduous, Forest – Conifer, etc.)
10. Major Vegetation Type (e.g., Poplar, Pine, Marsh Grass, etc.)

11. Minor Vegetation Type (e.g., Poplar, Pine, Marsh Grass, etc.)
12. Local Geomorphology (e.g., Gullies, Kettles, Plain, Ridge, etc.)
13. Local Vertical Relief (e.g., 0 to 2 m, 2-5 m, >5 m)
14. Site Description

Part B. Geological Description:

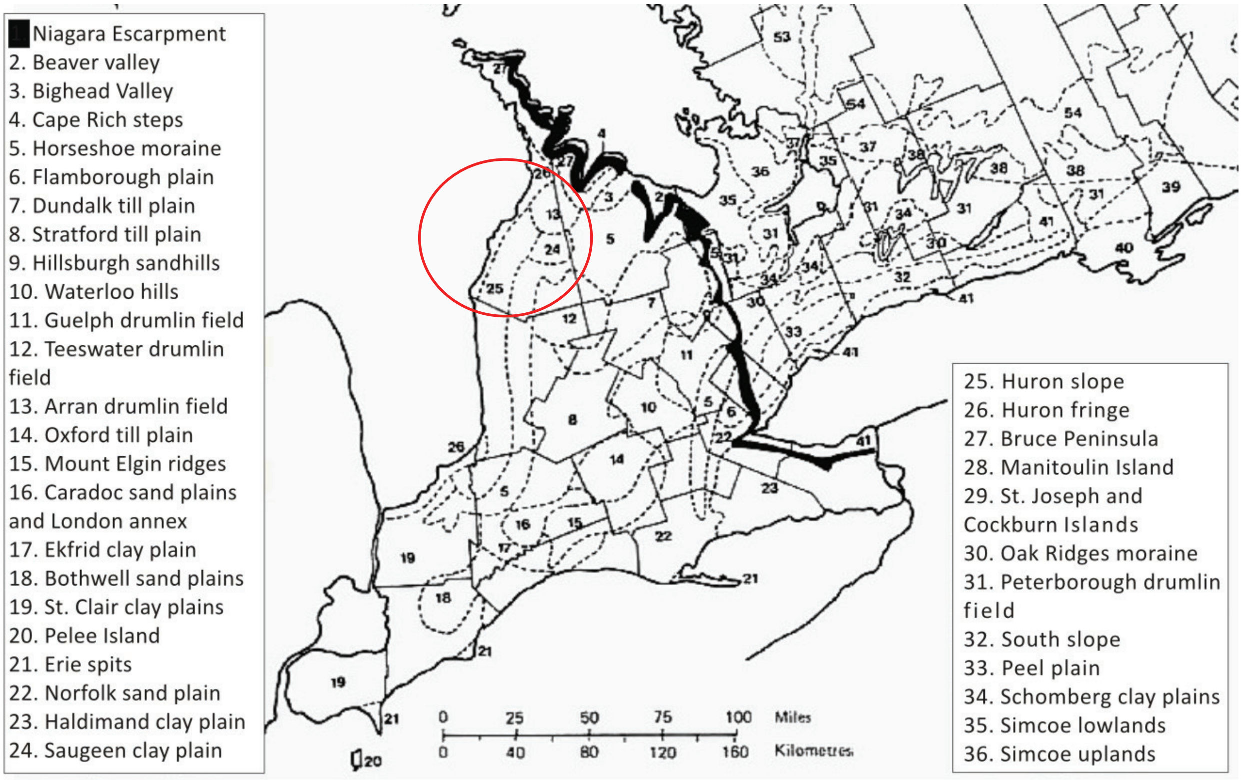
The description of sediment will closely follow that of visual-manual identification procedure found in ASTM D2488 - 09 Standard Practice for Description and Identification of Soils and techniques used in Folk (1974).

1. Site Number
2. Sample Number
3. Date Collected
4. Lithology (e.g., Diamicton, Sand, Sand and Gravel, etc.)
5. Genesis (e.g., Till, Glaciofluvial, Glacial Tectonic, Recent Fluvial, etc.)
6. Bedding (e.g., Laminated, Bedded, Cross-Bedded, etc)
7. Structure (e.g., Massive, Fractured, Fissile, etc.)
8. Sample Unit Depth (Upper and Lower – in metres below ground surface)
9. Sample/Unit Colour (e.g., grey, dk grey, brown, tan, etc.)
10. Munsell Soil Colour Number (if known)
11. Consistency (e.g., Loose, Friable, Hard, Cemented, etc.)
12. Matrix %
13. Clast %
14. Clast Composition (in %)
15. Clast Angularity (e.g., round, subround, angular, etc.)
16. Clast Shape (flat, elongate, etc.)
17. Presence of Rotten Clasts
18. Matrix Texture (e.g., Silty clay, Sandy silt, etc.)
19. Oxidation/Alteration Features (e.g., calcium carbonate, Fe stain, Mn Stain)
20. Organics
21. Brief description (including lithology, alteration, or other pertinent information such as genesis)

2. PHYSICAL SETTING

2.1 Physiography

Physiographic regions located within a 50 km radius of the Bruce nuclear site, as defined by Chapman and Putnam (1984), include the Niagara Escarpment, Cape Rich steps, Horseshoe moraines, Teeswater drumlin field, Arran drumlin field, Saugeen clay plain, Huron slope, Huron fringe and the Bruce Peninsula (Figure 2.1). A brief description of each region is provided below. For additional information concerning the physiography of the study area the reader is referred to Chapman and Putnam (1984).



Note: Red circle indicates approximate study area boundary. Figure is from Chapman and Putnam (1984).

Figure 2.1: Physiographic Regions within the Study Area

2.1.1 Niagara Escarpment

The Niagara Escarpment is the most prominent topographic feature in southern Ontario, extending more than 500 km from western New York, through Niagara Falls and the western part of the Greater Toronto Area (GTA), and north to Tobermory.

Rocks that compose the escarpment are the result of the accumulation of sediments in a shallow sea that occupied the area approximately 350 million years ago. Over time, these sediments were compacted forming a sequence of sedimentary rocks such as sandstone, shale, limestone and dolostone. Each sequence or formation dips toward the centre of the Michigan Basin at approximately 6 m/km.

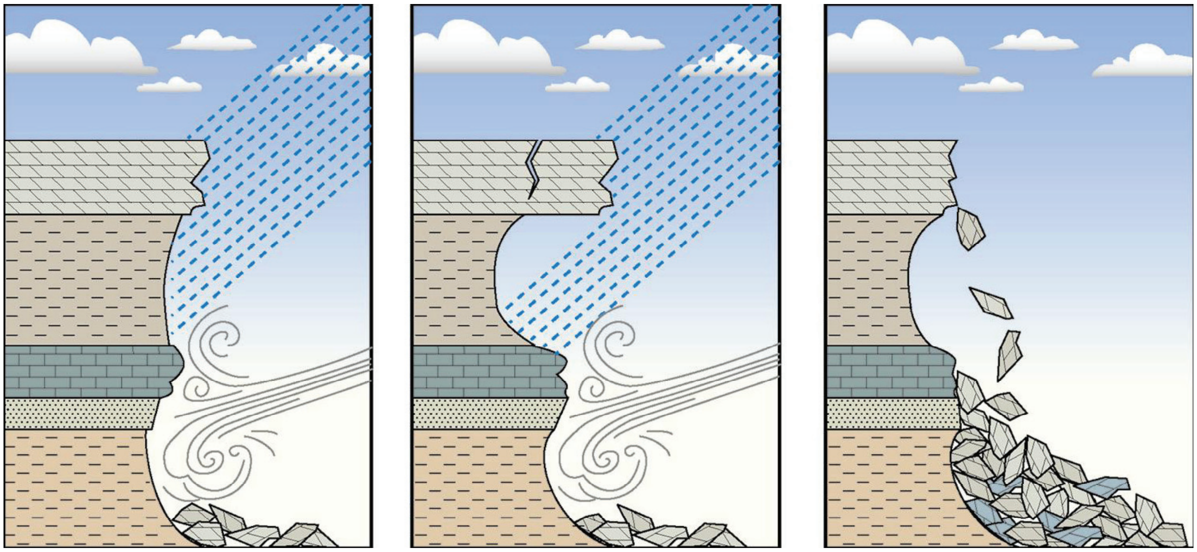
The present-day morphology of the escarpment is due to millions of years of preferential erosion of the 'softer' underlying sedimentary rocks that form the escarpment. Preferential erosion of these rocks, shales and sandstones, through physical weathering has left behind the more resistant dolostone cap. Over time this cap rock has broken away resulting in the vertical rock faces that we see today (Figure 2.2). The process, known as sapping, is largely responsible for the formation of the Niagara Escarpment (Hewitt 1971) as shown in Figure 2.3.

Figure 2.2: Vertical Rock Faces of the Niagara Escarpment near the Niagara River Gorge

2.1.2 Cape Rich Steps

The Cape Rich Steps are located in the northern portion of the study area and are defined as a series of bedrock uplands that separate the community of Owen Sound from Nottawasaga Bay (Figure 2.1). According to Chapman and Putnam (1984), these uplands directed two preglacial tributaries toward a main trunk channel which flowed through the Georgian Bay depression.

From Georgian Bay, the region rises approximately 152 m in a series of five steps. The first two steps, located near the present-day shore of Georgian Bay, are interpreted as narrow terraces formed by glacial lakes Algonquin and Nipissing. The next two steps are located above the Lake Algonquin terrace and are incised into rocks of the Manitoulin Formation. These terraces are defined by lag deposits composed of boulder gravels and coarse-grained beach ridges. The uppermost step marks the brow of the Niagara Escarpment in the region.



Note: Erosion of the Softer Underlying Shale and Sandstone Causing the More Resistant Dolostone Cap Rock to Break Away Under Its Own Weight. The process, known as sapping, has resulted in the vertical rock faces and overall formation of the Niagara Escarpment (from Doyle and Steele 2003).

Figure 2.3: Formation of the Niagara Escarpment by Differential Erosion

2.1.3 Horseshoe Moraines

The Horseshoe moraines physiographic region is located northeast of the Bruce nuclear site (Figure 2.1). The region is composed of three moraines, predominantly composed of tills. From oldest to youngest, they are the Singhampton Moraine, the Gibraltar Moraine and the Banks Moraine. The Tara Strands, a series of several small moraines that are superimposed on tills that form the Arran Drumlin Field, are often included within this physiographic region.

Collectively the region is defined morphologically by two subdivisions. As defined by Chapman and Putnam (1984) these include: (i) irregular, stoney knobs and ridges predominantly composed of till with lesser amounts of sand, and (ii) gravel and pitted sand, gravel terraces and swampy valley floors.

2.1.4 Teeswater Drumlin Field

The Teeswater Drumlin Field is located immediately south of the Horseshoe moraine system (southeast of the Bruce nuclear site, Figure 2.1) and occupies an approximate land area of 1489 km^2. Drumlins that form the region are defined morphologically by low-lying, oval hills with gentle slopes. Internally, drumlins are composed of a moderately compact, highly calcareous, pale brown to yellow coloured, slightly clayey silty sand to sandy silt diamicton.

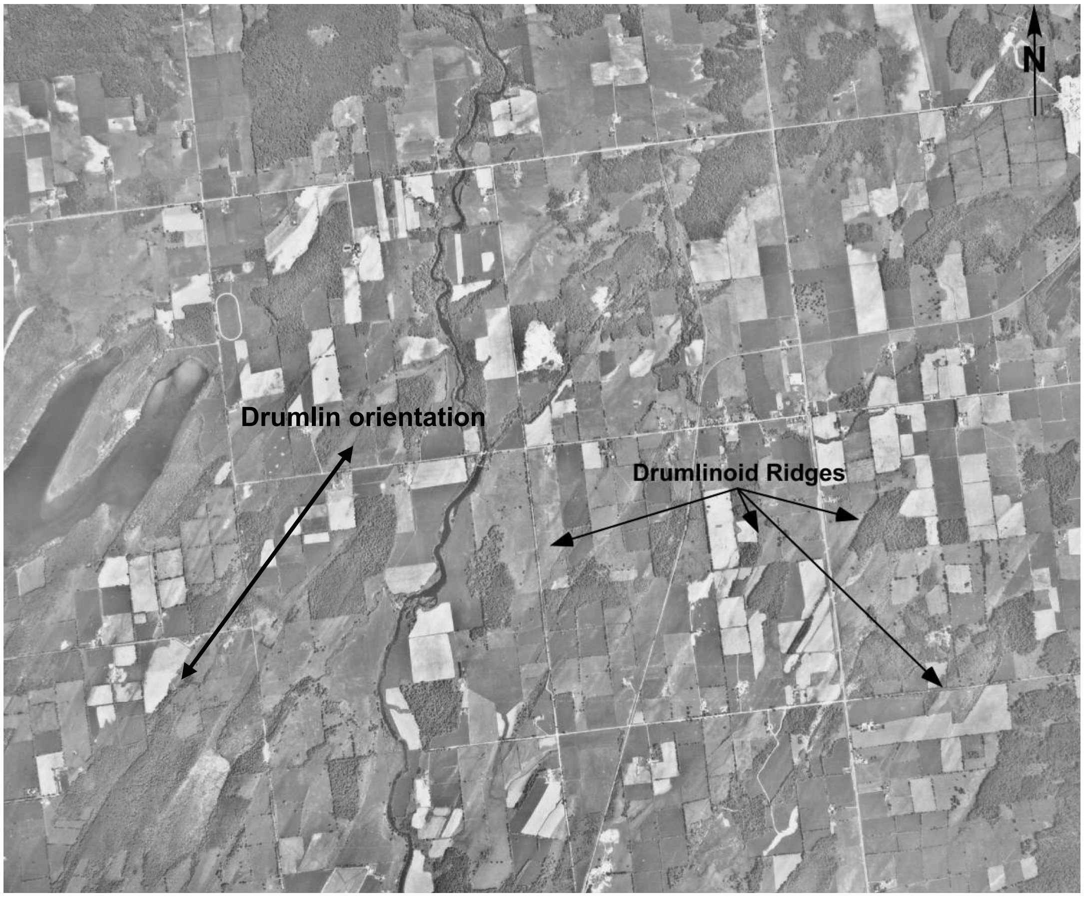
Drumlins that form the periphery of the region are less defined than those that form the central portion of the region. The morphological expression of peripheral drumlins and drumlinoid forms becomes weaker and generally fades toward the adjacent undulating till plain. The orientation of drumlin axes in this region is best described as variable. Near the communities of

Wingham and Teeswater (south of the Bruce nuclear site) drumlins are oriented southward whereas a southeast trend is evident between the communities of Palmerston and Harriston (southeast of the Bruce nuclear site).

Evidence of erosion by glacial meltwater is evident throughout the region. Broad, U-shaped valleys (former tunnel-channels?) that are now occupied by the Saugeen and Maitland Rivers incise the underlying diamicton and in some areas, such as Formosa Creek, have eroded through the diamicton and incised underlying bedrock.

2.1.5 Arran Drumlin Field

The Arran Drumlin Field is located in northeast of the Bruce nuclear site between the communities of Owen Sound and Southampton (northeast of the Bruce nuclear site, Figure 2.1). The region occupies an approximate land area of 518 km^2 and is characterized by several long narrow drumlins (Figure 2.4). This drumlin field lies north of the Horseshoe moraines and is younger than the Teeswater drumlin field to the south. In addition to the difference in shape, drumlins that form the region are oriented southwest, indicating that drumlin formation occurred by ice-advance from the Georgian Bay lobe. Internally, drumlins are composed of a highly calcareous, stoney, silt-rich till.



Note: Southwest orientation (~ 220° azimuth) of drumlins accented by black coloured lines on photograph (National Air Photo Library C8920 L4410-127).

Figure 2.4: Air Photograph of Drumlins in the Arran Drumlin Field

A series of several recessional moraines, referred to as the Tara Strands, are superimposed on drumlins that form the region. These moraines are oriented nearly perpendicular to the axes of drumlins. According to Chapman and Putnam (1984), the presence of these moraines suggests a fluctuating ice-margin (ice-marginal retreats and advances) of the Georgian Bay lobe during or shortly after drumlin formation.

2.1.6 Saugeen Clay Plain

The Saugeen Clay Plain is defined morphologically as a flat to undulating clay plain. Geographically, the region is isolated to within the Saugeen River drainage basin, north of the Walkerton moraine or northeast of the Bruce nuclear site. It is characterized by sequences of rhythmically bedded deposits of silts and clays deposited in glacial Lake Warren ~12,500 years before present (BP) (Figure 2.5) (Dreimanis 1966, Barnett 1992a). The thickest accumulations of these sediments occur between the Singhampton and Gibraltar moraines or between the communities of Walkerton and Chesley. Present day fluvial systems within the Saugeen River basin such as the Saugeen River, Teeswater River and Deer Creek have incised fine-grained sediments that constitute the region (38 m near the community of Paisley) resulting in lateral gullying and the development of river breaks.

Note: Two dollar coin for scale.

Figure 2.5: Fine-grained Sediments of the Saugeen Clay Plain Physiographic Region

2.1.7 Huron Slope

The Huron Slope physiographic region occupies a surface area of approximately 2589 km^2. It is located along the eastern side of Lake Huron and encompasses lands located between the Algonquin shoreline and the Wyoming moraine (Figure 2.1). The region is characterized by an undulating to flat-lying clay plain that has been modified by a narrow strip of sand-rich sediments and by beach ridges deposited by glacial Lake Warren which flank the Wyoming moraine.

Below the former elevation of the Lake Warren water plane, the topography of the region is defined as flat to gently undulating. Sediments that form this portion of the region are predominantly composed of glaciolacustrine silts and clays that conformably overlie a silt-rich till. Sediments located above the glacial Lake Warren water plane are defined by a calcareous, moderately stoney, silt-rich till. The narrow belt of sand-rich sediments described above, interpreted as a beach ridge(?), overlies the silt-rich till described above.

2.1.8 Huron Fringe

The Huron fringe is defined as a narrow strip of land that traverses along Lake Huron from Sarnia to Tobermory (Figure 2.1). It is characterized by scoured bedrock, eolian sediments, wave-cut terraces and beach ridges formed by glacial lakes Algonquin and Nipissing. The Fringe is approximately 321 km in length and occupies an approximate surface area of 1126 km^2.

Near the Bruce Peninsula physiographic region, the region is defined as a scoured belt of limestone that is overlain by a series of beach ridges and sand dunes. Near the communities of Port Elgin (north of the study area) and Inverhuron (southeast of the study area) the region is bordered by the Algonquin Bluff and is defined by numerous parabolic sand dunes, beach ridges and wave-cut platforms.

