MAPPING OF SURFACE SEDIMENTS IN OWEN SOUND AND COLPOY'S BAY

SIDE SCAN SONAR MAPPING OF SURFACE SEDIMENTS IN OWEN SOUND AND COLPOY'S BAY, ONTARIO, CANADA

By

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ABSTRACT

This thesis reports the results of a study that aims to develop and implement a simple, yet effective substrate identification and classification scheme for the Owen Sound and Colpoy's Bay region of southern Georgian Bay using side scan sonar data. Documentation of substrate types in the study area is required to enhance fish rehabilitation programs conducted by the Ontario Ministry of Natural Resources. Over 500km of side scan sonar data and 100km of sub-bottom seismic data were collected in Owen Sound and Colpoy's Bay during the summer of 2004. Analysis of the side scan images allowed identification of seven substrate types in the two bays including mud (Facies 1), sand (Facies 2), sand with ripples or dunes (Facies 3 and 4), sand with boulders (Facies 5), boulder rich lake floors (Facies 6) and bedrock (Facies 7). Patches of aquatic vegetation could also be identified on the images. Sub-bottom seismic data collected concurrently with the side scan data were used to validate interpretations of substrate type made from side scan images. This substrate identification system appears to serve as a rapid and cost-effective method of determining substrate characteristics based solely on the geophysical properties of acquired sonar and seismic data.

Lake floor sediment distribution maps of Owen Sound and Colpoy's Bay were subsequently created from the side scan data using both a computer-based and a more traditional hand-drawn technique. The hand-drawn mapping technique integrated interpretation of side scan images with sub-bottom seismic data and pre-existing knowledge of bathymetry, shoreline sediment types and environmental factors and appears to present the most realistic delineation of surface sediment distributions in Owen Sound and Colpoy's Bay. Substrate types within both bays can be subdivided into three distinct zones; Zone 1 is mud-rich and lies in water depths greater than 30m; Zone 2 includes sand dominated substrates and is found in water depths of between 0m and 40m and Zone 3, found on exposed shoals and in shallow water areas consists of the coarse-grained gravel and bedrock substrates preferred as fish spawning grounds.

This is the first side scan study to have been conducted in southern Georgian Bay and the results can be used to more effectively plan and design fish rehabilitation and restoration projects in the region.

ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

The Ontario Ministry of Natural Resources (OMNR) has identified rehabilitation of whitefish and lake trout stocks in Lake Huron as one of the top priorities of the Upper Great Lakes Management Unit. Early attempts to re-establish lake trout in the lower four Great Lakes were unsuccessful because the stocked fish did not reproduce successfully. Failure was attributed in part to stocking of lake trout over unsuitable substrate at locations other than those once used by native lake trout for spawning (Swanson, 1973; Rybicki and Keller, 1978). Current management plans are based on a strategy to stock lake trout in historical spawning sites over substrates known to be suitable for spawning. This practice ensures that stocked fish will encounter a substrate that will protect their eggs and fry from predators and from wave, current and ice action (Wagner, 1982). However, few studies have attempted to produce site-specific knowledge of the distribution and areal extent of suitable substrates in the Great Lakes (Edsall *et al.*, 1989), despite the fact that the success of fish rehabilitation efforts depends on this knowledge.

After several years of rehabilitation and the re-establishment of naturally reproducing lake trout in both Parry Sound and South Bay, emphasis has shifted to the assessment of other rehabilitation areas in Lake Huron (Ontario Ministry of Natural Resources, 2003). Owen Sound is one of the locations selected for rehabilitation efforts, and since 1986 pure strain lake trout have been stocked each year in the sound and an annual lake trout monitoring program has been conducted every fall since 1996. The monitoring programs have shown that lake trout spawning occurs throughout Owen

Sound in the fall and that some locations had a high enough lake trout catch per unit effort (CPUE) to warrant further investigation of this area as a site for enhanced rehabilitation efforts (Ontario Ministry of Natural Resources, 2003). Little is currently known about the physical conditions in the Owen Sound region that may affect fish spawning success, however.

This thesis reports the results of a study conducted in collaboration with the Ontario Ministry of Natural Resources, Upper Great Lakes Management Unit that seeks to identify limiting environmental factors on whitefish and lake trout spawning in Owen Sound and Colpoy's Bay (Fig. 1.1). Major environmental factors affecting fish spawning are water depth and substrate type, such as mud, sand, boulders and bedrock ledges. Most spawning occurs in water depths of between 0.5 and 18 meters (Marsden, 1995). Previous studies have shown that the most suitable habitat for the egg-fry life stages of whitefish and lake trout is rounded to angular rock, 5-50cm in diameter with interstitial spaces 30cm or more deep that can protect eggs and fry from predators and dislocation by water currents (Edsall et al., 1989). An understanding of the distribution of cobble and boulder substrates in water depths of between 0.5 and 18m is thus crucial to a successful whitefish and lake trout rehabilitation program.

Identification of substrate types in lacustrine environments is possible through the use of direct visual observations, submersible cameras, sediment cores, grab samples and geophysical methods such as side scan sonar and sub-bottom seismic profiling. Time and economic constraints make the use of direct visual observations, submersible cameras,