2.1.9 Bruce Peninsula

The Bruce Peninsula physiographic region is defined by Chapman and Putnam (1984) as a ~1292 km^2 zone of scour (Figure 2.1). With the exception of scattered drumlins, gravel bars and sand dunes, sediment thickness in the region is typically less than 1 m. Bedrock topography is defined as irregular throughout the region and typically contains numerous wetlands and small lakes.

2.2 Quaternary Geology

Glacial landforms and associated sediments examined within a 50 km radius of the Bruce nuclear site are of Late Wisconsinan age (23,000 to 10,000 years BP) and were deposited by the Huron and Georgian Bay lobes of the Laurentide Ice Sheet (LIS). Previous Quaternary geologic mapping for the area has been completed at scales of 1:50,000 by Sharpe and Edwards (1979) and Cowan (1977) and 1:1,000,000 by Barnett et al. (1991). Specific studies pertaining to paleolake level reconstructions or observations on local Quaternary geology features and landforms in the area are summarized by Prest (1970), Shilts et al. (1987), various authors in Fulton (1984, 1989), various authors in Karrow and Eschman (1985), Barnett (1992), and Lewis et al. (2005).

During the Late Wisconsinan three significant periods of ice-marginal advance of the LIS occurred. These advances are referred to as the Nissouri (~23,000 – 18,000 years BP), Port Bruce (~15,200 – 13,800 years BP) and Port Huron (~13,100 – 12,300 years BP) stades (Dreimanis and Karrow 1972, Barnett 1992a). These stades were separated by two periods of ice-marginal recession or warming periods, referred to as the Erie (~16,500 – 15,500 years BP) and Mackinaw (~14,000 – 13,000 years BP) interstades, that occurred during the Late Wisconsinan (Dreimanis and Karrow 1972, Barnett 1992a).

The Nissouri stade is the initial stage of ice-advance during the Late Wisconsinan. During this stade, the LIS reached the Niagara Escarpment by approximately 23,000 years BP (Hobson and Terasmae 1969). By ~20,000 – 18,000 years BP the LIS had advanced to its southernmost limit, marked by the Cuba and Hartwell moraines, in Ohio and Indiana (Dreimanis and Goldthwait 1973). Evidence of the Nissouri Stade within the study area is represented by the Catfish Creek Till, a fine-grained overconsolidated till, located immediately east of the site (discussed further below, Sharpe and Edwards 1979). As climatic conditions warmed and the onset of the Erie Interstadial occurred the margin of the LIS retreated southward into the Lake Ontario Basin (Morner and Dreimanis 1973). In the vicinity of the Bruce nuclear site, Quaternary mapping investigations completed by Sharpe and Edwards (Sharpe and Edwards 1979) suggest that the lack of fine-grained Port Bruce tills indicates that the margin of the LIS only retreated to a position near the community of Chelsey (east of the Bruce nuclear site).

During the Port Bruce Stade the LIS readvanced over much of southern Ontario extending well into the United States (Barnett 1992a). During the later part of this stade the Huron and Georgian Bay lobes separated and acted independently depositing the Elma Till of the Georgian Bay lobe and the Rannoch Till of the Huron lobe (Prest 1970, Barnett 1992a). Only the Elma Till is present within the study area and occurs as ground moraine, in drumlins that compose the Teeswater Drumlin Field (refer to section above) and forms the core of the Singhampton moraine (also referred to as the Saugeen Kames, Figure 2.6). Southeast of the study area near the community of Paisley (south of the Singhampton moraine, Figure 2.6), deposits of the Dunkeld Till overlain by fine-grained glaciolacustrine sediments occur at surface (Sharpe and Edwards 1979, Cowan 1977). This till occurs as ground moraine within the Saugeen River valley but also forms deposits associated with the Gibraltar Moraine (Cowan 1977) and the core of the Walkerton moraine. The limited areal extent of this till indicates that it resulted from minor readvance of the ice-margin over glaciolacustrine clays and silts of glacial Lake Saugeen (Barnett 1992a).

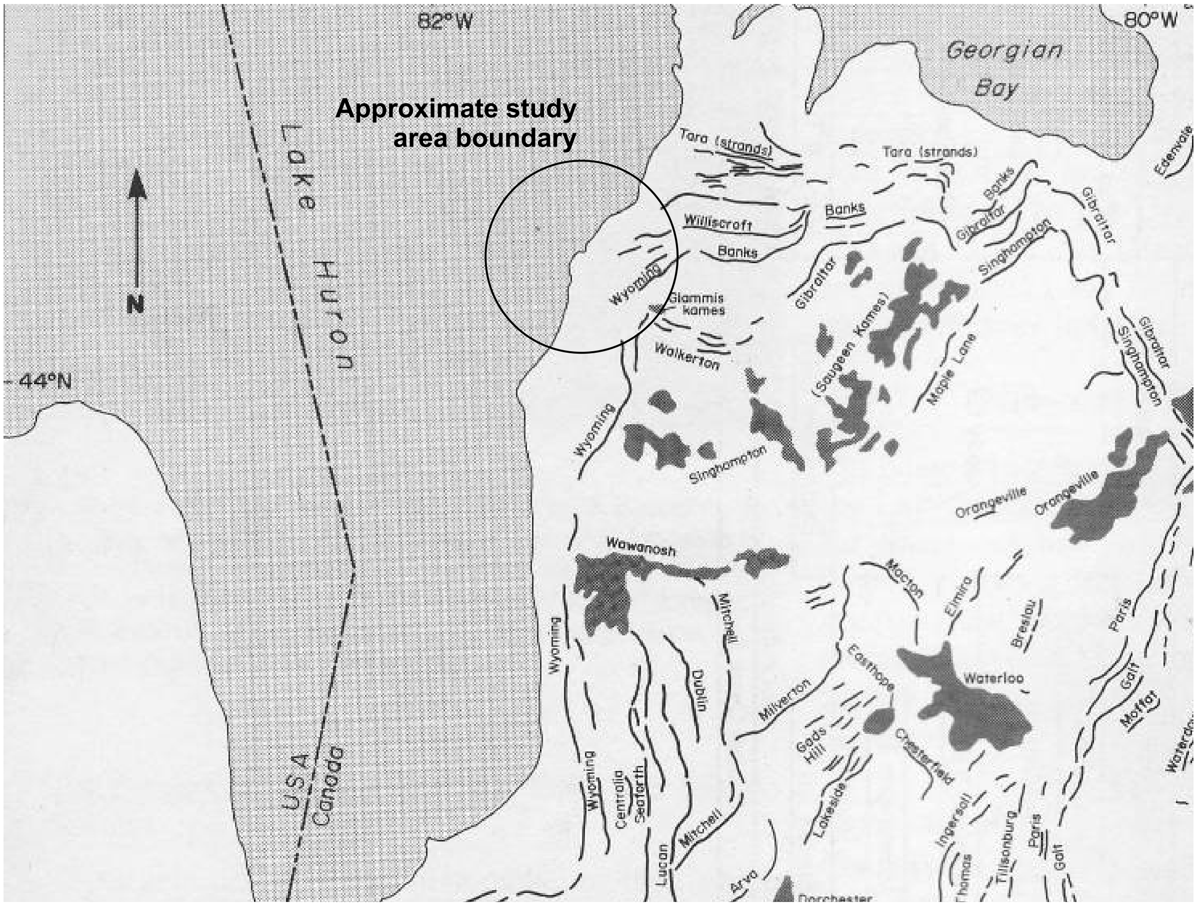
Following the Mackinaw Interstade, the LIS readvanced into the eastern end of Lake Erie basin and to the southern end of Lake Huron (Barnett 1992a). The most widespread till within the study area, the St. Joseph Till (Cooper and Clue 1974), was deposited during this readvance. The St. Joseph Till occurs as ground moraine throughout the study area, as drumlins in the Arran Drumlin Field and as end moraine complexes. The Wyoming moraine which parallels the shore of Lake Huron, the Banks and Williscroft moraines are all attributed to this readvance and are composed of the fine-textured St. Joseph till (Sharpe and Edwards 1979, Cowan 1977, Figure 2.6). North of the Williscroft moraine are a series of small recessional moraines referred to as the Tara Stands (refer to Figure 2.6). These moraines are also composed of St. Joseph Till, which cap deltaic sands and gravels likely deposited during the Mackinaw Interstadial, and are attributed to fluctuating ice-marginal conditions during final retreat of the LIS.

2.2.1 Study Area Till

The following section describes the lithological characteristics and aerial distribution of tills located within study area. For a more detailed assessment regarding the distribution of tills within the study area the reader is referred to Quaternary geologic mapping completed by Cowan (1977) and Sharpe and Edwards (1979).

2.2.1.1 Catfish Creek Till

The Catfish Creek Till is the oldest deposit observed in the study area and was deposited during the Nissouri Stade or the first of three advances of the LIS during the Late Wisconsinan. It is defined as hard, overconsolidated, stoney, sandy silt till that has been traced in the subsurface throughout southwestern Ontario (Barnett 1992a). Locally, the Catfish Creek Till outcrops at surface along the shore of Lake Huron north, south and east of the Bruce nuclear site below the elevation of the Algonquin Bluff (Sharpe and Edwards 1979). Above the elevation of the Algonquin Bluff, deposits of Catfish Creek Till have not been observed at surface but subsurface investigations completed by Sharpe (1977) indicate that this till directly overlies bedrock throughout the area.



Note: Figure is from Barnett (1992a).

Figure 2.6: Major Moraine Complexes of Southern Ontario

Measurements taken from striae (glacial striations on bedrock) in the Hie lake area (in the northern portion of the study area) indicate ice movement to the southwest (N140°W). According to Sharpe and Edwards (1979), pebble lithology of the Catfish Creek Till reflects ice movement from the northeast, as limestone clasts are less abundant than dolostone. This direction is also consistent with drumlin orientation.

2.2.1.2 Elma Till

The Elma Till (Karrow 1974) is a deposit of the Georgian Bay lobe and is associated with the Teeswater Drumlin Field and the Singhampton moraine complex (Figures 2.1 and 2.5). It is defined as non-plastic, fissile, calcareous silt, sandy silt to clayey silt till that ranges from 2 to 15 m in thickness (Barnett 1992a). Clast content ranges between 5 to 25% and is predominantly composed of dolomites and limestones. According to Barnett (1992a), the Elma Till was deposited during the later part of the Port Bruce Stade but deposition of this till likely continued during the Mackinaw Interstadial.

2.2.1.3 Dunkeld Till

In the study area the Dunkeld Till is defined as overconsolidated, blocky, brown silt to fine sandy silt till with low pebble content (less than 5%, Sharpe and Edwards 1979). It occurs at surface in a small area located east of the community of Lovat (east of the Bruce nuclear site) where it is partially covered by fined-grained glaciolacustrine clays, silts and sands. The areal extent of the Dunkeld Till is limited and it has not been observed north of the Banks moraine (Figure 2.6). It is mainly associated with deposits that form the Gibraltar Moraine (Cowan 1977) within the Saugeen River valley. The limited areal extent of this till implies that it is the result of a minor ice-marginal readvance that subsequently reworked glaciolacustrine clays and silts within the Saugeen River valley. According to Sharpe and Edwards (1979), this readvance occurred during the later part of the Port Bruce Stade.

2.2.1.4 St. Joseph Till

The youngest and most widespread till in the study area is the St. Joseph Till (Cooper and Clue 1974). It is defined as clayey silt to silty clay, stone poor, diamicton interpreted to reflect an ice marginal advance of the Huron lobe (Cooper and Clue 1974, Sharpe and Edwards 1979). In the western portion of the study area the till matrix is characterized by a clayey silt texture whereas in the eastern portion of the study area it is defined by a gritty silt texture. According to Sharpe and Edwards (1979) this textural inconsistency is a reflection of the incorporation of a variety of older underlying sediments from a more northerly provenance as it has not been observed to directly overly bedrock. Consequently, its lithology reflects Silurian-age dolostones modified by Devonian-age limestones. In addition, pebble counts completed by Sharpe and Edwards (1979) show a 0.7 limestone:1 dolostone ratio and the fine fraction has the same proportion of calcite to dolomite. These values are higher than those of the underlying sediment, and this indicates the effect of ice movement out of the Huron basin to supply Devonian-age limestone (Sharpe and Edwards 1979).

According to Sharpe and Edwards (1979) and Barnett (1992), the fine-grained matrix of St. Joseph Till is due to a readvance of the Huron lobe. During this readvance, glacial Lake Saugeen, a small proglacial lake which occupied the Saugeen River valley, was overridden and fine-grained glaciolacustrine sediments were incorporated into the matrix of the till. This event resulted in the structureless, stone-poor till that is commonly interbedded with contorted beds of fine-grained glaciolacustrine sediments. Evidence of this event is supported by contorted and deformed rhythmically bedded silts and clays (glaciolacustrine sediments) that underlie a silt-rich diamicton (St. Joseph Till). These beds were observed in several vertical sediment profiles observed in aggregate (sand and gravel) operations in the study area (refer to Chapter 3 of this report).

2.3 Ancestral Lakes of the Lake Huron Basin

Following the retreat of the LIS form the Huron basin several ice-contact and proglacial lakes occupied the Huron basin during Late Wisconsinan and Holocene times (Figure 2.7). An overview of these lakes is presented below followed by a discussion on isostatic recovery (crustal rebound) in the Lake Huron drainage basin. Further information pertaining to paleolake levels and isostatic recovery in the Huron basin has been documented by Goldthwait (1910), Stanley (1936, 1937, 1938), Deane (1950), Chapman (1975), Karrow et al. (1975), Karrow (1980, 1985, 1986, 1987), Chapman and Putnam (1984), Eschman and Karrow (1985), Kaszycki (1985), Lewis and Anderson (1989) and Lewis et al. (1994).

2.3.1 Lake Warren

The oldest ice-marginal lake to inundate the study area during was glacial Lake Warren (Spencer 1888). Lake Warren is represented by at least two distinct shorelines, commonly referred to as strands, that are typically 4 to 7 m apart vertically (Eschman and Karrow 1985). Lake Warren was held against the Michigan shore of the Huron Basin by an ice front located north of Saginaw Bay, at Tawas City (Figure 2.7b) (Burgis and Eschman 1981). The ice margin extended southward across Saginaw Bay to the base of the Bruce Peninsula, continuing along the base of a topographic high south of Georgian Bay to the southeast to or beyond Buffalo New York area (Figure 2.7a and 2.7b) (Calkin 1970, Calkin and Feenstra 1985). The duration of Lake Warren within the Huron Basin is controversial at best, according to Farrand and Eschman (1974), Lake Warren occupied a portion of the Huron Basin until 12,700 years before present (BP), whereas studies completed by Hansel et al. (1984) suggest that Lake Warren remained in the Huron Basin until 11,800 BP. According to Farrand and Eschman (1974), Burgis and Eschman (1981) and Hansel et al. (1985) all levels of Lake Warren drained westward through the Grand Valley outlet (Figure 2.7a).

Work completed by Cooper (1979), Sharpe and Edwards (1979) and Fitzgerald et al. (1979) have identified fragmented features related to Lake Warren near the northern shore of Lake St. Clair (Figure 2.7a). Cooper (1979) found evidence of two Lake Warren strands separated vertically by about 2 m and three Lake Warren bluffs near the community of Goderich (south of the study area between the Bruce Peninsula and the southern end of Lake Huron). Quaternary mapping by Sharpe and Edwards (1979), indicate that much of the dissected flat area west of the Wyoming moraine represents the Lake Warren plain (Figure 2.6). East of the study area near the community of Chelsey, poorly developed beach ridges located higher than the maximum water plain of glacial Lake Algonquin have been attributed to Lake Warren. Beach ridges developed on the flank of the Banks moraine at 280 mASL (metres above sea level) have also been attributed to Lake Warren by Sharpe and Edwards (1979).

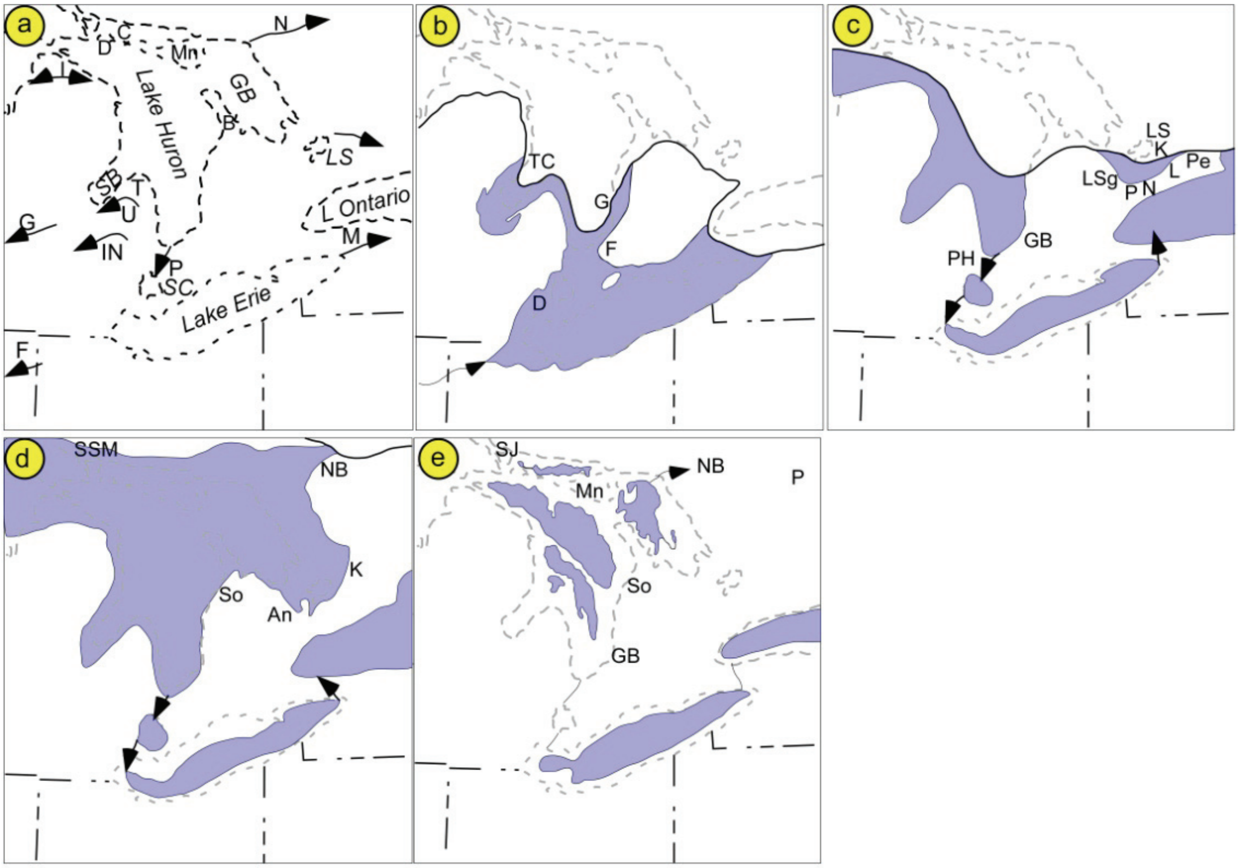
2.3.2 Lake Wayne

Glacial Lake Wayne is defined as a lower water stage that occupied the Huron Basin during the later part of the Lake Warren sequence (Gilbert 1873, Prest 1970). It is often referred to in older literature as the Lower Warren phase (Gilbert 1873). The formation of this lake is thought to have resulted from an ice-marginal retreat from the Huron basin (Eschman and Karrow 1985); however, the location of the Huron lobe that constrained Lake Wayne is not entirely clear. According to Muller and Prest (1985), Lake Wayne only occurred for a time span of less than 400 years eventually draining eastward through the Syracuse Channels in New York state (Figure 2.7a).