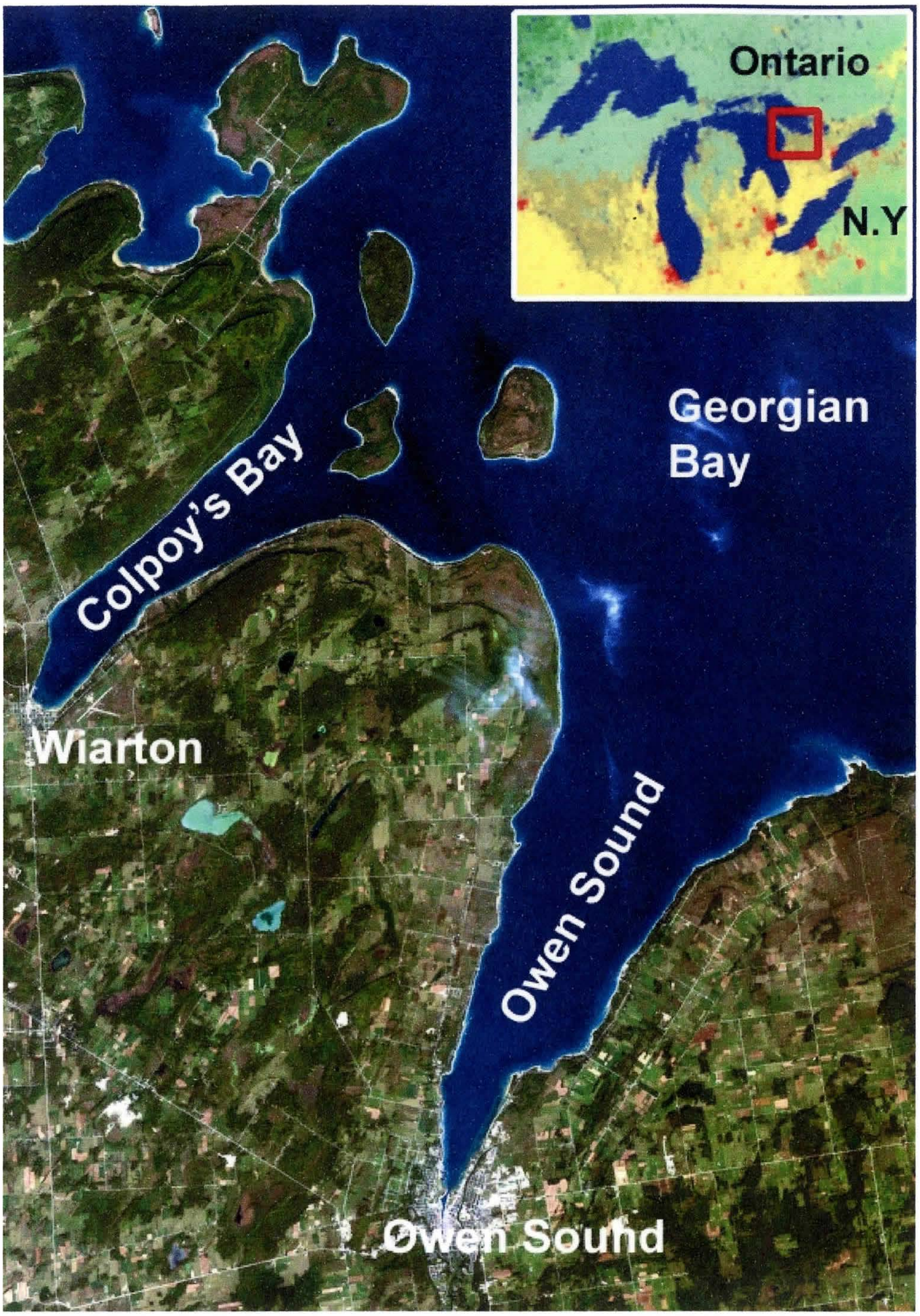


Figure 1.1: The locations of the study area are the two flooded re-entrant valleys of Owen Sound and Colpoy's Bay (air photograph courtesy of OMNR).

core and grab sampling impractical for this type of study that requires relatively large geographic areas to be surveyed rapidly and at low cost. The Owen Sound/Colpoy's Bay study reported here mapped substrate types through analysis of geophysical data collected by systematic side scan and sub-bottom seismic surveys during the summer of 2004. Both of these techniques collect data pertaining to substrate type from analysis of sound wave energy that either passes through or is reflected by the lake floor sediment. The database compiled for this study includes more than 500km of side scan data and 100km of CHIRP sub-bottom seismic profiles.

1.1 Aim of the study

The aim of this study is to establish and implement a simple, yet effective, substrate identification and classification scheme for the Owen Sound and Colpoy's Bay region that defines recurrent lake bottom types on the basis of their geophysical and geological characteristics. The scheme must be able to identify and delineate the range of substrate types found in the region and establish an effective framework for longer term mapping projects by the Ministry of Natural Resources in their assessment of whitefish and lake trout spawning sites. The substrate identification and classification scheme will be used in this study to create a sediment distribution map for Owen Sound and Colpoy's Bay, which can be used by the Ministry of Natural Resources for the identification of future fish rehabilitation sites and netting studies.

1.2 Organization of the thesis

This thesis is organized in the following way. Chapter 1 is an introduction to the study. Chapter 2 will provide an introduction to the geologic history of the study area of Owen Sound and Colpoy's Bay, important for establishing the geological context in which the lake floor sedimentary cover has developed. Chapter 3 will fully explain the methods used in this study, beginning with an explanation of the operation of the side scan sonar system and the basics of side scan image interpretation, and concluding with a discussion of the sub-bottom system and seismic transect interpretation. The fourth chapter presents results from the analysis of side scan data and describes the substrate facies types identified in this study. Chapter 5 examines the process of creating surface sediment distribution maps from the side scan data. This chapter also discusses the distribution of substrate types in Owen Sound and Colpoy's Bay, environmental controls on sediment distribution and the significance of this distribution for fish spawning studies. The final chapter (Chapter 6) summarizes the main findings of this investigation and provides suggestions for future studies.

CHAPTER 2: GEOLOGIC & PHYSIOGRAPHIC SETTING

2.1 Introduction

Chapter two provides an overview of the geologic and physiographic setting of the study area which lies on the south shore of Georgian Bay in southern Ontario and includes the lake filled embayments of Owen Sound and Colpoy's Bay (Fig. 1.1). Factors that affect the characteristics of the bedrock valleys in which Owen Sound and Colpoy's Bay are located and the nature of their sedimentary infill are discussed below. These factors include the bedrock geology of the area, formation of the Niagara Escarpment and re-entrant valleys, the nature of Quaternary sediments deposited in the area, the history of lake level changes in southern Georgian Bay and characteristics of modern shoreline and nearshore environments. These geologic factors can have a significant influence on the type and distribution of substrate materials currently found in the embayments and the location of suitable fish spawning areas (Marsden et al,. 1995).

2.2 Bedrock geology

The geology of southern Ontario can be broadly categorized into three layers, each separated by a major unconformity (Fig. 2.1). Layer one is composed of Precambrian-age rocks of the Canadian Shield, which were formed during the Archean and Proterozoic eons between 2,500 and 570 million years ago (Eyles, 2002). These

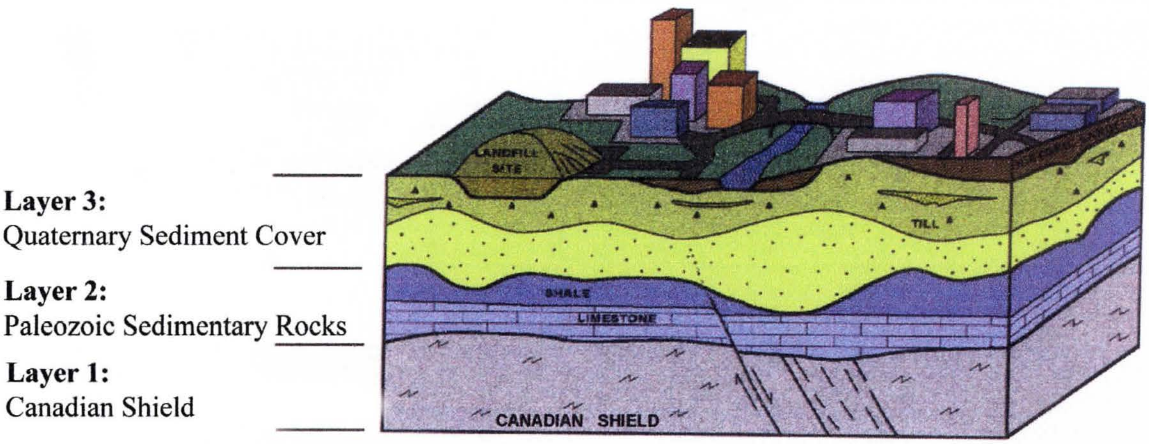


Figure 2.1: The geology of southern Ontario can be divided into 3 major layers. From oldest to youngest these are (1) the Canadian Shield, (2) Paleozoic sedimentary rocks and (3) Quaternary sediment cover (modified from Eyles, 2002).

rocks are covered by a second layer, up to 500m thick (Fig. 2.1), consisting of younger, Paleozoic-age sedimentary rocks deposited between 600 and 350 million years ago in seas that covered a large portion of North America at this time (Johnson *et al.*, 1992; Eyles, 2002). Paleozoic rocks are exposed in extensive outcrops along the Niagara Escarpment of southern Ontario. Successive episodes of glacial and fluvial erosion during the Tertiary and Quaternary are responsible for the creation of an irregular topography on the surface of the Paleozoic rocks in southern Ontario (Straw, 1968a; Karrow, 1973), which consists of deeply dissected valleys and broad interfluves (Fig. 2.2). The third layer that underlies most of the surface landforms of southern Ontario is a soft surficial sediment cover of Quaternary age (2.5Ma – present), deposited by glacial, fluvial and lacustrine processes (Eyles, 2002). Each of these layers will be discussed in more detail below.

2.2.1 Layer 1: The Canadian Shield

The North American craton has long been considered to be a relatively stable tectonic area. However, recent studies have shown that the craton is made up of many smaller terranes that accreted together along suture zones (Hoffman, 1988; Wallach *et al.*, 1998); these suture zones contain closely spaced faults which may be reactivated by modern stress fields acting on the craton, and can be the foci of neotectonic earthquake activity (Thurston *et al.*, 1992). Several reactivated subbasement faults and lineaments have been discovered in southern Ontario (Eyles *et al.*, 1993), one of which, the Georgian

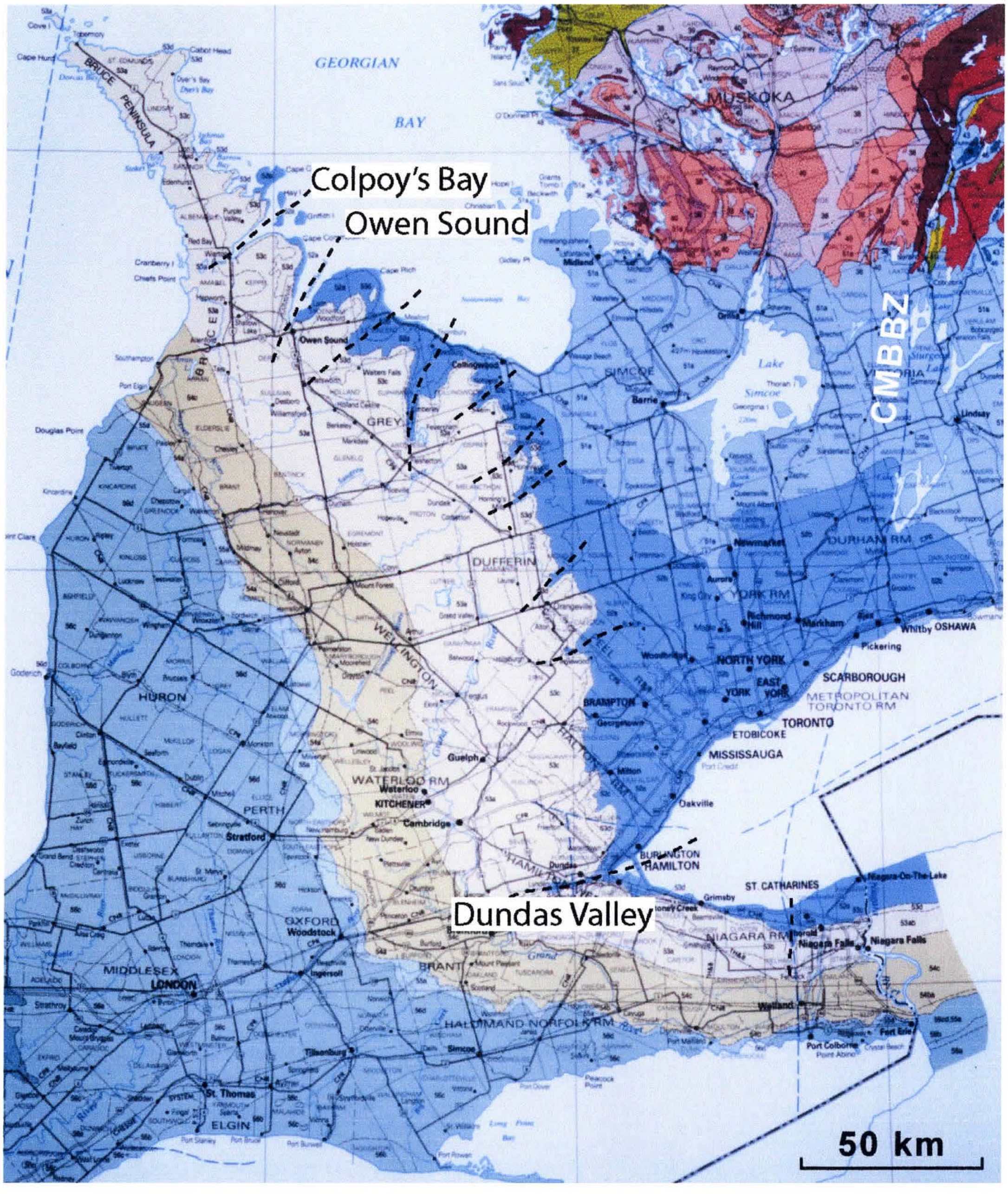


Figure 2.2: The bedrock geology map of southern Ontario clearly shows the position and orientation of re-entrant valleys along the Niagara Escarpment; these valleys are indicated with black dashed lines (modified from Ontario Geological Survey Map 2544).

Bay linear zone (Wallach *et al.*, 1998), lies relatively close to the Owen Sound region on the eastern shore of Georgian Bay (Seeber and Armbruster, 1993).

2.2.2 Layer 2: Paleozoic sedimentary rocks

The southwest-dipping Paleozoic sedimentary rocks that overlie the Precambrian craton are exposed along natural outcrops and road cuts along the 700km-long Niagara Escarpment (Eyles, 2002), which extends from Niagara Falls in the south to Manitoulin Island in Lake Huron in the north. The rocks forming the escarpment lithified from sediments deposited during the Ordovician and Silurian periods when a marine transgression flooded the North American craton, allowing the development of extensive shallow inland seas across much of northeastern North America. Two intracratonic sedimentary basins developed at this time, the Appalachian and Michigan Basins, which were separated by the Findlay-Algonquin Arch, a Proterozoic structural high with a distinct northeast trend. The basins formed as a result of crustal loading in response to orogenic activity on the eastern margin of North America and development of the Taconic Mountain chain (Johnson *et al.*, 1992; Eyles *et al.*, 1993).

Alternating successions of fine-grained clastic and carbonate rocks deposited during this period are interpreted as transgressive-regressive sequences, which may record sea level changes caused by tectonic activity in the Taconic Mountains (Caley, 1940; Bond and Kominz, 1991; Stott and Aiken, 1993; Eyles, 2002). Upper Ordovician strata consist predominantly of shales interbedded with limestone, and are represented in the study area by the Georgian Bay and Queenston formations (Fig. 2.3; Liberty, 1966).