2.3.3 Lake Grassmere

Glacial Lake Grassmere represents a lower water phase in the Lake Huron Basin following the drainage of glacial Lake Wayne and further northward retreat of the LIS (Eschman and Karrow 1985). The lake was originally named by Lane (1900) after the recognition of glaciolacustrine features near a small village in northern Michigan (Figure 2.7a). Following the drainage of glacial Lake Wayne, water levels dropped to ~195 m in the Lake

Huron Basin, this low water level is thought to reflect the Lake Grassmere water plain (Cooper 1979).



Note: **(a)** Paleodrainage outlets related to the Lake Huron Basin. Arrows indicate direction of outflow. Outlets: F – Ft. Wayne, G – glacial Grand River, I – Indian River Lowland, IN – Imlay City-North Branch, M – Mohawk, N – North Bay, P – Port Huron, T – Trent Lowland, U – Ubly. Other letters indicate: B – Bruce Peninsula, C – Cockburn Island, D – Drummond Island, GB – Georgian Bay, Mn – Manitoulin Island, SC – Lake St. Clair, LS – Lake Simcoe and T – Michigan's "thumb". **(b)** Maximum areal extent of Lake Warren (210 m). D – Detroit, F – Forest, G – Goderich and TC – Tawas City. **(c)** Maximum aerial extent of early glacial Lake Algonquin and Schomberg. Letters refer to GB – Grand Bend, K – Kirkfield, LS – Lake Simcoe, LSg – Lake Schomberg, L – Lindsay, N – Newmarket, P – Palgrave, Pe – Peterborough and PH – Port Huron. **(d)** Areal extent of Main Lake Algonquin (184 m). Letter symbols: An – Alliston, K – Kirkfield, M –Mackinac Island, NB – North Bay, SJ – St. Joseph Island, So – Southhampton, SSM – Sault Ste. Marie and Su – Sudbury. **(e)** Lakes Stanley (~45 m) and Hough. Letter symbols: GB – Grand Bend, Mn – Manitoulin Island, NB – North Bay, P – Petawawa, SJ – St. Joseph Island, So – Southhampton (modified from Eschman and Karrow 1985).

Figure 2.7: Ancestral Lakes of the Lake Huron Basin

Evidence of Lake Grassmere in the study area was not identified by the author, however, investigations completed by Cooper (1979) and Fitzgerald et al. (1979) identified features related to the Lake Grassmere water plain east of Lake Huron along the St. Clair River. It is generally accepted that Lake Grassmere was relatively short-lived, lasting less than 100 years (Eschman and Karrow 1985).

2.3.4 Lake Lundy

Further ice-marginal retreat of the LIS from the Huron Basin resulted in the formation of glacial Lake Lundy at approximately 13,000 years BP (Eschman and Karrow 1985). Lake Lundy was short lived and only occupied the Huron Basin from 13,000 to 12,400 years BP. The Lundy water plain is slightly lower than that of glacial Lake Warren and occurs at approximately 189 mASL. It is typically marked by a linear ridge of windblown sand at the appropriate elevation. Quaternary investigations completed by the author found no evidence of Lake Lundy in the study area. Similarly, Cooper (1979) failed to observed evidence for Lake Lundy in the Grand Bend area (south of the study area), however, investigations by Fitzgerald et al. (1979) identified a strandline related to glacial Lake Lundy along the southern end of Lake Huron.

2.3.5 Lake Algonquin

The history of glacial Lake Algonquin is best defined as complex. During its existence between (12,500 to 10,600 years BP, Karrow et al. 1975, Futyma 1981) it occupied portions of the basins of Lake Huron and Michigan Basins (Karrow 1985). For additional information pertaining to glacial Lake Algonquin the reader is referred to Karrow et al. (1975), Futyma (1981), Eschman and Karrow (1985), Finamore (1985) and Larsen (Larsen 1987).

The history of glacial Lake Algonquin is generally subdivided into four parts following Eschman and Karrow (1985).

1. An early Lake Algonquin southward-draining, high lake-level phase that is thought to have occurred simultaneously with glacial Lake Schomberg (located east of the study area) and possibly after waters of Lake Schomberg waters had coalesced with those of Early Lake Algonquin (Figure 2.7c). Water levels associated with this phase of Lake Algonquin are estimated to have been ~184 mASL.
2. A low lake level phase termed the Kirkfield phase defines the period when the outlet for glacial Lake Algonquin switched to the east (Fenelon Falls outlet, Figure 2.7c, Finamore 1985, Kaszycki 1985) allowing overflow to bypass the Lake Erie basin. Investigations completed by Miller et al. (1979) indicate that this phase occurred between 11,300 to 10,500 years BP.
3. A high lake level phase termed the main Algonquin phase when drainage was redirected southward after the closing of the Kirkfield outlet due to isostatic recovery. Water levels of glacial Lake Algonquin rose to 184 mASL (Figure 2.7c).
4. An Algonquin-Stanley low level lake phase of falling water levels which occurred as a series of outlets became ice-free (uncovered) to the northeast across Algonquin Park and into the Ottawa River (Figure 2.7c).

Evidence of erosional features and landforms associated with glacial Lake Algonquin within the study area are abundant. Lake Algonquin deposits consist mainly of well-sorted, medium to coarse-grained sands in the form of beach ridges and glaciolacustrine plains. Typically these deposits are several metres in thickness. The most pronounced Algonquin feature in the study area is the Algonquin Bluff, traversing parallel along the Lake Huron shoreline for several kilometres. Near the community of Port Elgin (north of the Bruce nuclear site), the bluff occurs at an elevation of 221 mASL. At this elevation wave-action within glacial Lake Algonquin incised a 30 m high bluff into the St. Joseph Till. Eroded sediments of the St. Joseph Till were subsequently redeposited on a broad plain adjacent to Lake Huron (Sharpe and Edwards 1979).

2.3.6 Lake Hough and Lake Stanley

Glacial lakes Hough and Stanley are related to the continued, step-wise dropping of water levels in the Lake Huron Basin. A very low level lake phase in the Huron Basin was first recognized by Hough (1962) through the results of lake coring. Hough's (1962) investigation identified glaciolacustrine sequences indicating the existence of lake levels ~100 m below the present elevation of Lake Huron. Further investigations by Prest (1970) indicate that drainage of this lake occurred to the east through the Ottawa River. Many of the beaches and/or features related to Lake Hough are submerged by present day water levels of Lake Huron or were destroyed by the partial inundation of the Huron Basin by glacial Lake Stanley (Eschman and Karrow 1985).

The results of carbon dates obtained from submerged tree stumps and peat bogs below Lake Huron suggest that Lake Stanley began 10,000 years BP or slightly later (e.g., Barnett 1992a). According to Eschman and Karrow (1985), during the next 500 years isostatic recovery of the North Bay outlet raised water levels in the Huron basin (above present day water levels) allowing southward drainage near Chicago and Port Huron near the southern extent of Lake Huron. This period of rising water levels is termed the Stanley-Nipissing transgression (Hough 1958).

2.4 Post Glacial Lakes

2.4.1 Nipissing Transgression

Approximately 5,000 years ago the northern drainage route for Lake Huron, located at North Bay (Figures 2.7a and 2.7e), rose differentially to the same elevation as drainage outlets located at Chicago and Port Huron at the southern ends of Lake Michigan and Lake Huron (Eschman and Karrow 1985). This event resulted in the formation of what is termed the Nipissing Great Lakes in the basins of lakes Superior, Huron, Michigan and Georgian Bay (e.g., Barnett 1992a). This period of transgression is incorrectly, but more commonly, referred to as glacial Lake Nipissing.

The first lake to occur within the Huron basin during this transgression, glacial Lake Nipissing, formed numerous beach ridges located within the study area. Aside from these, the most pronounced feature is an extensive bluff located approximately 4 to 5 m above the present day waters of Lake Huron (Cowan 1977, Sharpe and Edwards 1979). Near the communities of Port Elgin and Kincardine (immediately north and south of the Bruce nuclear site) at 190 mASL, an extensive Nipissing bluff is cut into the Algonquin sand plain.

Continued erosion of the Port Huron outlet is thought to have resulted in the step-wise lowering of Lake Nipissing and partial inundation of the Huron Basin by Lake Algoma, however, Eschman and Karrow (1985) suggest that climatic-fluctuations may explain strandlines located below the Nipissing water plain. In the study area, a weak shoreline at an elevation of 184 mASL, that parallels the present day Lake Huron shoreline, may represent postglacial Lake Algoma (Sharpe and Edwards 1979). As lake levels continued to drop in Lake Huron Basin, localised ponding of glacial meltwater occurred. This resulted in several, isolated proglacial lakes such as glacial Lake Saugeen which occupied the Saugeen River basin.

3. FIELD-BASED INVESTIGATIONS

3.1 Introduction

This section of the report provides the results of the field-based portion of the Bruce nuclear site investigation. As previously stated, for the purpose of this investigation the study area was subdivided into two zones based on proximity to the Bruce nuclear site. The majority of field-based observations were completed within the inner study zone, Zone A, that was assigned a buffer zone or radius of 5 km from the Bruce nuclear site. Additional analysis in Zone A was facilitated by high-resolution light detection and ranging (LiDAR) imagery. Observations completed within the outer zone, Zone B, were largely completed by air photo interpretation facilitated by a 10 m grid-spaced digital elevation model accented with hillshaded relief.

This section of the report is subdivided into two parts. The first describes features and/or landforms deemed as having a probable neotectonic origin as identified through the interpretation of air photographs viewed in stereo and the analysis of a DEM and LiDAR imagery. The validation or rejection of a neotectonic origin for each of the features and/or landforms identified is discussed below.

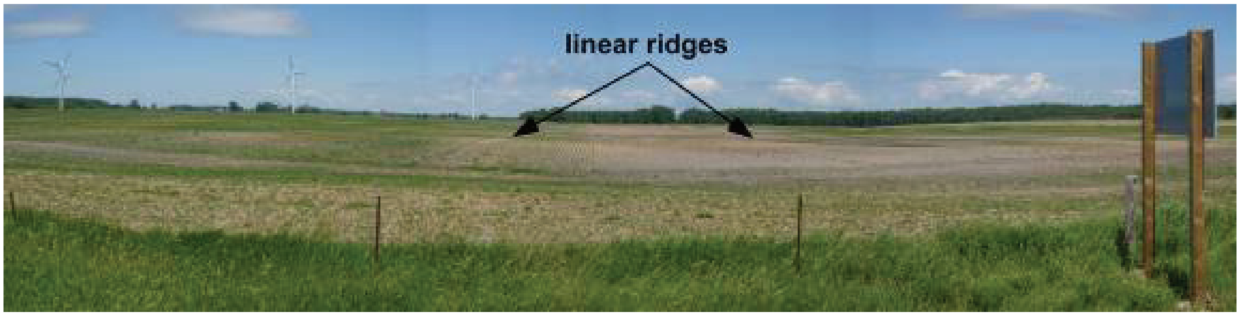
The second part of this section describes the analysis of vertical and lateral sediment profiles within study Zone A as observed through natural (i.e., river banks) and manmade (aggregate operations, etc.) exposures. The analyses of these profiles, and discussions pertaining to genesis (neotectonic vs. non-neotectonic), are discussed below. In conclusion, an overview of the features and/or landforms, and sediment profiles examined are summarised below in Table 3.1.

3.2 Part I: Air Photograph Interpretation and LiDAR Analysis

A total of 118 monochrome air photographs (scale of ~1:40,000) facilitated by a 10 m grid spaced DEM accented with hillshaded relief, were interpreted in order to determine the location, or lack thereof, of neotectonic features within study Zones A and B. Of the interpreted air photographs only 4 features and/or landforms necessitated further analysis to confirm or negate a neotectonic origin. Based on the analysis of LiDAR imagery, an additional two areas located near the community of Inverhuron (immediately east of the Bruce nuclear site), required field-based examination to determine genesis. The features and associated landforms near the community of Inverhuron are discussed separately below.

3.2.1 Linear Ridges

Several linear, northwest - southeast trending ridge-like features occur throughout the study area (Figure 3.1). Ridges are typically 5 m in length and 1 to 2 m in height (Figure 3.1). Similar ridge-like landforms superimposed on features such as wave-cut platforms were identified by Barnett (1986, 1992b) west of the study area near the community of Barrie, Ontario. Internally, landforms identified by Barnett (1986, 1992b) are composed of the same lithotype assemblages in which they overlie. More specifically, ridge-like features that overly wave-cut notches are predominantly composed of coarse-grained, stratified sediments whereas those superimposed on ground moraine cover are typically composed of till. The superimposition of these landforms, similarity of sediments in which they overlie and the preservation of these landforms suggests that ridge formation occurred in post-glacial time (following ice-marginal retreat from the area). Although not documented and largely conjecture-based, a neotectonic origin has been postulated for these landforms. Based on the information above it is has been inferred that ridges are the by-products of underlying fault zones, formed in response to neotectonic activity.



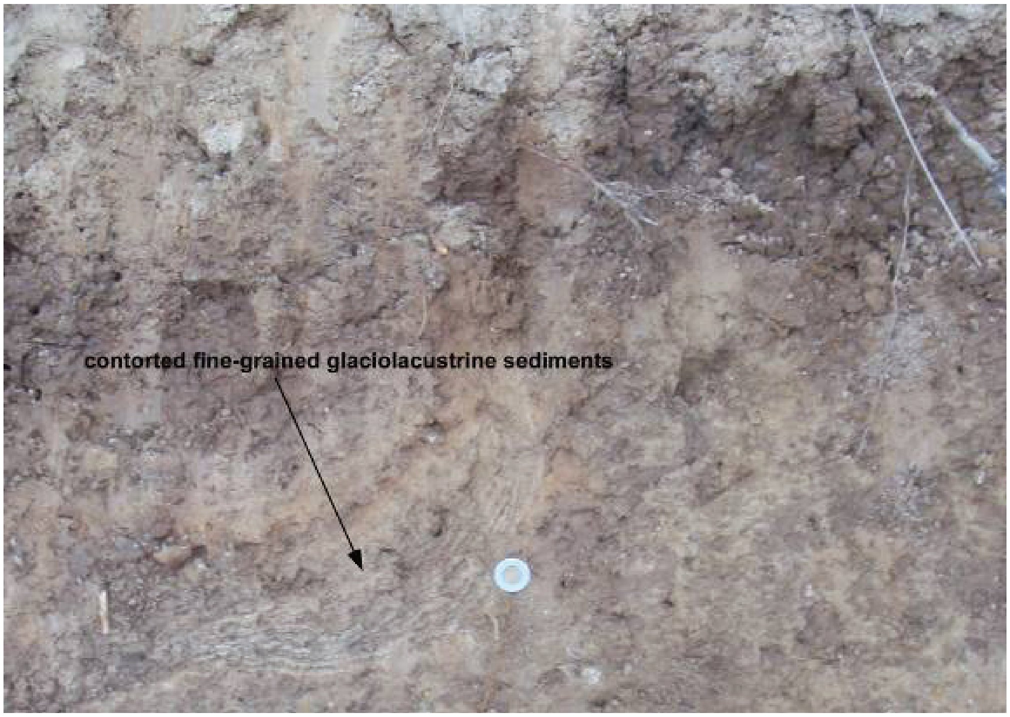
Note: Arrows point to the crests of ridges. Observer is looking northeast.

Figure 3.1: Linear Ridges (Oriented Northwest to Southeast) within Study Zone A

In the study area, linear ridges occur as nests (several ridges within an area), solitary ridges were not identified. The crests of ridges are generally linear to sinuous in shape and are oriented northwest to southeast (Figure 3.1). Internally, ridges are composed of a silt-rich, relatively stone-poor (less than 3%) diamicton that contains blocks, often rotated, and contorted beds of rhythmically bedded very-fine sands, silts and clays (Figure 3.2). In the examined study zones (Zones A and B), ridges are confined to within the mapped limits of the St. Joseph Till boundary as defined by Sharpe and Edwards (1979) and do not occur within the mapped boundaries of dissimilar sediment types (i.e., fine-grained glaciolacustrine plains, etc.). Superimposition of these landforms on features of dissimilar lithotype assemblages, such as wave-cut platforms, was not observed by the author.

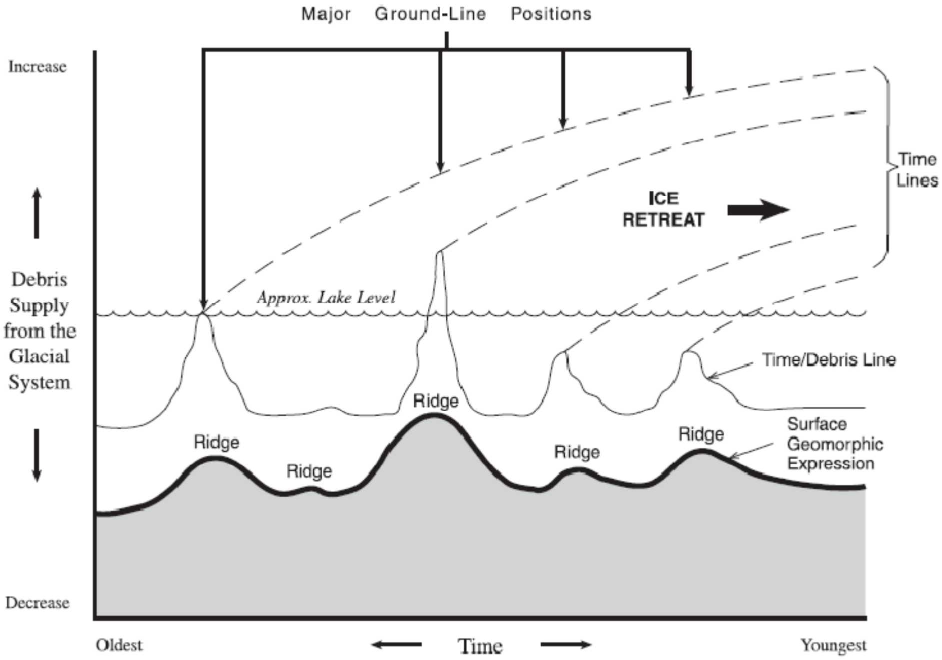
Collectively, the orientation of these landforms, which coincides to the direction of ice-marginal advance from Lake Huron (Huron-lobe) and not the orientation of underlying basement faults (Sanford et al. 1985), the limited aerial distribution in which they occur, the lack of identifiable liquefaction features and the consistency of sediments that compose them strongly negates a neotectonic origin for these landforms.

It is more plausible to infer that these landforms reflect ice-press processes which occurred during or shortly after ice-marginal advance of the Huron-lobe during Port Bruce time. As documented by Sharpe and Edwards (1979) and Barnett (1992a), the St. Joseph Till is a result of ice-marginal readvance from the Huron-lobe which overrode glacial Lake Saugeen. This readvance is called upon to explain the incorporation of fine-grained glaciolacustrine sediments and the presence of flow-till facies commonly associated with this till. The formation of ridge-like features examined in the study areas is also attributed to this event and likely represents a time in which the ice-margin was temporarily grounded. Upon ice-marginal grounding, saturated sediments were incorporated or “pressed” into crevasse and/or voids located at the base of the ice sheet resulting in a landscape of linear to sinuous crested ridges. The resulting ridges mirror the inverted morphology of the former ice sheet. Similar interpretations have been called upon by Menzies (2001) to explain the morphology and formation of larger-scale ridges in glaciolacustrine settings (Figure 3.3).



Note: Two dollar coin for scale.

Figure 3.2: Contorted and Rotated Fine-grained, Rhythmically Bedded Glaciolacustrine Silts and Clays within a Linear Ridge



Note: Figure is from Menzies (2001).

Figure 3.3: Formation of Ridge-like Features along Ice-marginal Grounding Lines

3.2.2 Dendritic Patterns

Numerous dendritic and perpendicular to pseudo-trellis patterns occur on ground surface in study Zones A and B. These patterns are clearly visible on air photographs viewed in stereo (Figure 3.4) and typically reflect the natural drainage patterns of present day fluvial systems. In addition, some of these patterns are the result of surface water runoff and reflect patterns of soil erosion. Of concern however, are the origin of pseudo-trellis patterns and isolated dendritic patterns that are not associated with present day fluvial systems (Figure 3.4).

Note: Source is National Air Photograph Library N80074 L4406-69.

Figure 3.4: Isolated Dendritic Pattern with a Scale of ~1:40,000

Perpendicular to trellis shaped drainage patterns are sometimes associated with structurally induced bedrock terrain (i.e., faulted terrain; Peltier, 1998). In these areas stream drainage patterns typically mirror the underlying bedrock morphology. As sediment thickness typically exceeds 50 m throughout the study area (inner and outer zones), the exception being in areas proximal to Lake Huron where sediment thickness can vary between 0 to 20 m, it is not plausible to assume that these patterns reflect underlying bedrock faults.

Alternatively, the morphology of observed drainage patterns may reflect lateral spreading or the natural venting of underlying sediments caused by a tectonic event (e.g., Obermeier 1999). To verify or reject a neotectonic or paleoseismic origin for these patterns, isolated dendritic and perpendicular to pseudo-trellis patterns were subjected to field-based investigations. Based on data obtained from these investigations, examined perpendicular to pseudo-trellis shaped drainage patterns are the result of anthropomorphic processes. As illustrated in Figure 3.5, drainage patterns have been altered by the owners/operators of agricultural properties. These alterations, when viewed in plan, illustrate a perpendicular to trellis-shaped drainage pattern (commonly associated with underlying bedrock faults), thereby leading to the invalid assumption that these patterns overly bedrock faults and are the products of neotectonic activity.

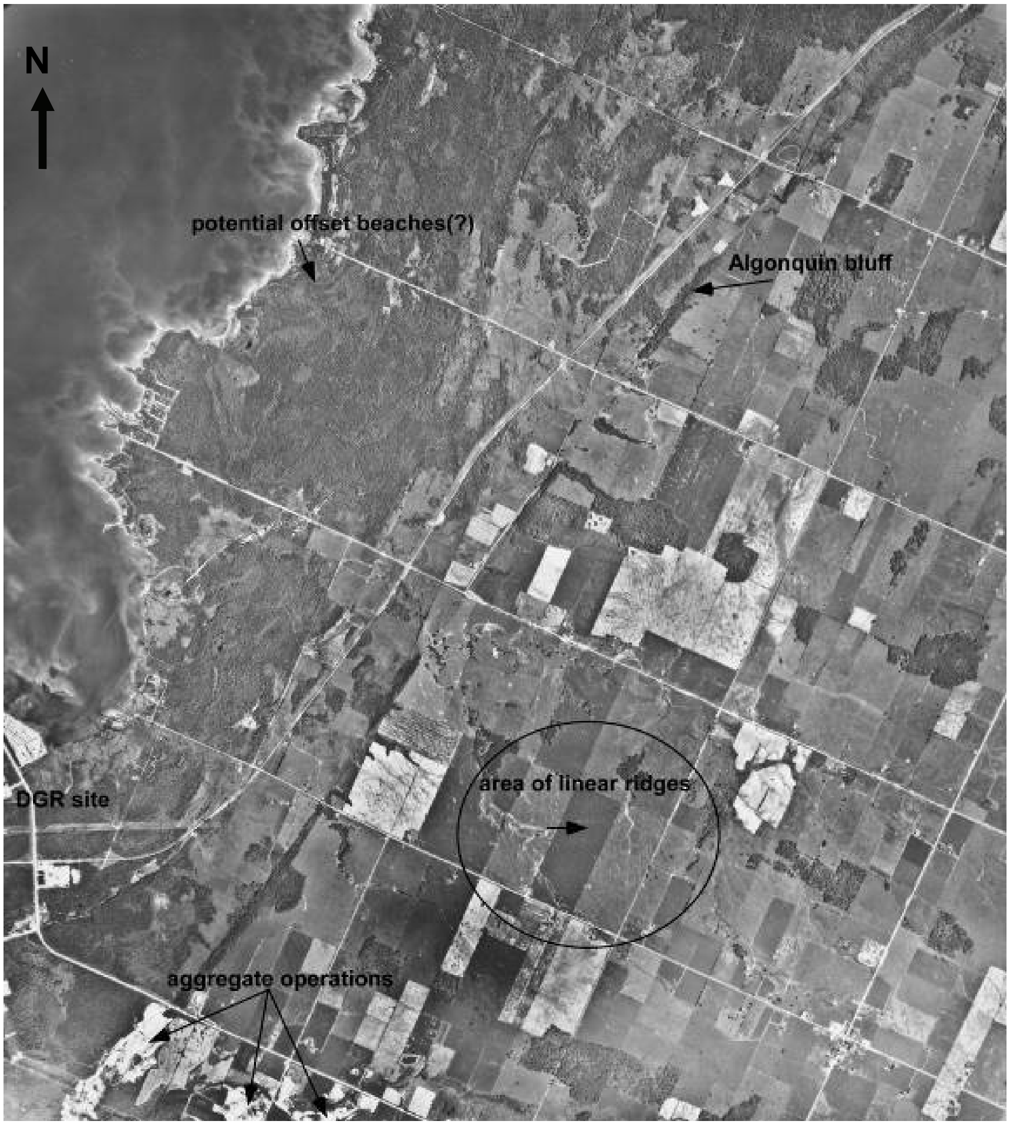
Figure 3.5: Anthropomorphically Induced Perpendicular to Trellis-like Pattern of Drainage System

Isolated dendritic drainage patterns examined are the result of natural soil erosion likely caused by ephemeral discharge events such as spring runoff. Based on evidence obtained from field examinations it is concluded that these patterns are not related to neotectonic activity. The absence of sand boils, areas of sediment venting, commonly associated with lateral spreading, adjacent to drainage patterns further aids in negating a neotectonic origin for observed patterns.

3.2.3 Offset Beach Ridges and Lake Bluffs

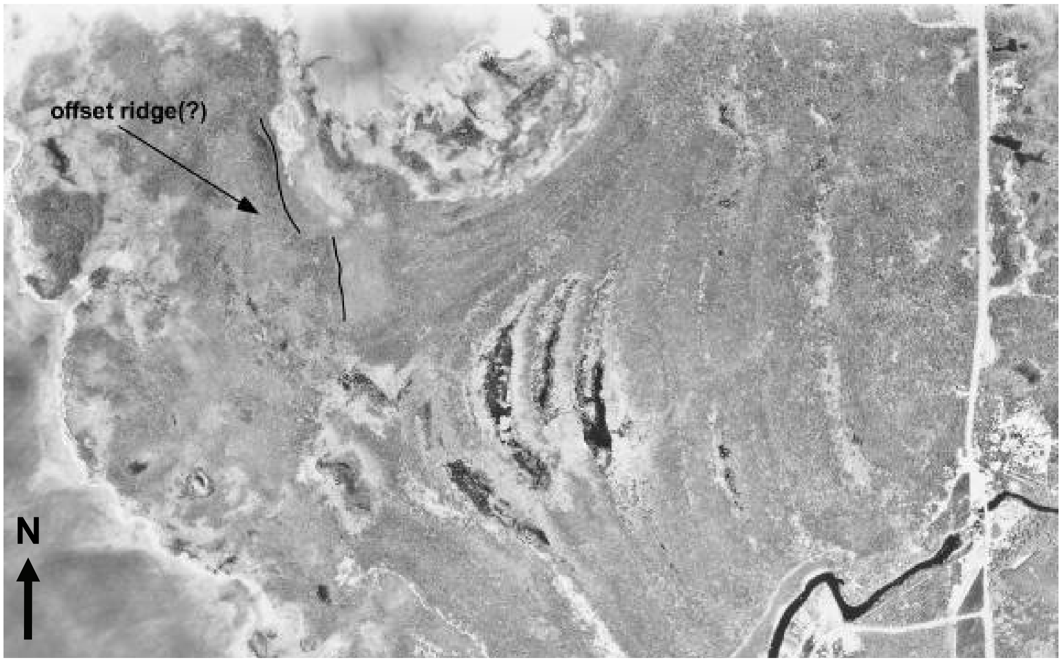
Investigations completed on offset beach ridges and their association to neotectonic events (ground shifting) has been completed by numerous authors (e.g., Gorrell 1988, Obermeier 1996a, 1996b). In the study area, beach ridges that appeared to be ‘offset’ on air photographs viewed in stereo were subjected to field-based examination (Figures 3.6 to 3.9). As a result of observations completed during the field investigation, none of the 'offset' beach ridges examined is a result of neotectonic activity.

The offset-like appearance of examined beach ridges is explained by anthropomorphic processes such as road building and residential development, scattered vegetation growth and subsequent dune (eolian) development. Collectively, these processes have altered the original morphology of the examined ridges creating an offset-like appearance when viewed in plan or in stereo (Figures 3.6 to 3.9). The direct cause(s) of the offset-like appearance in the areas examined is explained in the accompanying figure captions (Figures 3.6 to 3.9).



Notes: Offset appearance of beach ridges in air photograph is due to scattered vegetation growth and dune (eolian) development. Air photograph is at a ~1:40,000 scale (National Air Photograph Library N80074 L4406-69).

Figure 3.6: Location of Linear Ridges, Potential Offset Beach Ridges, Lake Algonquin Bluff and Aggregate Operations in Study Zone A

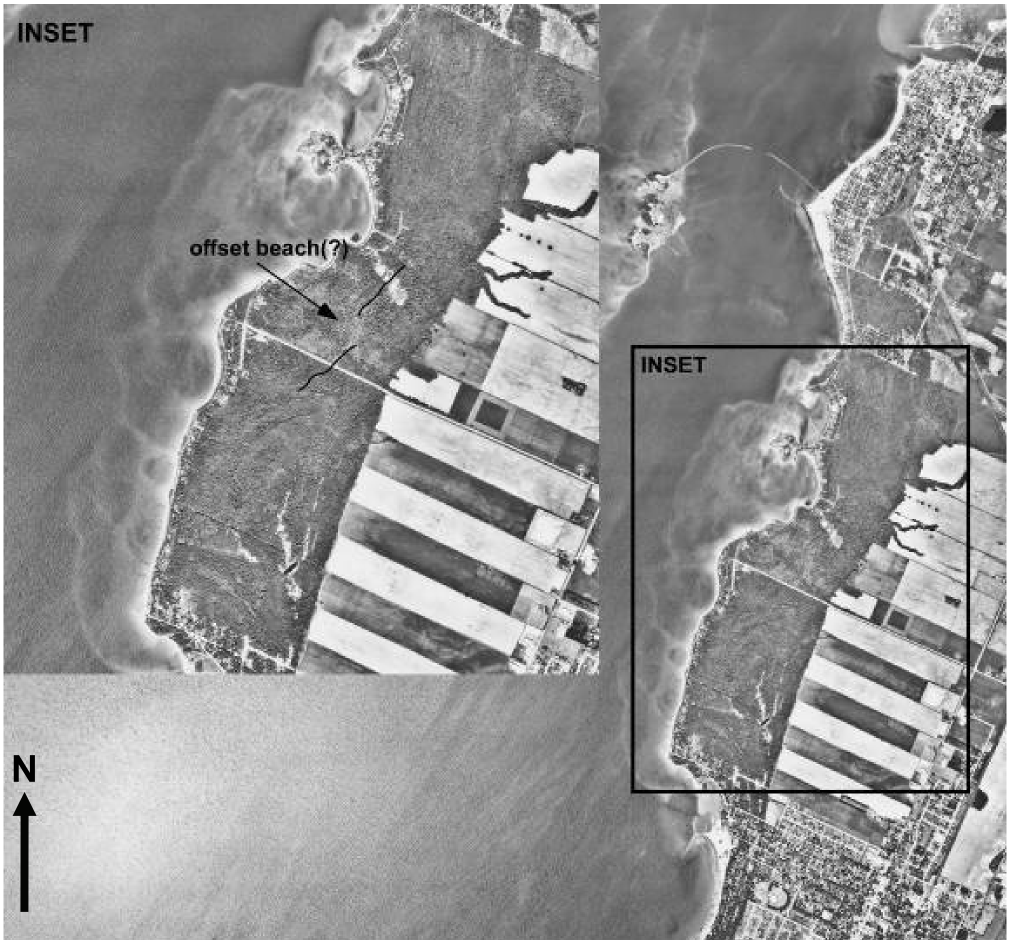


Notes: Offset appearance of the ridge (black lines in photograph) is due to inundation of adjacent wetland area. The ridge which is accented by the vegetation marks the periphery of the wetland. Scale of air photograph is ~1:40,000 (National Air Photograph Library N80086 L4411-243).

Figure 3.7: Location of Offset Ridge North of the Bruce Nuclear Site in Study Zone A

Notes: Black lines indicate offset ridges. Air photograph scale of ~1:40,000 (National Air Photograph Library N80086 L4411-243).

Figure 3.8: Offset Appearance of Ridges due to Walking Trail Construction



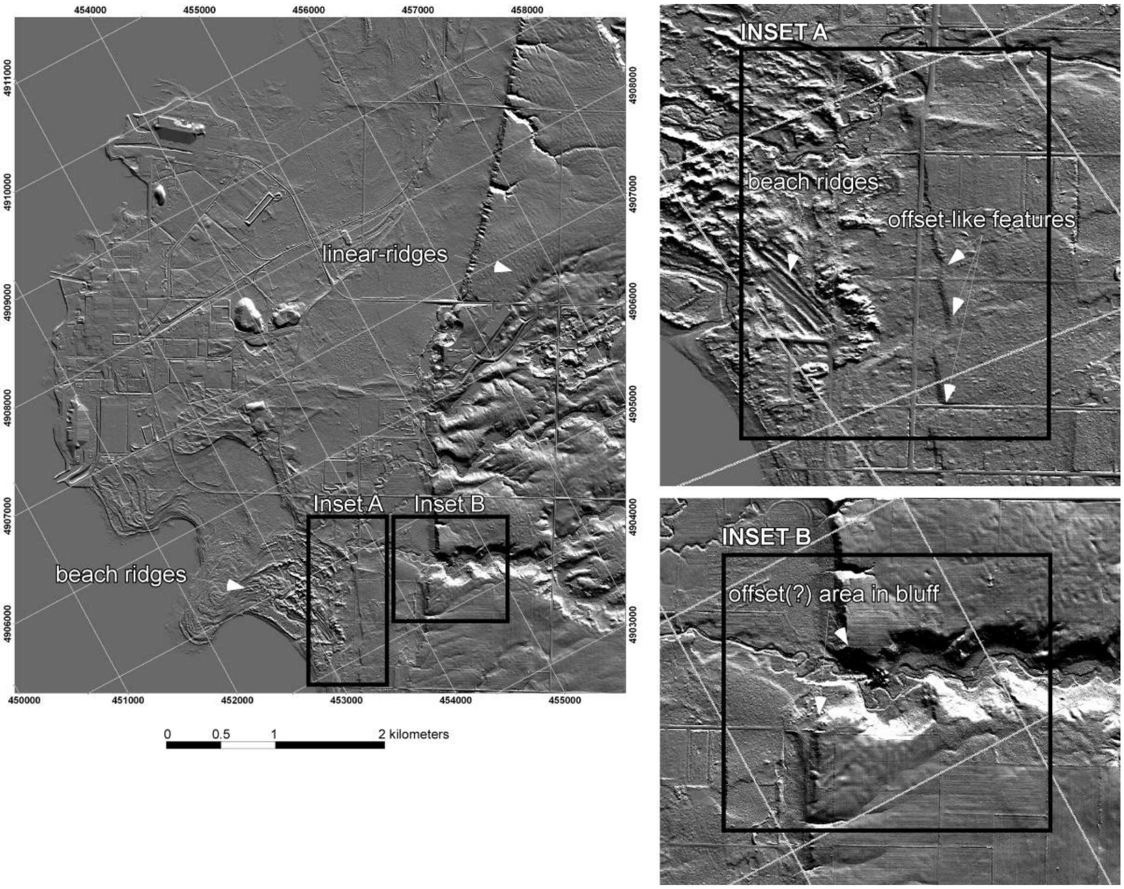
Notes: Crest of the ridge is continuous but altered in plan view due to eolian sand complexes. Scale of air photograph is ~1:40,000 (National Air Photograph Library N80074 L4407-167).

Figure 3.9: Offset Appearance to Beach Ridge in Air Photograph Due to Scattered Vegetation and Dune Development

3.2.4 Inverhuron Offsets

Analysis of LiDAR imagery resulted in the identification of four offset-like features east to the community of Inverhuron (southwest of the Bruce nuclear site, Figure 3.10, Inset A). Three of these offset-like features collectively form a single, westward sloping, ridge-like feature as illustrated on Figure 3.10 whereas the fourth and final offset-like feature observed is located within a lake bluff immediately east of Inverhuron (Figure 3.10, Inset B).