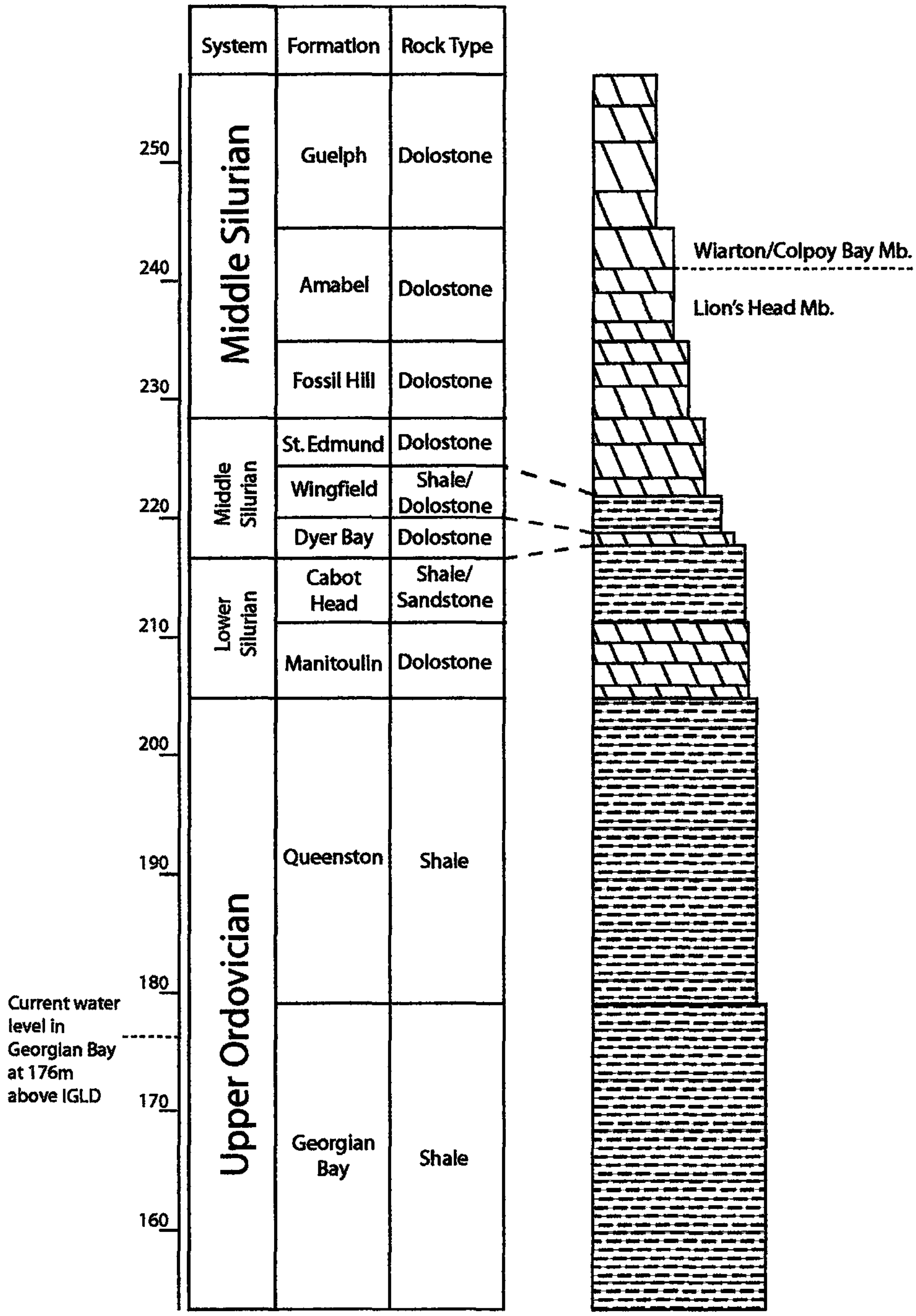


Figure 2.3: Stratigraphic column identifying the Paleozoic strata exposed along the Niagara Escarpment close to Owen Sound and Colpoy's Bay. Numbers to left of column represent elevation in meters above the International Great Lakes Datum (I.G.D.L.). Data compiled from Liberty (1969); Liberty (1971); Johnson *et al.* (1992); Eyles (2002) and The Bruce-Grey Geology Committee (2004).

Overlying lower and middle Silurian strata are composed primarily of sandstone and shales, such as the Cabot Head formation of the Cataract group, or limestones and dolostones, such as the Lockport-Amabel and Guelph formations (Liberty, 1966; Liberty 1969).

2.3 Formation of the Niagara Escarpment and bedrock valleys

Originally laid down horizontally, the Paleozoic sedimentary rocks have been gently tilted and now dip at an average of a few degrees to the southwest. Over time, fluctuating sea and lake levels, surface and groundwater movement, and repeated glaciations allowed erosion of the Paleozoic strata and created major topographic features, such as the Niagara Escarpment and the Great Lakes Basins (Hough, 1958; Johnson *et al.*, 1992).

During the Mesozoic and early Cenozoic the Paleozoic bedrock surface was sub-aerially exposed and was extensively eroded to form a series of deep valleys separated by broad interfluves. The Niagara Escarpment was also created during this time due to differential erosion of gently dipping layers of resistant and less resistant Paleozoic rock (Eyles, 2002). The most resistant rock types seen in the Niagara Escarpment are included in the dolomitic upper Guelph and Lockport-Amabel Formations (Fig. 2.3; Straw, 1968a) which act as a protective cap rock along the entire length of the escarpment, and have a variable thickness of about ten meters east of Hamilton to fifty-three meters near Owen Sound (Straw, 1968a). The Silurian-age Guelph and Lockport-Amabel Formations and underlying carbonate-rich deposits of the Clinton and Cataract Groups are extensively exposed along the escarpment in the Owen Sound region. Less resistant Ordovician shales that underlie the harder Silurian cap rocks are seen in topographic lowlands and valleys (Karrow, 1989), including Owen Sound and Colpoy's Bay (Fig. 2.3). The Georgian Bay Formation is the lowermost and oldest formation exposed sub-aerially at modern lake level in Owen Sound (Liberty, 1966), followed up section by the younger Queenston formation.

The Niagara Escarpment forms a prominent topographic feature on the landscape of the southern Georgian Bay region and wraps around both Owen Sound and Colpoy's Bay. The steep slopes of the escarpment are especially prominent on the western shore of Colpoy's Bay, where steep cliff faces rise vertically less than 50 meters from the lake shoreline (Fig. 2.4). In other areas, the escarpment face is less prominent, particularly to the western side of the city of Owen Sound where a thick sediment cover partially masks the topography.