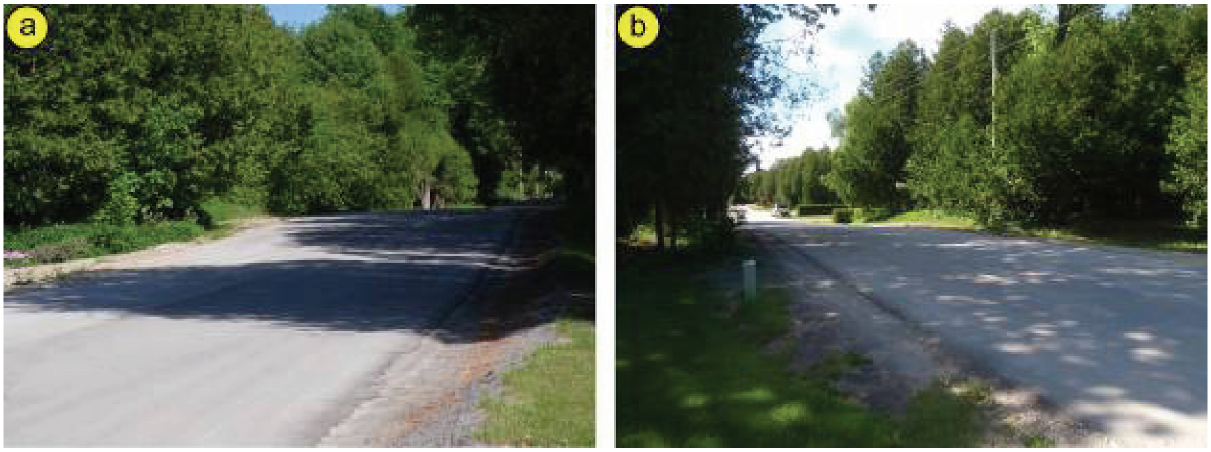
Based on field examination, the ridge is a westward sloping lake bluff formed by glacial Lake Nipissing approximately 5,000 years BP (Karrow and Eschman 1985, Figures 3.11a and 3.11b). The offset-like trend observed in LiDAR imagery is likely the result of preferential erosion of the bluff. Based on field inspection of the bluff an offset-trend was not observed. The feature is described as a continuous bluff with an irregular trending crest-line (Figures 3.11 and 3.12). It is likely that areas irregularity or areas of greater erosion along the crest-line of the bluff have been amplified through LiDAR imagery thereby illustrating an offset-like trend. The absence of any offset-like trends in adjacent beach rides located less than 100 m west from the bluff (Figure 3.10, Inset A) argue against a neotectonic origin for the observed offset-trend.



Notes: Linear ridges are located in the western portion of the image. Inset A depicts three offset-like trends in Nipissing-aged lake bluff. Adjacent beach ridges to the west are not offset. Inset B illustrates an offset-like area in the Algonquin-aged bluff formed by preferential erosion.

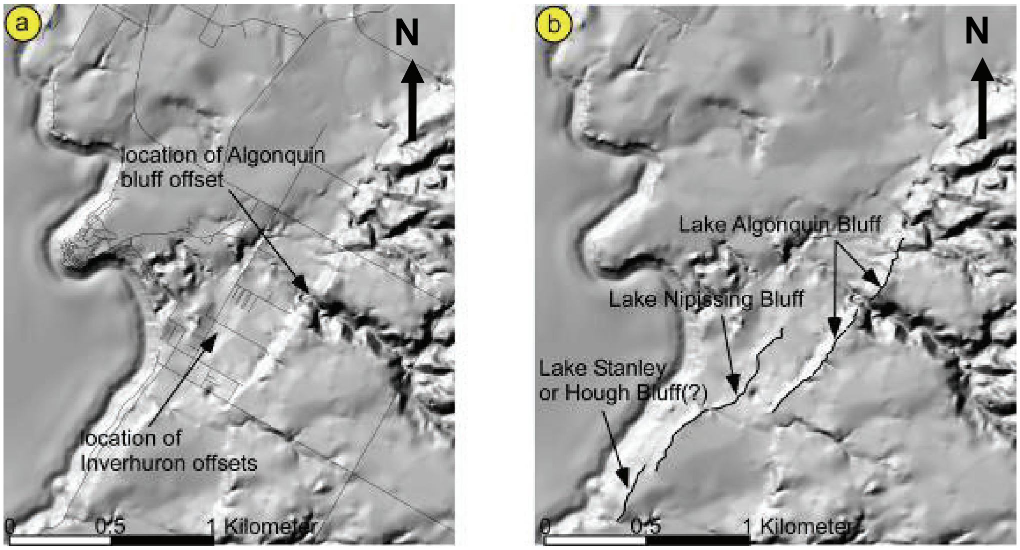
Figure 3.10: LiDAR Imagery of Offset-like Features near the Community of Inverhuron

A single offset-like trend immediately west of the community of Inverhuron is visible where the Lake Algonquin bluff is dissected by the Sauble River (Figure 3.10, Inset B). Similar to the offset-like trend described above, a visible offset was not noted during the field-based investigation. This offset-like trend is also attributed to selective erosion within the bluff as it is not apparent in adjacent beach ridges.



Notes: **(a)** Photograph of the Lake Nipissing bluff looking west. Note the eastward (toward observer) slope of the bluff. **(b)** Photograph of the Lake Nippissing bluff looking east.

Figure 3.11: Photographs of the Lake Nipissing Bluff



Notes: **(a)** Hillshaded DEM of the offset-trend in the Lake Nipissing bluff near the community of Inverhuron. Hillshade is vertically exaggerated by a factor of 10. Arrows depict areas of offsets noted in LiDAR imagery. **(b)** Lines depict irregular crests of the Nipissing and Algonquin bluffs formed through preferential erosion. Roads have been removed to provide clarity.

Figure 3.12: Hillshaded LiDAR Assessment of Lake Bluffs near the Bruce Nuclear Site

3.3 Part II: Results of Field-Based Examinations

This part of the section describes the analyses of vertical and lateral profiles of sediment-outcrop sections examined in road-cuts, river valleys and aggregate operations (sand and gravel pits) within the study area. The analysis of sections was completed to locate and determine the origin of observed paleoliquefaction features. In this section, the term liquefaction refers to the conversion process of moderately cohesive, unconsolidated sediments into a fluid, water-saturated mass as defined by Ankertell and Dzulynsky (1968). Prior to discussing the results of field-based examinations, an overview of liquefaction processes is provided below. The intent of this overview is to provide the reader with a better understanding of liquefaction processes.

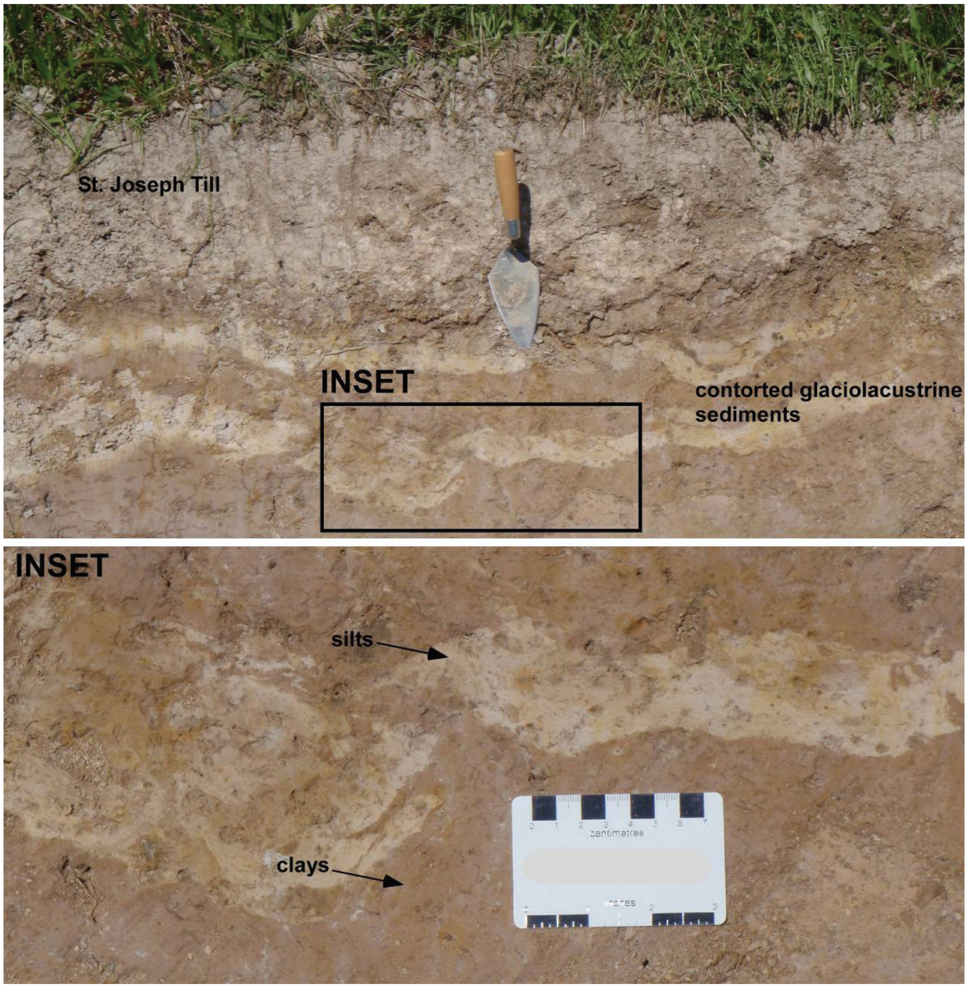
According to Allen (1984), sediment strain and subsequent liquefaction processes are largely dependent on the initial void ratio of sediments. In response to loading, sediments can undergo one of two processes: strain-softening or strain-hardening (Allen 1984, Vaid et al. 1985). Strain-softened sediments, loose sands for example, can be triggered to collapse, either monotonically or cyclically, if the static shear stress is greater than the ultimate shear strength of the sediment (Zdravkovic 1996). In this case flow liquefaction occurs, where the sediment deforms at a low constant residual shear stress (Zdravkovic 1996). If the sediment strain-hardens (moderately dense to dense sand) flow liquefaction will generally not occur (Vaid et al. 1985). However, strain-softening can also occur due to cyclic undrained loading (tectonic loading, Robertson and Fear 1995, Robertson and Wride 1998) Deformation during cyclic loading will depend on the density of the sediment, the magnitude and duration of the cyclic loading, and amount of shear stress reversal (Robertson and Fear 1995, Robertson and Wride 1998). If stress reversal occurs, the effective shear stress can reach zero, then cyclic liquefaction can take place. If stress reversal does not occur, zero effective stress is not possible, and then cyclic mobility will occur (Robertson and Fear 1995, Robertson and Wride 1998).

Liquefaction attributed to seismic activity results from the mobilization of sediment grains facilitated by an increase in pore-fluid pressure within loosely packed, water-saturated sediment (e.g., Obermeier and Pond 1999). This phenomenon can be the result of seismic shocking and has been reproduced in laboratory settings by Kuenen (1958), Weaver and Jeffcoat (1978) and Owen (1996). Other types of deformation commonly associated with seismic activity include convex-down stacking of shells, fault-grading, microfracturing, water-escape structures, recumbent folds, contorted bedding, various types of clastic dikes and sills, sand blows, some turbidites, submarine slumps and slump folds, debris beds, tsunami deposits, and homogenized beds (Seilacher 1969, 1983, Tuttle and Seeber 1991). However, attributing a seismic origin to deformational features can be problematic as many of the above mentioned features can be caused by other factors such as gravity-flow unrelated to seismic activity (Allen 1984). In order to properly assess liquefaction features and their relationship to tectonic activity several other factors such as study area location (known seismically active area), stratigraphic relationships, lateral continuity and regional abundance of liquefaction features, cyclic repetitions of liquefaction structures, etc. must be incorporated into the investigation (Seilacher 1969).

3.3.1 Road Cuts

A total of 17 road-cuts were examined in the study area (Zones A and B). Of these, liquefaction features were only evident in glaciolacustrine sediments located stratigraphically below the St. Joseph Till (Figures 3.13 and 3.14).

At all of these localities (refer to Appendix A), the stratigraphic assemblage is consistent and defined by an upper silt-rich, stone poor diamicton (St. Joseph Till) that unconformably rests on deformed, rhythmically bedded deposits of glaciolacustrine silts and clays (Figures 3.13 and 3.14).



Notes: Trowel for scale in top photograph. Inset depicts contorted beds of silt (light coloured sediment) and clays (dark coloured sediment). Soft-sediment deformation structures (dewatering) can be seen to left of scale card.

Figure 3.13: Sediment Outcrop Section of St. Joseph Till Unconformably Overlying Contorted Glaciolacustrine Sediments

Rhythmically bedded sequences observed within the St. Joseph Till are interpreted as sediments deposited within glacial Lake Saugeen, an ice-contact lake that occupied the Saugeen River valley during Port Bruce time. According to Sharpe and Edwards (1979) and Barnett (1992), the fine-grained texture of the St. Joseph Till and the presence of isolated blocks glaciolacustrine sediments within the till are attributed to subsole drag processes which occurred at the glacier bed during deposition of the till (Boulton et al. 2001). Liquefaction features and deformed beds, largely a result of dewatering processes, are interpreted as syndepositional, forming during or shortly after ice-loading and deposition of the St. Joseph Till. Similar interpretations have been called upon by several researchers to explain the origin of deformed glaciolacustrine strata below till (Eyles and Clague 1991, Barnett 1992a, Hambrey 1994).

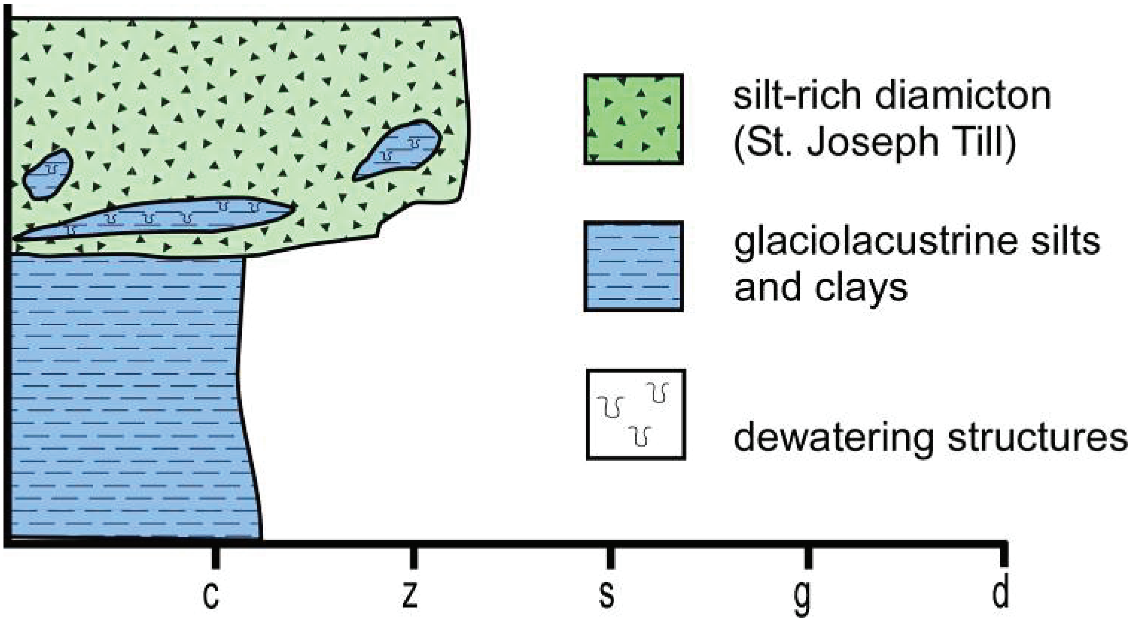


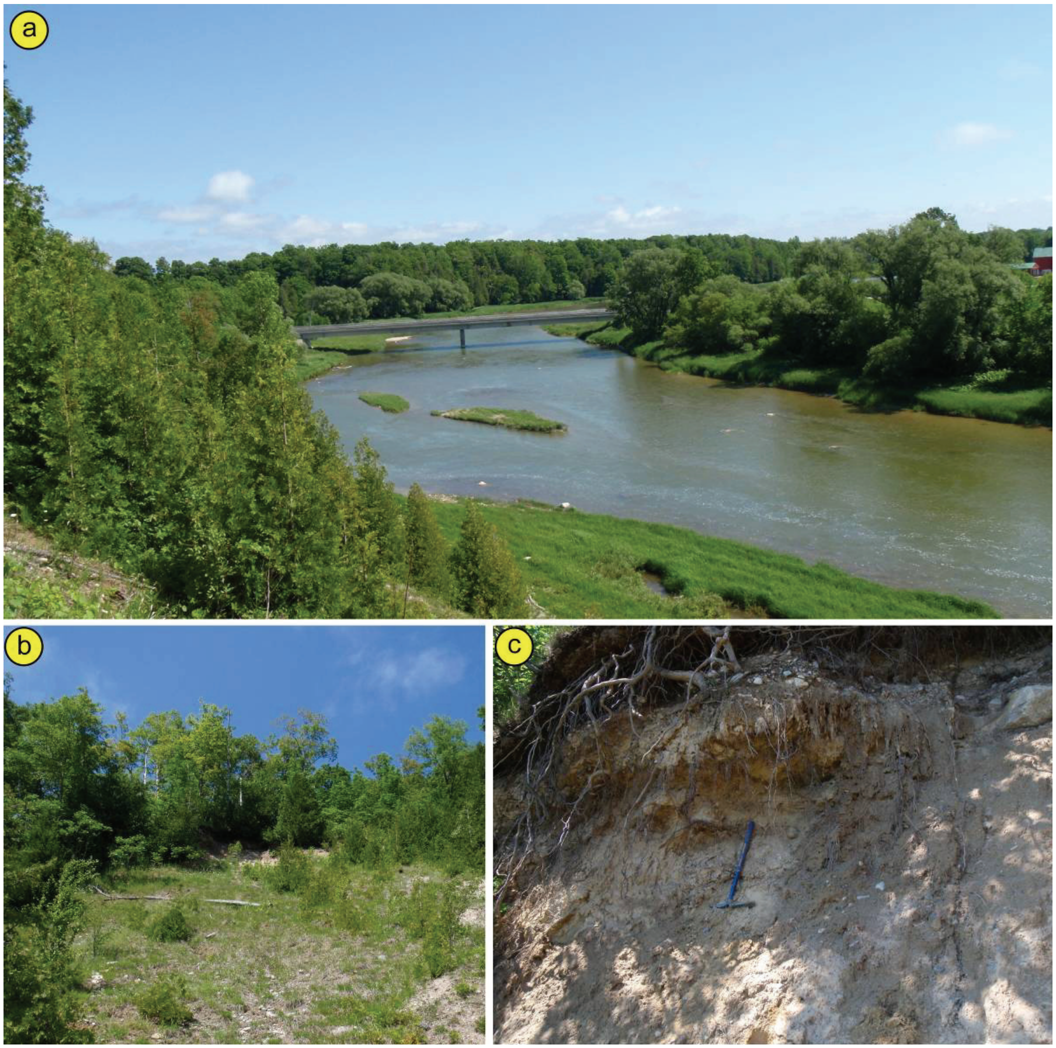
Figure 3.14: Conceptual Stratigraphic Section of the St. Joseph Till and Underlying Glaciolacustrine Sediments

Despite the information presented above, evidence obtained from sediment-outcrop sections exposed at road-cuts is not sufficient enough to dismiss a neotectonic origin for observed liquefaction structures. Although an ice-marginal readvance origin is plausible, a tectonic origin for observed liquefaction features can only be negated through the observation of stratigraphically lower sediments. More specifically, if liquefied beds grade into intact beds (unaffected by soft-sediment deformation processes) within the lithotype, it is plausible to assume that the source of liquefaction was ice-loading and not neotectonism.