Owen Sound and Colpoy's Bay lie in two of the many re-entrant valleys cut into the eastern edge of the Niagara Escarpment. The formation and origin of these re-entrant valleys, and other topographic features in the bedrock, is controversial. Previous studies have speculated that the bedrock valleys were the result of fluvial erosion (Spencer, 1890, 1907; Grabau, 1901), glacial erosion (Straw, 1968a, b) and/or a combination of both processes (Hurst, 1962; Karrow, 1973, 1984; Edgecombe, 1999). Recent research by Eyles *et al.* (1993, 1997) shows that regional joint set patterns and the orientation of basement structures align with bedrock valley orientations, and could act as a control on the form and distribution of bedrock valleys. There is also speculation about the role of

Figure 2.4: The steep face of the Niagara Escarpment rises vertically to an elevation of 240 m.a.s.l. less than 50m from the shoreline of Colpoy's Bay.

groundwater movement and spring sapping along the contact between the lower Ordovician shales and overlying carbonate formations in the escarpment, which may help create V-shaped valley platforms (Terlaky *et al.*, 2004).

2.3.1 Shape and orientation of re-entrant valleys

The shape, size, and orientation of the re-entrant valleys in which Owen Sound and Colpoy's Bay are located is similar to that of other re-entrant valleys along the Niagara Escarpment, such as the Dundas Valley in Hamilton and the two re-entrant valleys south of Thornbury and Meaford (Fig. 2.2). The orientation of the most prominent re-entrant valleys is northeast-southwest (Eyles *et al.*, 1993, 1997; Terlaky *et al.*, 2004), consistent with the direction of regional joint sets in bedrock, and there appears to be an association of valley orientation with the strike of deep seated basement structures in the underlying North American craton (Eyles *et al.*, 1993, 1997).

Re-entrant valleys form large V-shaped valleys that resemble enlarged gorges and are an indicator of locally accelerated erosion and retreat of the bedrock in response to water flowing over the edge of the escarpment (Hurst, 1962; Karrow, 1973, 1984). The most prominent example is the Niagara Gorge with Niagara Falls at its head; most re-entrant valleys have smaller waterfalls near the head of the valley, such as Inglis Falls in Owen Sound and the numerous waterfalls around the rim of Dundas Valley in the Hamilton region. Re-entrant valleys have a large range in size, with the Dundas Valley and Owen Sound, which each measure about 20km in length and over 10km in width, being two of the largest.

2.3.1.1 Owen Sound:

The Owen Sound bedrock re-entrant valley is about 20km long, and ranges from 7km wide at the city of Owen Sound to 15km wide at the mouth of the sound (Fig. 2.5). South of the town of Owen Sound the bedrock valley separates into two distinct sections, each containing a stream; the eastern section contains the Sydenham River with Inglis Falls flowing over the escarpment, and the western section contains the Potawatomi River and Jones Falls (Fig. 2.5; Liberty, 1966). Both waterfalls are 12-15 meters in height, with Inglis Falls being slightly higher. The area within the bedrock re-entrant valley that is above modern lake level has a variable topography on the surface of underlying Quaternary sediments (Fig. 2.5; Chapman and Putnam, 1984).

The bathymetry of the submerged portion of Owen Sound is characterized by a relatively shallow inner bay area south of Squaw Point, with a predominantly flat lake floor and water depths of up to 20 meters (Fig. 2.6). North of Squaw Point water depths increase towards the north and reach depths of 100 meters near the mouth of the bay. The eastern side of the bay has lower bathymetric gradients than the western side, but on both sides a rapid increase in water depths can be seen at about 20 meters (Ministry of Natural Resources, 2004). A shallow shoal can be seen at Vail's Point near the mouth of Owen Sound where water depths are as low as one meter (Fig. 2.6).

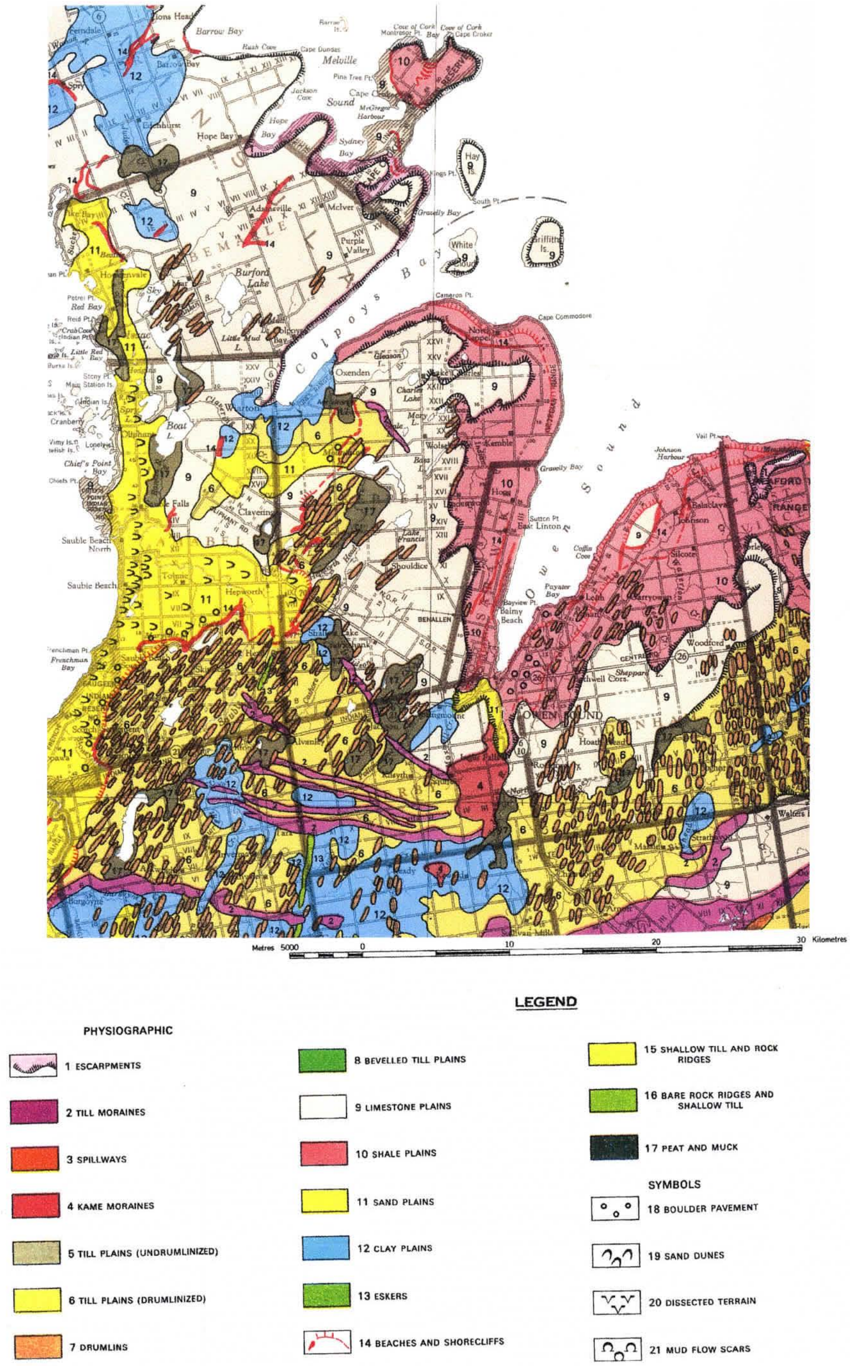


Figure 2.5: Map showing the physiography of the Owen Sound and Colpoy's Bay area. The Niagara Escarpment is a prominent feature that wraps around both flooded re-entrant valleys (modified from Chapman and Putnam, 1984).

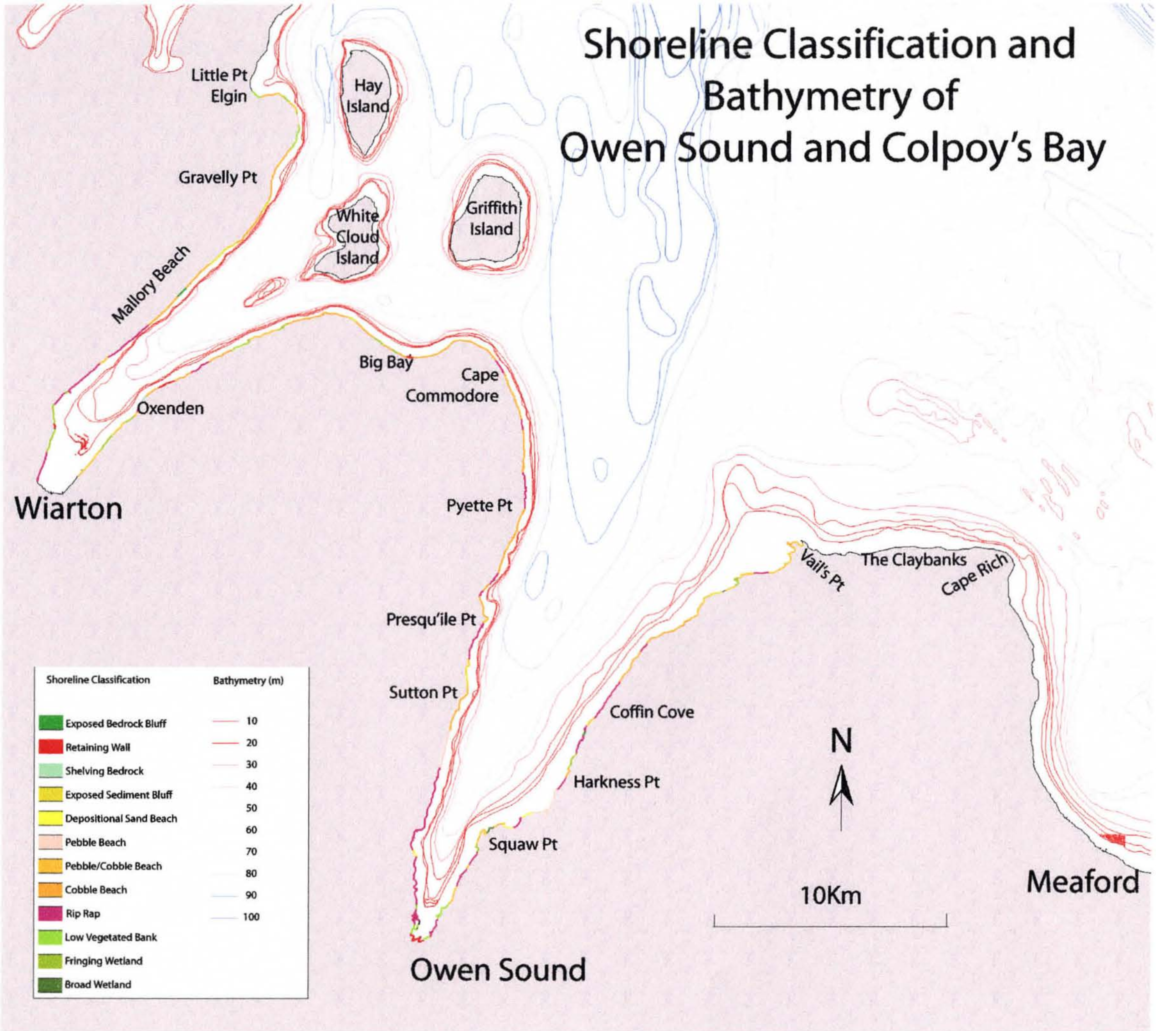


Figure 2.6: Map showing the bathymetry of Owen Sound and Colpoy's Bay (data from Ontario Ministry of Natural Resources, 2004) and shoreline classification according to the Environmental Sensitivity Index (data from Environment Canada, 1994b).

2.3.1.2 Colpoy's Bay:

The bedrock re-entrant valley of Colpoy's Bay is about 18km long, but is narrower than Owen Sound reaching only 7km wide at the mouth of the bay (Fig. 2.5). The Niagara Escarpment lies much closer to the modern lake shore than in Owen Sound, with less than 50m separating the steep cliffs and the lake shoreline on the western side of the bay and about one kilometer on the eastern side (Fig. 2.5; Chapman and Putnam, 1984). In Owen Sound the face of the Niagara Escarpment lies further from lake shore and is also less prominent due to Quaternary sediment masking some of the bedrock topography.

Colpoy's Bay is similar to Owen Sound in that it has an 'inner bay' area south of the town of Colpoy's Bay (Fig. 2.6) with water depths of less than 20m, and a low relief lake floor topography. The outer bay area contrasts with that of Owen Sound as the lake floor has relatively high relief with steep bathymetric gradients on the margins of bedrock highs (Fig. 2.6); a prominent bedrock high lies to the southwest of White Cloud Island and forms a shoal with water depths of less than 10m (Ministry of Natural Resources, 2004). Water depths in Colpoy's Bay reach a maximum of 70m to the east of White Cloud Island (Fig. 2.6).

A major difference in the physiography of Colpoy's Bay and Owen Sound is the presence of three islands near the mouth of Colpoy's Bay (Fig. 2.6). The northernmost island is teardrop-shaped and has a long axis that runs north-south; the other two islands, White Cloud Island and Griffith Island, have more complex shapes and have northeast-southwest long axis orientations (Fig. 2.6). Bathymetric gradients around all three islands are very steep; on the western side of Hay Island water depths increase to 70 meters within 500m of the shoreline (Fig. 2.6; Ministry of Natural Resources, 2004).

2.4 Quaternary sediment cover

During the past 2 million years southern Ontario has experienced many glacial/interglacial cycles, but only four cycles are recorded in the Quaternary sediment record (Table 2.1). The oldest Quaternary glacial deposits exposed in Ontario, of Illinoian age, are found in the Toronto Don Valley Brickyard and are represented by the York Till. The Illinoian glaciation was followed by the Sangamonian interglaciation, which lasted from 120-80ka (Berger and Eyles, 1994). The Sangamonian interglacial period is recorded by the Don Beds, which are also found in the Don Valley Brickyard (Eyles and Clark, 1988; Eyles and Schwartz, 1991; Eyles and Williams, 1992).

The most recent glaciation in North America was the Wisconsin glaciation, which started at about 80ka, and lasted until 10ka (Berger and Eyles, 1994). During this time the Laurentide Ice Sheet advanced as far south as Illinois, Indiana and northern Iowa (Flint, 1967) and covered the entire area of southern Ontario. The Wisconsin glacial stage is subdivided into three substages, early, middle and late Wisconsin, and into a number of stadial and interstadial episodes (Table 2.1). The stadial and interstadial episodes mark the advance and retreat of the southern margin of the Laurentide Ice Sheet, which repeatedly covered and exposed the study area, building a complex stratigraphy of interbedded sub-glacial and glaciolacustrine sediments.