In neotectonic settings liquefied and/or deformed layers are often stratigraphically located between undeformed stratigraphic intervals (Bowman et al. 2001). Clear rhythmic alternation of deformed beds with undisturbed strata may also indicate the instantaneous nature of seismic triggering (Rossetti, 1999), implying that deformation occurred very shortly after deposition (Jones and Omoto, 2000). Analysis of underlying sediments demonstrates that liquefaction features are confined to within the upper fine-grained glaciolacustrine beds and that these beds pass into undeformed beds and/or laminae, thereby supporting an ice-loading (refer to Section 3.3.3).

3.3.2 Saugeen River

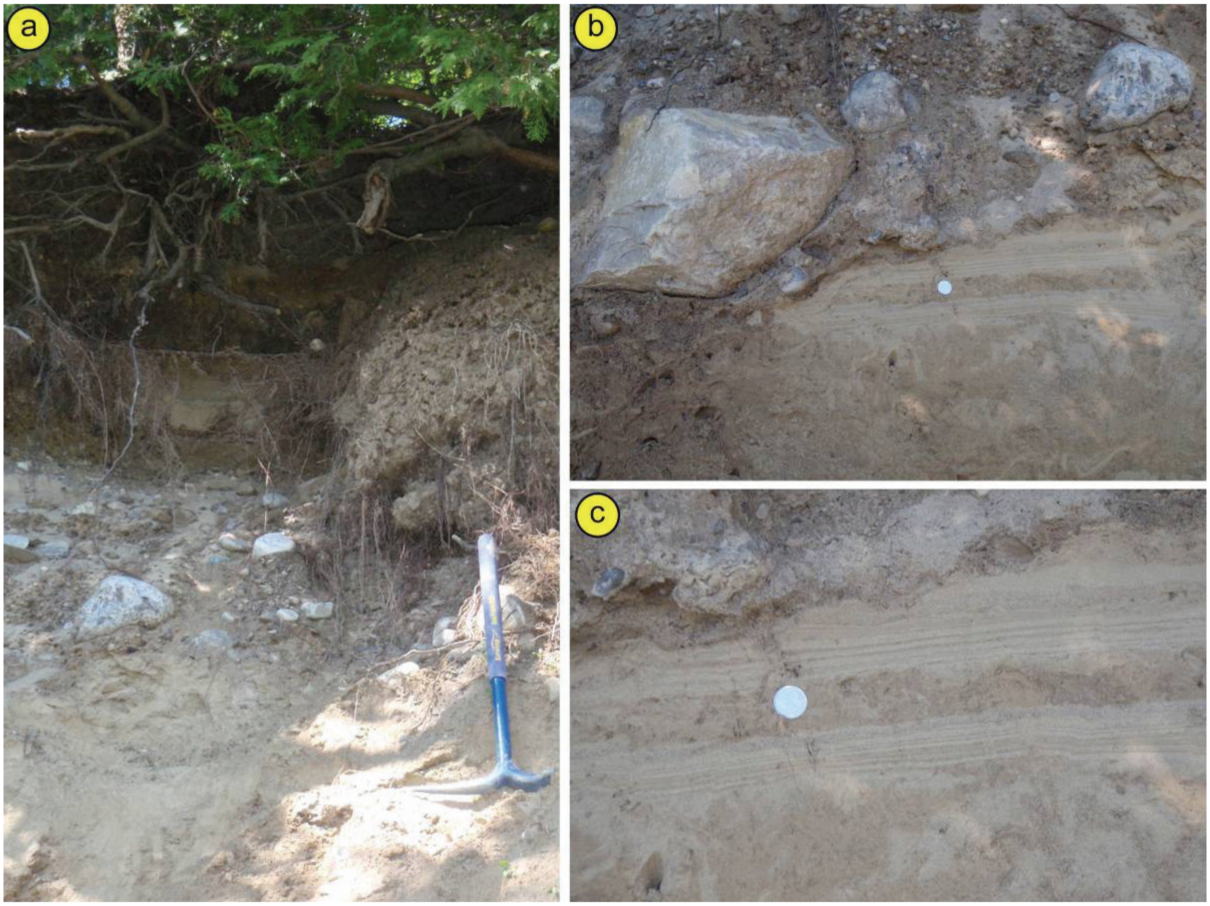
Sediment-outcrop sections along the Saugeen River were examined near the community of Chelsey, east of the Bruce nuclear site (Figure 3.15a).The majority of observed sediment profiles were covered with of screen and were not workable due to limited lateral and vertical extent (Figure 3.15b).



Notes: **(a)** View of Saugeen River looking east from sediment-outcrop section. **(b)** Screen cover over sediment along the Saugeen River. **(c)** Examined sediment-outcrop section along the Saugeen River. Geologic pick for scale.

Figure 3.15: Sediment Outcrop Sections Along the Saugeen River near Chelsey

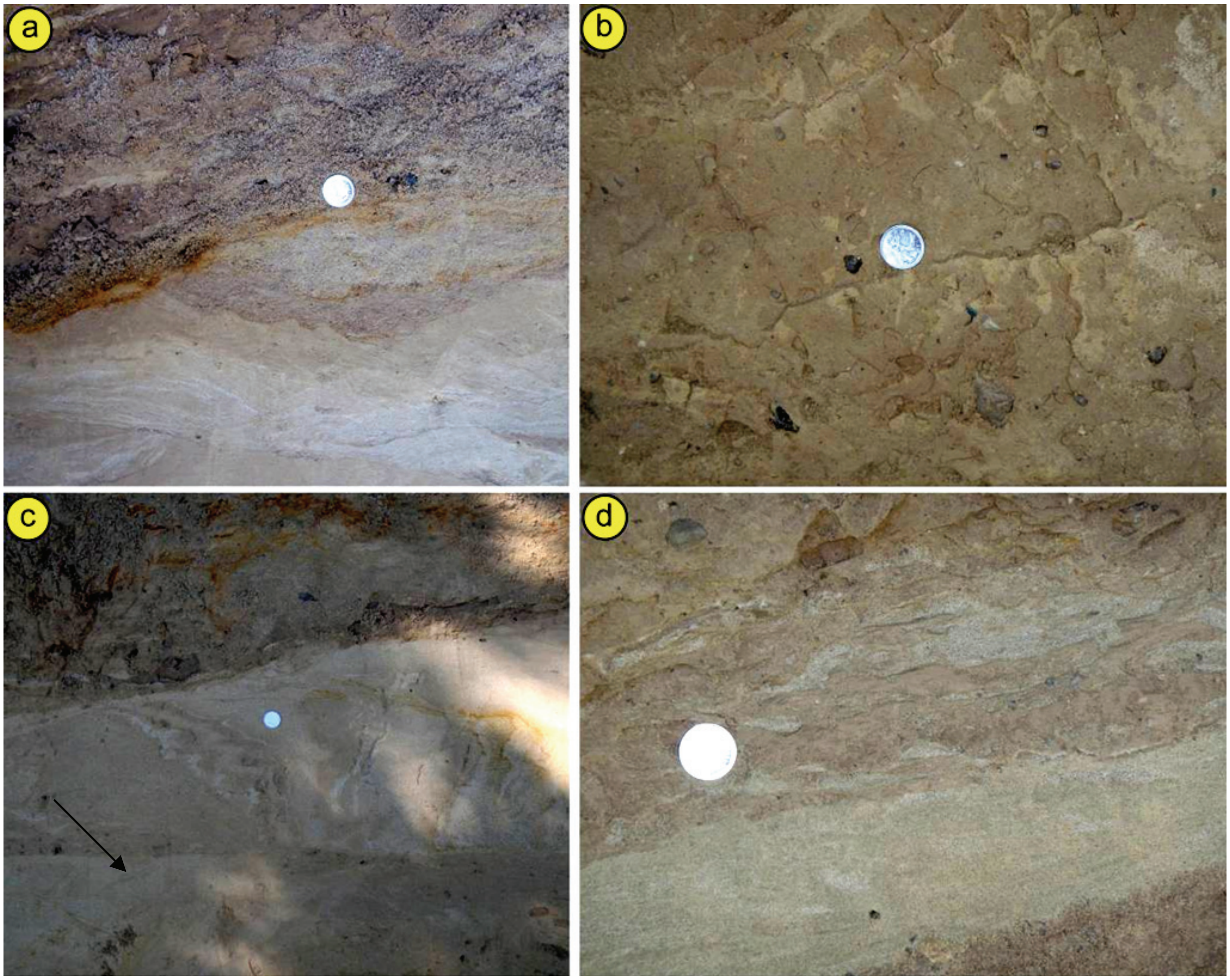
Where exposures were laterally and vertically extensive (Figures 3.15c and 3.16a), sediments were characterised by an uppermost lithotype predominantly composed of planar to tough-cross stratified pebbly, fine to medium grade sands. This lithotype passes into trough-cross stratified pebble to boulder gravels and is bound by a lowermost, erosive concave-up bounding discontinuity that incises underlying lithotype assemblages (Figures 3.16b and 3.16c). Underlying lithotypes are defined by a silt-rich sequence composed of interbedded, planar to flat-bedded fine to medium grade sands, rhythmically bedded silts and clays and a clayey and a clayey, silt-rich, stoney diamicton (Figures 3.16b and 3.16c). Liquefaction features and deformed bedding were only observed in the lower, silt-rich, assemblage (Figure 3.17).



Notes: **(a)** Vertical sediment profile along the banks of the Saugeen River with geologic pick for scale. **(b)** Erosive contact between boulder-rich gravels and underlying silt-rich assemblage with deformed/convoluted bedding. Twenty-five cent coin for scale. Dark coloured beds between flat lying laminae are composed of a silt-rich diamicton (debris flow). **(c)** Close-up of convoluted and liquefied laminae of sandy silt from (b).

Figure 3.16: Saugeen River Lithotype Assemblages

The transition from sand to gravel in upper lithotype assemblages is a reflection of reduced flow or current velocities within the system, from conditions of upper flow regime (gravel) to lower flow regime (sand) (e.g., Allen 1984). Sets of trough-cross stratified boulder to cobble gravels observed in the upper lithotype assemblage represent slugs that formed minor channel-fill deposits within the system and acted as nuclei for bar generation (Leddy et al. 1993). Events such as rainfall and lobe switching likely had a catastrophic effect on the system, promoting bank collapse and the release of gravel slugs into the system (Hein and Walker 1977). The abundance of this lithotype within the sediment-outcrop section is interpreted to reflect low bank stability due to the lack of rooted-vegetation within the system (Bluck 1974, Rust 1975).



Notes: **(a)** Deformed, contorted and liquefied beds of fine to medium grade sands. **(b)** Clayey, silt-rich, stoney diamicton. **(c)** Arrow depicts lower bounding discontinuity. Note that rotated, deformed and liquefied beds are confined to within the bounding surfaces. **(d)** Rip-up clasts of sand in overlying diamicton indicative of lateral movement, traction and drag processes. Twenty-five cent coin for scale in all photographs.

Figure 3.17: Saugeen River Lithotype Assemblages

Deposits of fine-grained sediments (muds) within the lower lithotype assemblage likely reflect periods of low flow or wane flow events within the system deposited through suspension fallout (e.g., Miall 1996). Evidence of channel abandonment during waning flow stage is limited in examined strata. Beds and laminae composed of silts and clays within strata suggest that fine-grained sediments may have been deposited in channel thalwegs during falling stage conditions. Similar features have been recorded in shallow, gravel-bed braided river deposits (Miall 1996). Diamictons observed within the lower lithotype assemblage (Figure 3.17b) resemble cohesive debris flow deposits identified by Sharp and Nobles (1953) and Lowe (1975, 1976, 1982). Studies by Lowe (1976, 1982) indicate that this type of sediment gravity flow behaves as a Bingham fluid, with plastic flow behaviour, in which sediment is supported by a cohesive matrix, and deposited due to cohesive freezing. Dislocated and overturned flat-bedded strata that underlie or are interbedded with observed diamictons reflect soft-sediment deformation processes and the formation of liquefaction features were triggered by the introduction of mass-flow deposits (bank collapse, Ankertell and Dzulynski 1968, Ortner 2005). Similar features have been recorded from shallow, gravel-bed braided river deposits (Miall 1996).

Observed rotational blocks observed in examined sediment-outcrop sections are typical of slump deposits as shown in Figure 3.17c (Mills 1983). Liquefaction features indicate loading of sand above water-saturated, soft and fine clay-rich sand and silt, and build up of pore-water pressure, which caused the loss of bearing capacity (Lowe 1975, Allen 1982). Evidence of floating clasts (rip ups), lateral movement and orientation is indicative of current motion and subsequent drag (Allen 1984).

The presence of sediment gravity flows (diamictons), related to bank undercutting (composed of till) and subsequent collapse are deemed responsible for the occurrence of liquefaction features observed within lower lithotype assemblages. Similar lithotype assemblages and associated liquefaction features have been documented and attributed to bank collapse by several authors (e.g., Allen 1984, Miall 1992).

3.3.3 Aggregate Operations

The majority of sand and gravel pit operations within the study area are located within the lake Algonquin bluff. Although many of these pits are now abandoned due to resource exhaustion, in some rare cases, where slumping of pit walls has not occurred, vertical and horizontally extensive sediment profiles exist (Figure 3.18).

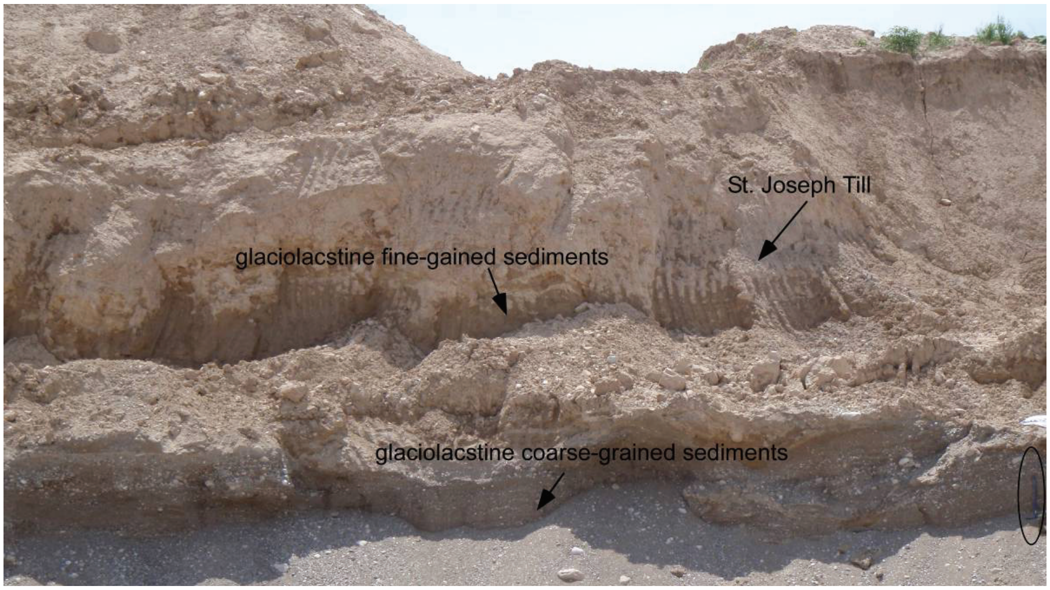
In the abandoned pits examined, observed stratigraphic assemblages are similar to those observed at road-cuts. Typically, these assemblage are defined by an upper silt-rich, stone poor diamicton (St. Joseph Till) that unconformably rests on deformed, rhythmically bedded, glaciolacustrine silts and clays (Figures 3.13, 3.14 and 3.18). As previously discussed, the incorporation of glacial Lake Saugeen sediments (silts and clays) is attributed to an ice-marginal readvance of the Huron-lobe (Sharpe and Edwards 1979, Barnett 1992a). Isolated blocks of glaciolacustrine sediments within the till are attributed to subsole drag processes which occurred at the glacier bed during deposition of the till (Boulton et al. 2001). Liquefaction features and deformed beds, noted within sediment outcrop sections are the result of ice-loading.

3.3.3.1 Jackson Construction

In the Jackson pit extensive exposures of glacial strata yielded the most complete stratigraphic assemblage within the study area (Figure 3.19). Based on observed sediment-outcrop sections four main lithotype assemblages were identified within the pit (Figures 3.20 and 3.21). These assemblages, associated lithotypes and depositional regimes in relation to position of the former ice-margin are discussed below.

Note: Inset depicts dislocated, flat-bedded, fine-gained glaciolacustrine sediments interbedded with St. Joseph Till. Two dollar coin for scale.