Table 2.1: Chronostratigraphy of Quaternary deposits found in eastern North America deposited in Late Pleistocene glacial and interglacial stages (dates taken from Barnett, 1992; Berger and Eyles, 1994).

<table>
<tr><th>Age (y.b.p)</th><th>Epoch</th><th>Stage</th><th>Substage</th><th>Glacial Stage</th></tr>
<tr><td>7,000 –</td><td>Holocene</td><td colspan="3"></td></tr>
<tr><td>11,500 –</td><td rowspan="14">Pleistocene</td><td rowspan="8">Wisconsin</td><td rowspan="6">Late Wisconsin</td><td>Twocreekean Interstade</td></tr>
<tr><td>12,500 –</td><td>Port Huron Stade</td></tr>
<tr><td>13,200 –</td><td>Mackinaw Interstade</td></tr>
<tr><td>14,000 –</td><td>Port Bruce Stade</td></tr>
<tr><td>15,500 –</td><td>Erie Interstade</td></tr>
<tr><td>18,000 –</td><td>Nissouri Stade</td></tr>
<tr><td>25,000 –</td><td colspan="2">Mid-Wisconsin</td></tr>
<tr><td>53,000 –</td><td colspan="2">Early Wisconsin</td></tr>
<tr><td>80,000 –</td><td colspan="3">Sangamonian Interglaciation</td></tr>
<tr><td>130,000 –</td><td colspan="3">Illinoian Glaciation</td></tr>
<tr><td></td><td colspan="3">Yarmouth Interglaciation</td></tr>
<tr><td></td><td colspan="3">Kansan Glaciation</td></tr>
<tr><td></td><td colspan="3">Aftonian Interglaciation</td></tr>
<tr><td></td><td colspan="3">Nebraskan Glaciation</td></tr>
</table>

The Quaternary sediment cover overlying bedrock is of variable thickness in the southern Georgian Bay region. In areas immediately on top of the Niagara Escarpment, the cover is relatively thin and limestone plains with some sand predominate (Chapman and Putman, 1984). Areas lying farther away from the escarpment face (to the south) tend to have a thicker Quaternary sediment cover and extensive till plains lie south of Colpoy's Bay (Fig. 2.5). Drumlin fields are found throughout the region, with concentrations of drumlins lying just west of Colpoy's Bay, on the peninsula between the two bays and on the eastern shore of Owen Sound (Fig. 2.5; Chapman and Putnam, 1984). Drumlins have a long axis orientation parallel to the long axis of both bays and suggest that the topography of the re-entrant valleys influenced local ice flow directions. The drumlin field that lies on top of the escarpment to the east of Owen Sound contains drumlins that have a more north-south long axis orientation (Fig. 2.5).

In areas lying below (to the north of) the escarpment, the Quaternary sediment cover consists of lacustrine clay plains, with some raised beaches and shorecliffs that run parallel to the modern lake shore (Chapman and Putnam, 1984). These deposits formed when lake levels were substantially higher than at present (see Section 2.4.1below). In Owen Sound, a sand plain lies immediately below the escarpment face near Inglis and Jones Falls and may have been deposited by fluvial processes.

2.4.1 Lake level changes in Georgian Bay

The Great Lakes Basins were carved out of the bedrock surface during the Quaternary glaciations of the past 2.5 million years, and since the establishment of the basins, each of the Great Lakes has gone through many environmental and complex lake level changes (Farrand, 1988; Eyles, 2002). The lake level history of the Great Lakes is based on the sedimentary record found in southern Ontario (also see Section 2.4), and is fairly well understood (Moore and Rea, 1994). This Section will focus on lake level changes that occurred in Georgian Bay in the past 13,000 years, since the retreat of the Laurentide Ice Sheet.

Lake Algonquin, once a prominent proglacial lake in the Great Lakes Basins, started forming about 13,000 years ago (Eyles, 2002), near the end of the Port Huron Stade (Table 2.1; Barnett, 1992), as a result of melt water runoff and ice damming by the Laurentide Ice Sheet (Thurston *et al.*, 1992; Moore and Rea, 1994). Moore and Rea (1994) estimate that the maximum depth Lake Algonquin reached was about 10 meters higher than current lake levels in Georgian Bay (184.4 meters above sea level [m.a.s.l.], compared to 175 m.a.s.l. for the modern lake level; Fig. 2.7). At its highest stage, Lake Algonquin covered all of modern Lake Michigan, Lake Huron and Georgian Bay (Plummer *et al.*, 2004). During this time period of relatively high lake levels the retreating ice margin supplied large amounts of fine-grained sediment to the lake. This sediment settled to the bottom of Georgian Bay and now forms thick successions of laminated fine-grained sediment in the deeper parts of the basin (Karrow and Calkin, 1985).

As the Laurentide Ice Sheet retreated further north, Lake Algonquin overflowed in the North Bay area towards the Ottawa River and started to drain into the North Atlantic Ocean (Karrow and Calkin, 1985; Moore and Rea, 1994; Eyles, 2002). Lake