Figure 3.18: Abandoned Aggregate Operation Stratigraphy

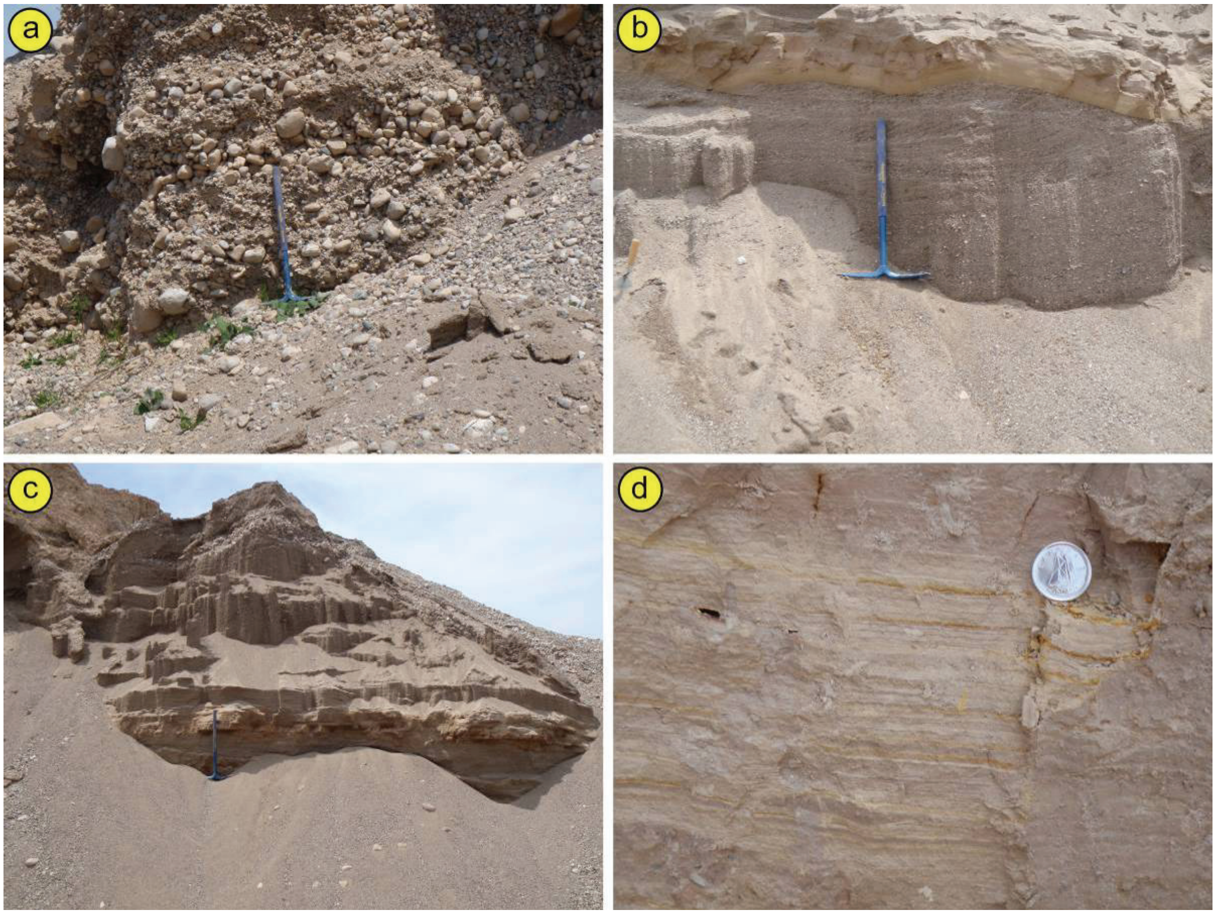


Note: St. Joseph Till unconformably rests on fine-grained glaciolacustrine sediments that conformably overlie coarse-grained glaciolacustrine sediments. Circle in lower right of photo indicates geologic pick for scale.

Figure 3.19: Stratigraphic Sequence in the Jackson Construction Pit

Lithotype Assemblage A

Assemblage A marks the highest stratigraphic unit identified in the Jackson pit. It is defined by a 2 to 5 m thick, planar, sheet-like body that can be traced laterally for several metres. Internally, the assemblage is best described as structureless and is composed of a clayey, silt-rich, moderately stoney diamicton interpreted as the St. Joseph Till. Stringers or small lenses composed of silty, fine-gained sand are common throughout the assemblage. Stringers are typically centimetres thick and can be traced vertically for several centimetres. Rotated and contorted blocks of rhythmically bedded silts and clays occur throughout the assemblage (Figures 3.20, 3.21 and 3.22). Liquefaction features are common within these beds.



Notes: **(a)** Boulder gravel assemblage with normal grading (lithotype assemblage D). Direction of paleoflow is right to left. **(b)** Trough and planar cross-stratified sands (lithotype assemblage C) with mud cap overlying planar cross-beds. Direction of paleoflow is from right to left. **(c)** Diffusely bedded sands (lithotype assemblage C). Direction of paleoflow is toward the observer. Geologic pick for scale in (a), (b), and (c). **(d)** Rhythmically bedded and/or laminae composed of silts (light coloured beds) and clays (dark coloured beds). Ten cent coin for scale.

Figure 3.20: Jackson Construction Pit Lithotype Assemblages

Lithotype Assemblage B

Assemblage B directly underlies assemblage A and is defined by rhythmically bedded to flat-laminated silts and clays. Individual couplets are typically 3 to 5 cm thick and can be traced laterally for several metres. Normal faulting, dewatering and load structures are common within this assemblage (Figure 3.23c).

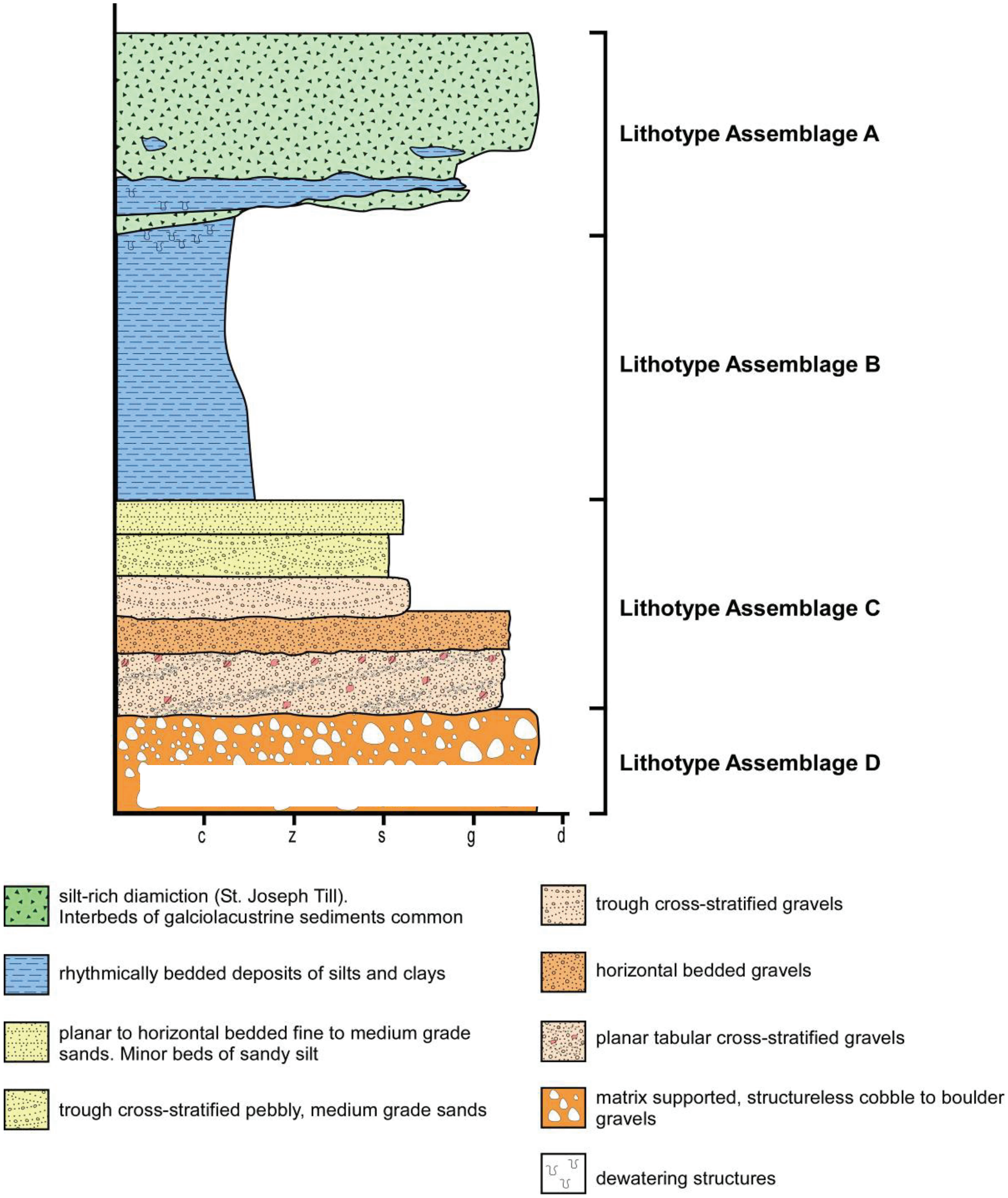
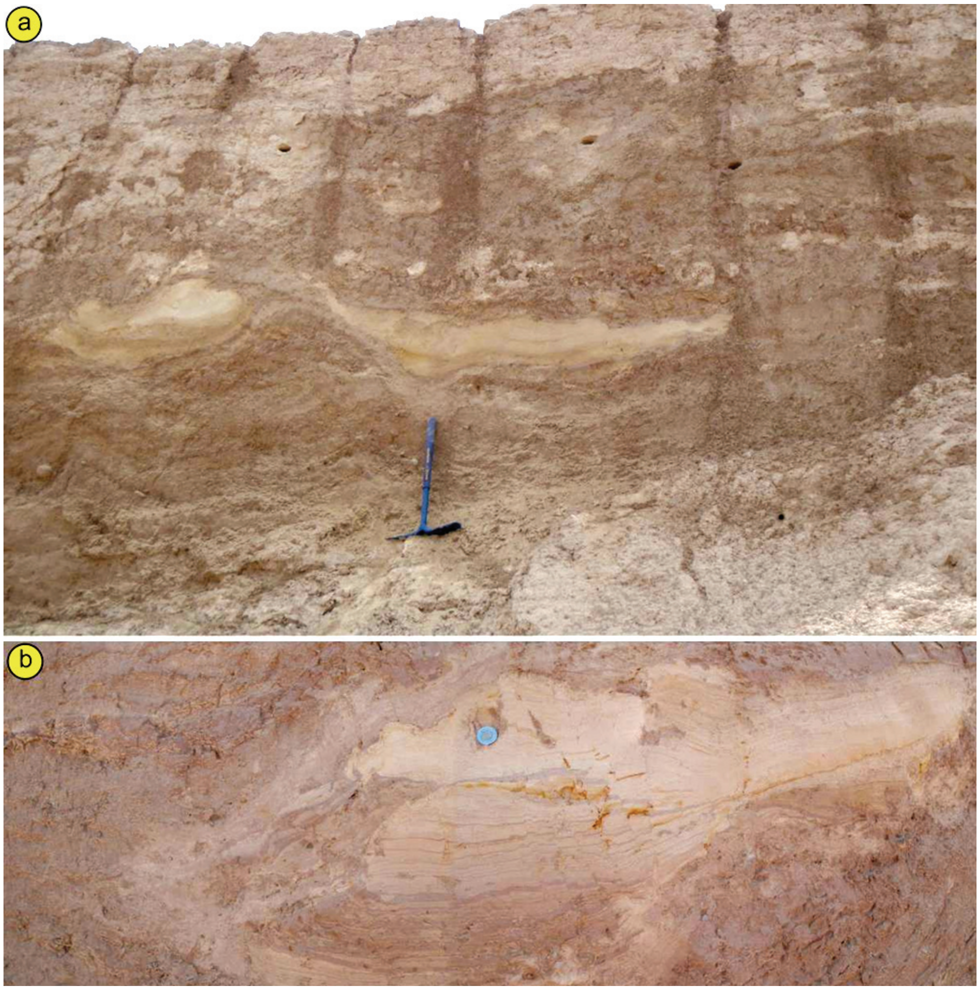


Figure 3.21: Conceptual Stratigraphic Section of the Jackson Pit



Notes: **(a)** Interbeds of deformed glaciolacustrine silts and clays (light coloured beds) in St. Joseph Till. Geologic pick for scale. **(b)** Isolated block of fractured, liquefied and rotated glaciolacustrine sediments in St. Joseph Till. Two dollar coin for scale.

Figure 3.22: Jackson Construction Pit Lithotype Assemblage A

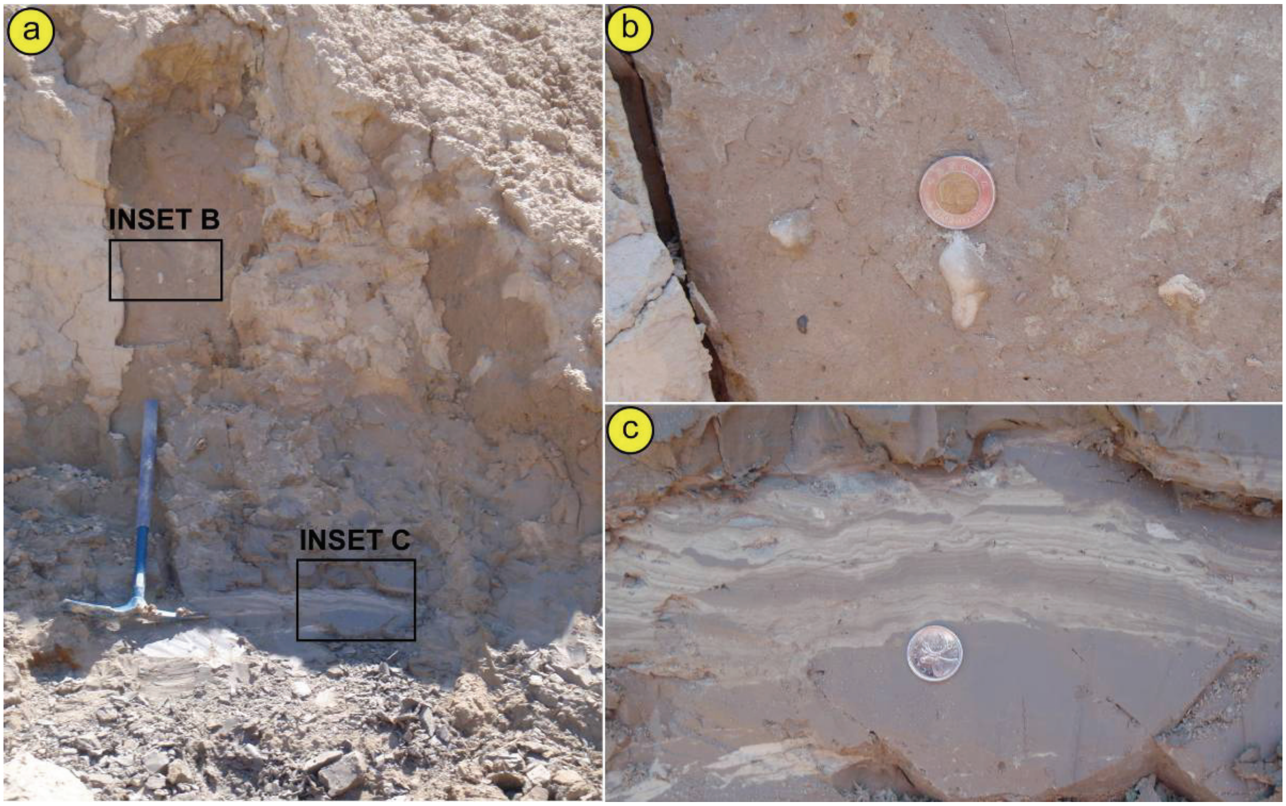
Lithotype Assemblage C

Assemblage C underlies lithotype assemblage B and is composed of slightly silty, fine- to medium-grained, horizontally (Sh), trough (St) and planar-cross (Sp) stratified sands. Lithotype Ss, defined by diffusely bedded deposits of medium grade sands, was identified in sediment-outcrops but is considered rare within the assemblage (Figure 3.23).

Co-sets of Sh are 1.5 to 3 m thick and can be traced for up to 9 m. These sequences display normal grading and commonly pass laterally into lithotype Ss. Lithotype Ss is defined by broad, shallow, concave-up, erosive, lowermost assemblage bounding surfaces. Ss units are typically 1 to 1.5 m thick and can be traced laterally for up to 7 m. In some localities dewatering and load structures were observed in deposits of Sh located below lithotype Gmm (lithotype assemblage D).

St units are typically 0.25 m deep and 0.5 m wide. Troughs are defined by lower, concave-up, erosive contacts that incise several centimetres into underlying St and Sh units. Residual lags of granule to medium pebble grade material are common at the base of troughs. Sp units are typically 0.5 m thick and can be traced on average for approximately 2 m.

Drape-like deposits of silty clay to clayey, fine sandy silt that conformable overlie Sh and Sp units were observed throughout lithotype assemblage C. Typically these units are 0.2 to 0.5 m thick and extend laterally up to 2 m. Liquefaction and sediment loading structures are common amongst these beds (Figure 3.24).



Note: **(a)** Vertical sediment outcrop section of St. Joseph Till and underlying glaciolacustrine sediments. Inset boxes refer to adjacent photographs. Geologic pick for scale. **(b)** Inset: silt-rich, stoney St. Joseph Till. Two dollar coin for scale. **(c)** Inset: Displaced and contorted glaciolacustrine silts (light coloured beds) and clays (dark coloured beds). Twenty-five cent coin for scale.

Figure 3.23: Jackson Construction Pit Lithotype Assemblage B

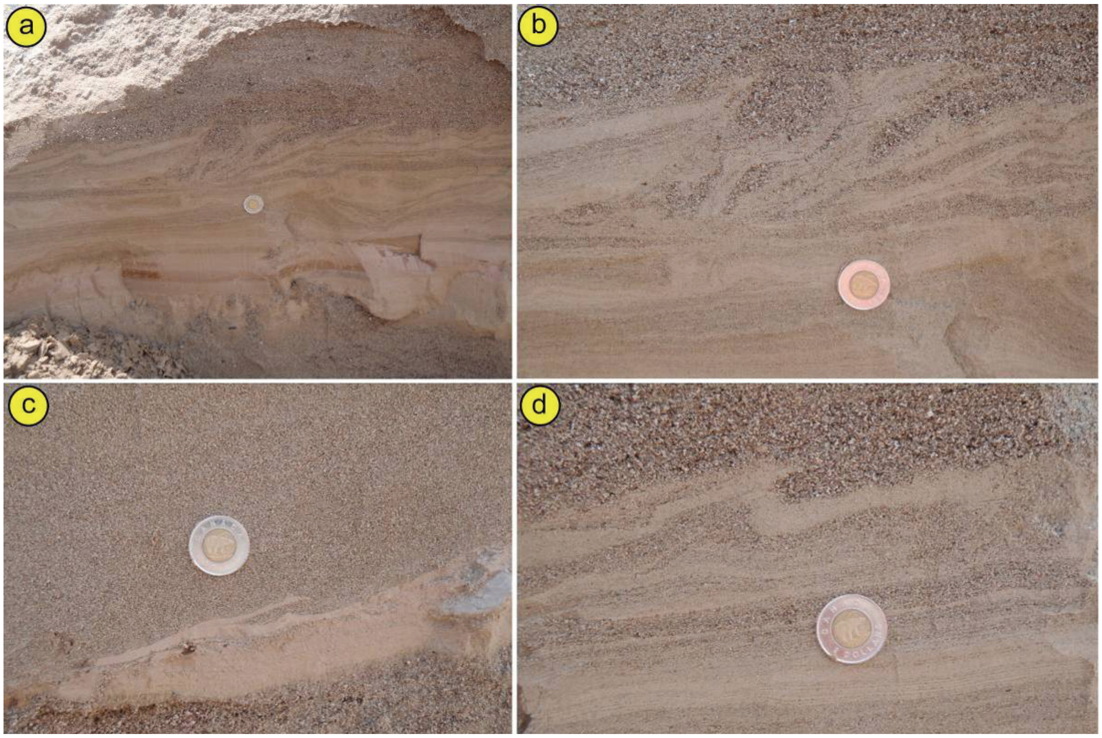
Lithotype Assemblage D

Lithotype Assemblage D marks the terminus of the stratigraphic assemblage observed in the Jackson pit. It is defined by deposits of massive, matrix supported and trough-cross stratified cobble to boulder gravels (lithotypes Bmm and Bt, Figures 3.20 and 3.21). Lithotype Bmm is defined by planar-tabular sheet-like units that are 0.3 to 1 m thick and can be traced laterally for several metres. Framework clasts within Bmm are of cobble to boulder grade and form 50 to 70 % of individual beds whereas the matrix is composed of medium to very coarse sand and pebble grade material that constitutes 30 to 50 % of each bed. Only normal grading was evident in observed Gmm, although most units lack identifiable internal structure and are best described as structureless. Sets of Bmm are defined by layers of imbricated and/or stacked pebble to cobble grade that occur along erosional basal contacts.

Lithotype Bt is considered rare within the assemblage and occurs as solitary units. Gt are defined by lower, concave-up, erosive contacts that are typically 0.25 m deep and 0.5 m wide. Residual lags of granule to medium pebble grade material are common at the base of lowermost basal contacts.

Paleoflow Analysis and Depositional Setting

The orientation of paleoflow vectors obtained from sedimentary structures in lithotype assemblages C and D (described above) indicates an overall south to southeasterly paleoflow direction. The unimodal character of paleoflow vectors obtained from planar and trough-cross strata suggests that sedimentation occurred in a confined setting.



Note: **(a)** Liquefaction structures in clayey, silt-rich beds. Drag structures at the top of the structure whereas underlying silt-rich beds are planar and unaffected by the liquefaction processes. **(b)** Detailed view of liquefaction features in silt-rich beds. **(c)** Detached lens of clayey silt within fine- to coarse-grained sands. **(d)** Load structure (flame structure) in fine sandy silt. Underlying beds (below two dollar coin) are unaffected by sediment loading processes. Two dollar coin for scale in all photographs.

Figure 3.24: Jackson Construction Pit Lithotype Assemblage C

Horizontal and tabular sets of planar cross-stratified sands (Sh and Sp) within assemblage C represent migrating sand-sheets and plane-bedded simple bars (Allen 1983). Lateral continuity amongst bedforms of dissimilar lithotypes (Sh and Ss) within the assemblage implies a genetic relationship between bedforms governed by fluctuating flow regimes (Allen 1983, 1984). Upper-flow regime conditions, represented by Sh, that pass laterally and vertically into Ss, are considered to represent falling stage or conditions of lower flow regimes. Sequences of nested or stacked St (lithotype assemblage A) with subordinate deposits of Sp are interpreted as migrating 3-D and 2-D dunes (Levey 1978, Cant and Walker 1978). The stacked nature of these lithotypes suggests rapid aggradation of sediments under falling stage conditions and further supports a confined, channelized depositional setting.

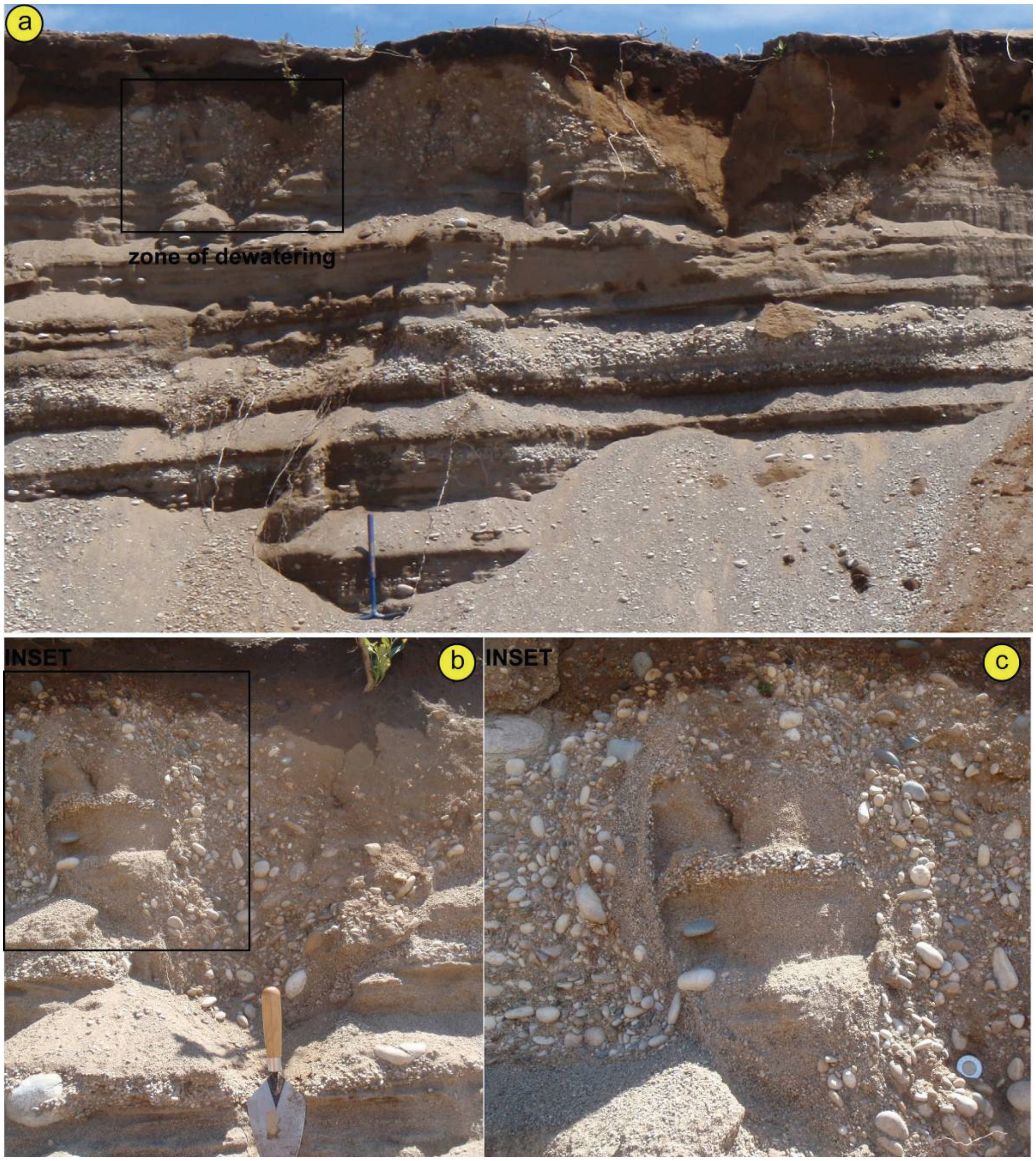
Strata exposed in lithotype assemblage D may reflect the cyclic nature of the sediment supply from the ice-margin. Diurnal oscillations of water-flow, and associated sediment transport and deposition are believed to have resulted in the rhythmic presentation of lithotype Bmm. The bipartite nature of this lithotype likely reflects daily fluctuations in meltwater discharge. Elevated daytime temperatures may have promoted ablation, resulting in increased meltwater discharge (Church and Gilbert 1975, Hammer and Smith 1983) and deposition of the coarsest grain size fraction in lithotype Bmm. At night, decreasing temperatures would have reduced stream discharge and sedimentation rates (Hammer and Smith 1983). This would have influenced the textural composition of the sediment load, with a decrease in both the volume and grain size of the bedload, as is seen in lithotype Bmm.

Blanket-like units of clayey, sandy silt and clayey silt that cap Sh and Sp units within lithotype assemblage C reflect small-scale wane flow events within the system. Isolated zones of dewatering and liquefaction structures within these beds and laminae are interpreted as syndepositional. These features are related to the loading of sand above water-saturated, soft and fine clay-rich sand and silt, and build up of pore-water pressure, which caused the loss of bearing capacity (Lowe 1975, Allen 1982, 1984). Liquefaction features display evidence of lateral movement and orientation, suggesting current motion and drag (Figure 3.24). Structures are typically accompanied by floating clasts typical of high-energy flow deposits which would be expected following current shear on liquefied sand (Allen 1984) thereby dismissing a neotectonic origin.

The occurrence of rhythmically bedded silts and clays that conformable overlie lithotype assemblage C also reflects conditions of lower flow regime and deposition through suspension fallout (Shaw 1985, Ashley 1989). This general fining upwards trend and the abundance of fine-grained sediments that cap coarse-grained strata suggests a migrating sediment source (lateral shifting of the sediment feeder system). Similar lithotype assemblages have been described and interpreted as depositional assemblages in ice-contact subaquatic fan settings (Shaw 1985, Cheel and Rust 1986, Burbidge and Rust 1988, Rust 1988, Russell and Arnott 2003). Similarly, lithotype assemblages observed in the Jackson pit are also interpreted as an ice-contact subaqueous fan associated with the Huron-lobe of the LIS.

3.3.3.2 Welsch Sand and Gravel

The Welsch Pit is located approximately 6 km northeast of the community of Port Elgin. Sediments that characterise the pit are predominantly composed of fine to medium grained, pebbly sands and pebble to cobble grade gravels that occur as broad, gently dipping channel-fill sequences (Figure 3.25).



Note: **(a)** Gently dipping channel-fill sequences in the Welsch pit. Former direction of paleoflow is west or toward the observer. Box depicts area of dewatering noted in upper section of sediment-outcrop. Dewatering structures are confined to upper limits of outcrop section. Geologic pick for scale. **(b)** Dewatering feature in the Welsch pit. Trowel for scale. **(c)** Detailed view of observed dewatering feature. Block of sand beds (between gravels) is undisturbed. Two dollar coin for scale.

Figure 3.25: Welsh Sand and Gravel Pit Sedimentary Sequences

Paleoflow analysis completed on planar and trough-cross stratified sands within the sequences and the orientation of bounding surfaces indicate a former westward paleoflow direction. Based on proximity to the present day Saugeen River, it is likely that observed sediments are of outwash origin related to an ancestral fluvial system that occupied the Saugeen River.

Dewatering features were only observed sporadically throughout the uppermost portions of examined observed sediment outcrops (Figure 3.25). As these features are confined to within uppermost bounding discontinuities (beds that contain specific lithotype assemblages) and lack any notable lateral continuity throughout the pit, a common prerequisite for the identification of neotectonically induced liquefaction features (Allen 1986, Obermeier 1996), a neotectonic origin is not favoured.

The exact mechanism responsible for dewatering structures is difficult, if not impossible, to determine as the upper unit of sediment in the profile has been removed by aggregate operations. However, based on observed lithotype assemblages and associated sedimentary structures within the pit and adjacent stratigraphic relationships the following explanation is offered.

Dewatering structures may be related to the emplacement of an upper diamicton unit (St. Joseph Till) that has since been removed by aggregate operations. Ice-marginal advance and subsequent deposition of St. Joseph Till would account for observed dewatering structures. The presence of undisturbed fine to medium grade sands between dewatered sands and gravels would imply that sand-rich lithologies were frozen at the time dewatering occurred.

Table 3.1 is an overview of investigated landforms/features in study areas A and B. Landform characteristics, interpretations and origin are provided below.

Table 3.1: An Overview of Investigated Landforms/Features in Study Areas A and B – Landform Characteristics, Interpretations and Origin

Landforms and/or Features	Characteristics of landforms/features	Interpretations	Origin (Neotectonic vs. non-neotectonic)
Linear Ridges	Sinuous to straight crested ridges. Ridges typically 1 to 2 m in height, 2 to 3 m in length. Ridges are typically oriented southeast (~115° azimuth)	Ice-press features related to an ice-marginal advance of the Huron ice lobe.	Non-neotectonic
Dendritic- to trellis-shaped ground surface patterns	Dendritic- to trellis-shaped ground surface patterns	Natural soil erosion and anthropomorphic alterations to land surface drainage.	Non-neotectonic
Offset-like beach ridges and bluffs	Offset-like appearance of beach ridges and lake bluffs	Anthropomorphic processes (i.e., road construction), scattered vegetation growth and subsequent dune (eolian development) result in an offset-like appearance of these landforms.	Non-neotectonic

Landforms and/or Features	Characteristics of landforms/features	Interpretations	Origin (Neotectonic vs. non-neotectonic)
Inverhuron Offsets	Offset-like features noted in glacial lake Nipissing and Algonquin bluffs east of the community of Inverhuron (east of the Bruce nuclear site)	Preferential erosion of lake bluffs causes an offset-like appearance.	Non-neotectonic
Road cut examinations of sediment-outcrop sections	Lenses of silt and clay underlying the St. Joseph Till are contorted and contain paleoliquefaction features	Paleoliquefaction features are attributed to ice-loading and deposition of the St. Joseph Till.	Non-neotectonic
Saugeen River sediment-outcrop section	Rip-up structures and liquefaction features and deformed bedding observed in the lower, silt-rich, sediments	Floating clasts (rip ups), lateral movement and orientation is indicative of current motion and subsequent drag. The presence of sediment gravity flows (diamictons), related to bank undercutting (composed of till) and subsequent collapse are deemed responsible for the occurrence of liquefaction features.	Non-neotectonic
Abandoned Aggregate Operations (sediment-outcrop sections)	Isolated blocks of glaciolacustrine sediments within till, liquefaction features and deformed beds, noted within sediment outcrop sections	Isolated blocks of glaciolacustrine sediments within the till are attributed to subsole drag processes which occurred at the glacier bed during deposition of the till. Liquefaction features and deformed beds, noted within sediment outcrop sections are the result of ice-loading.	Non-neotectonic
Jackson Construction (sediment-outcrop sections)	Isolated zones of dewatering and liquefaction structures	Isolated zones of dewatering structures in sediment-outcrop sections are interpreted as syndepositional and related to the loading of coarser-grained sediments above water-saturated, soft and fine clay-rich sand and silt, and build up of pore-water	Non-neotectonic

Landforms and/or Features	Characteristics of landforms/features	Interpretations	Origin (Neotectonic vs. non-neotectonic)
		pressure, which caused the loss of bearing capacity Liquefaction features display evidence of lateral movement and orientation, suggesting current motion and drag.	
Welsh Sand and Gravel	Dewatering structures observed in upper assemblage of sediment-outcrop section	Emplacement of an upper diamicton unit(?)	Non-neotectonic

4. CONCLUSIONS

Collectively, based on the interpretation of air photographs viewed and stereo, the analysis of a 10 m grid spaced DEM accented with hillshaded relief, LiDAR imagery and field-based examinations of sediment-outcrop sections the Bruce nuclear site and adjacent lands (within the limits of the study area) is not considered as an area of past tectonic activity.

From the Bruce nuclear site investigation the following conclusions strongly argue against a neotectonic origin for observed liquefaction features and landforms.

1. The Bruce nuclear site is located in a tectonically stable zone with no active fault zones (Park and Jaroszewski 1994, van der Pluijm and Marshak 2004).
2. Offset-like features observed in LiDAR imagery are likely related to artefacts induced during data processing. Features illustrated in LiDAR imagery were not evident during field-based examination.
3. Offset beach-ridges were not observed in the study area. Those which appeared “offset” when viewed on air photographs in stereo are explained by anthropomorphic processes such as road building and residential development, scattered vegetation growth and subsequent dune (eolian) development. Collectively, these processes altered the original morphology of the examined ridges creating an offset-like appearance.
4. Perpendicular to pseudo-trellis patterns on ground surface are the result of anthropomorphic processes. Stream drainage patterns have been altered by the owners of agricultural properties and are not related to neotectonic activity.
5. Contorted beds of rhythmically bedded very fine to fine-grained sands, silts and clays found with St. Joseph Till are associated with an ice-marginal readvance of the Huron-lobe during Port Bruce time. During this readvance glacial Lake Saugeen was overridden and glaciolacustrine sediments were incorporated through subsole drag processes (Boulton 1987) thereby explaining the deformed nature of these sediments (Sharpe and Edwards 1979, Barnett 1992a).
6. Observed liquefaction features in sediment-outcrop sections are not similar to structures formed experimentally under conditions of earthquake-induced shaking by Kuenen (1958), Weaver and Jeffcoat (1978) and Owen (1996) or those reported elsewhere as neotectonically induced features (Seilacher 1969, Scott and Price 1988, Ringrose 1989).
7. The absence of liquefaction-induced venting features and water escape flow paths in examined sediment-outcrop sections, and the dominance of plastic deformation, indicates a regime in which vented liquefaction features (neotectonically induced) could not develop (e.g., Obermeier 1996).
8. Liquefaction features that are bound stratigraphically by undeformed stratigraphic intervals (often used as criteria for neotectonic activity, e.g., Rossetti 1999, Jones and Omoto 2000) show evidence of lateral movement and orientation indicating current movement and subsequent drag (Allen 1984) thereby implying a syndepositional origin formed through current shear on liquefied sand.

9. Cyclic repetitions of liquefaction structures were not observed within the study area. Although cyclicity of these structures is, however, by itself, not diagnostic of a neotectonic origin it is expected by many researchers in seismic zones due to reoccurring seismic activity (Obermeier 1996, Bowman et al. 2001).

10. Lateral continuity of liquefaction features was not identified within the study area. According to Allen (1986) and Obermeier (1996) deformation structures and their regional abundance are prerequisites for regarding them as neotectonically induced.

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6. ABBREVIATIONS AND ACRONYMS

ASTM	American Society for Testing and Materials
BP	Before present
DEM	Digital elevation model
GSC	Geological Survey of Canada
LiDAR	Light detection and ranging
LIS	Laurentide Ice Sheet
M	Moment magnitude
MNR	Ministry of Natural Resources
NTS	National Topographic System
OGS	Ontario Geological Survey
OMAF	Ontario Ministry of Agriculture and Food
UTM	Universal Transverse Mercator

APPENDIX

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APPENDIX A: STUDY SITE LOCATION MAPS AND DETAILED SITE DESCRIPTIONS

(on enclosed CD)