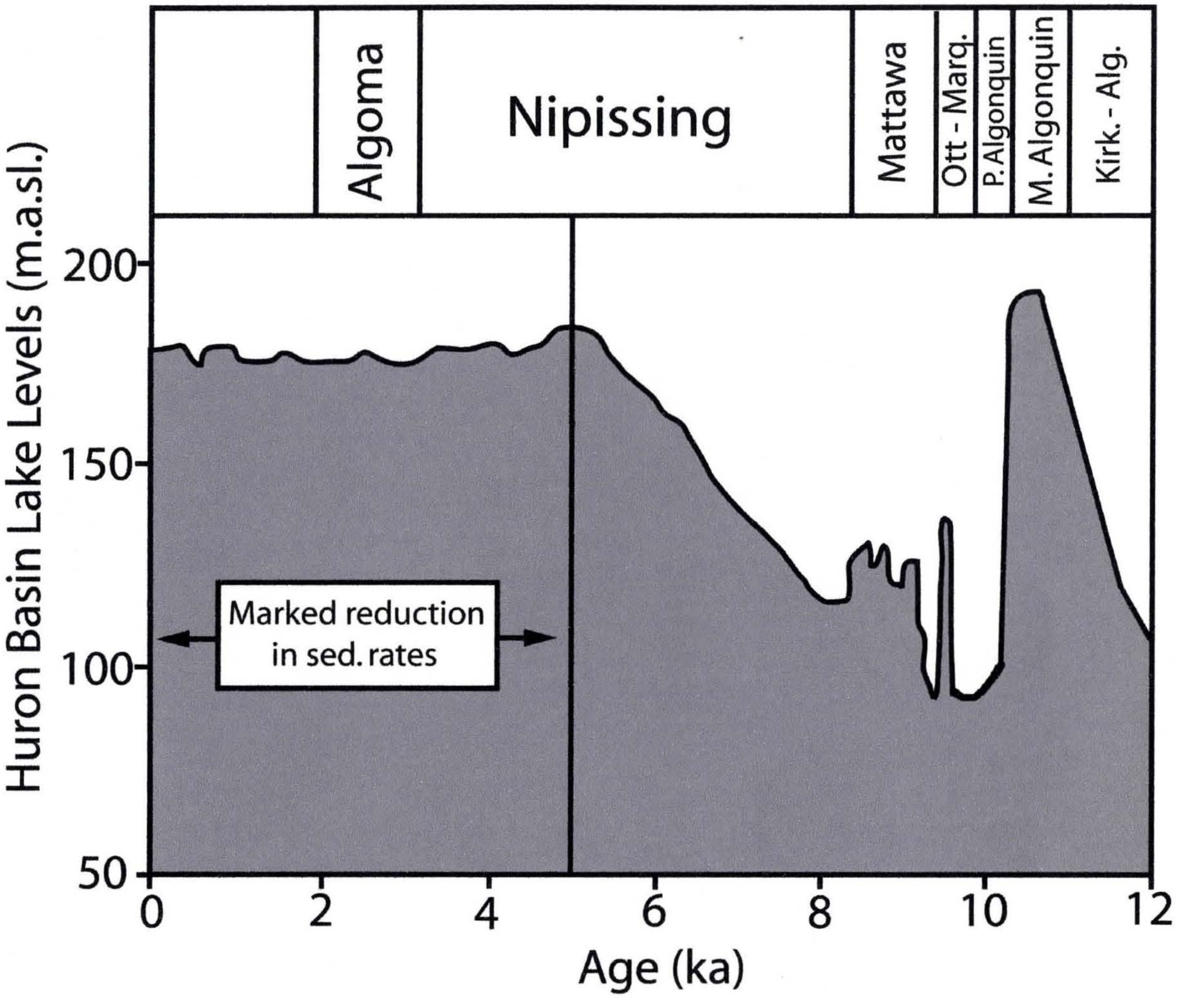


Figure 2.7: Lake level curve for the Huron Basin following deglaciation of southern Ontario (modified from Moore and Rea, 1994). Note high Lake Algonquin levels around 11,000 y.b.p. and subsequent post-Algonquin low levels.

levels were at a low point about 10,200 years ago when water levels dropped to approximately 100 m.a.s.l., almost 75 meters lower than current water levels in Georgian Bay (Thurston *et al.*, 1992; Moore and Rea, 1994; Rea and Moore, 1994). These extremely low lake levels were caused by the outlets of the Great Lakes basins having been lowered in elevation due to crustal depression under the weight of the Laurentide Ice Sheet. Over time the outlets rebounded to their present elevation, allowing the basins to fill up to their present levels (Rea and Moore, 1994; Eyles, 2002).

Before the lake basins filled up to present levels, lake floor sediments exposed during the post-Algonquin lowstand were eroded sub-aerially. This erosion is seen as truncation of sediment layers on sub-bottom seismic profiler images from the northern part of Lake Huron and Georgian Bay (Moore and Rea, 1994), and from Owen Sound and Colpoy's Bay (Terlaky *et al.*, 2004; Radomski, 2005).

Finally, as lake levels slowly increased to their current levels a new, acoustically "transparent" layer of Holocene mud began to form on top of the post-Algonquin erosional surface (Rea and Moore, 1994). This relatively thin sediment drape is not continuous and does not have a uniform thickness across the Great Lakes basins (Terlaky *et al.*, 2004; Radomski, 2005), indicating variable but low rates of lacustrine sedimentation during the Holocene.

2.5 Modern lacustrine conditions in southern Georgian Bay

The geology of the Owen Sound region, as described above, is continually affected and changed by modern processes. Weather patterns and wave climates influence the modern lake shore and stream inputs to both Owen Sound and Colpoy's Bay and have a large influence on current patterns and sediment transport in both bays. This Section will give an overview of the weather patterns and wave climates of both Owen Sound and Colpoy's Bay, followed by a description of modern coast and shoreline types and stream inputs.

2.5.1 Local weather patterns and wave climate

The available information pertaining to local weather conditions in the southern Georgian Bay region, such as prevalent wind directions, current directions, ice cover and its thickness, is very limited. Most available data refers to Georgian Bay as a whole, and does not have sufficient resolution to be useful for local scale investigations.

Local wind direction data, found in pleasure craft weather guides, such as the Weather Guide for Pleasure Crafts, Georgian Bay (1992) indicate that Owen Sound can experience southwesterly wind gusts due to down-valley winds. When the area experiences easterly winds, a significant wind set-up can develop in the inner harbor, which can reach up to ½ meters in height. Northeasterly winds can create large storm swells entering the sound, with wave crests of 2m height. These winds also increase in speed through funneling effects and cornering at Squaw Point (Fig. 2.6). Currents occur mostly down the west side of the bay (Weather Guide for Pleasure Crafts, Georgian Bay, 1992).

Colpoy's Bay is more protected from winds than Owen Sound, by both the steep walls of the Niagara Escarpment, and by the three islands located just outside the mouth of the bay (Fig. 2.6). Northeasterly winds have the most effect on conditions within the bay, but are significantly dampened by the three islands.

Ice cover starts to develop on the eastern shore of Georgian Bay in the second half of December and maximum ice thickness is reached in the middle of February (Environment Canada, 2002). Undisturbed ice can reach thicknesses of 45 to 75 centimeters, but rafting, ridging and windrows of ice can achieve thicknesses of up to 18 meters. Break-up normally begins during March with the lake clearing rapidly thereafter. Normally the entire lake clears by the second week of April. The variations from year to year can be drastic, with warm years only experiencing a total cover of 29% in Georgian Bay, while in other years 100% of the lake is ice covered (Environment Canada, 2002).

2.5.2 Coast and shoreline types

Environment Canada conducted a survey of shoreline environmental sensitivity within the Great Lakes in 1994 and produced a number of maps classifying shoreline sensitivity according to a standardized scheme (Environmental Sensitivity Index, or ESI). The shorelines of both Owen Sound and Colpoy's Bay were mapped during this survey and are shown to be diverse with a variety of shoreline types (Fig. 2.6; Environment Canada, 1994b).

The northeastern shore of Owen Sound is characterized by cobbly and gravelly beaches with a number of artificially reinforced sections where cottages are present (Fig. 2.6). Paynter Bay and Squaw Point are rimmed by sandy beaches and wetlands that extend out into shallow waters. Further south in the sound near Owen Sound, most of the shoreline is artificially reinforced (Fig. 2.6). Elsewhere along the western shore of Owen Sound are artificial shorelines, cobbly beaches and some bedrock outcrops north of Sutton Point.

In Colpoy's Bay the northwestern shore is characterized by sandy and cobbly beaches (Fig. 2.6). Near Oxenden, at the mouth of the "inner bay", bedrock outcrops at the shoreline and forms a shallow shoal offshore. The western side of the inner bay has sandy beaches, while the southern and eastern sides are mostly artificially reinforced. Between Wiarton and Colpoy's Bay village, a small natural wetland can also be found. Further north along the eastern shore is mixture of artificially reinforced areas where cottages are present, and some bedrock outcrops. Near the mouth of the bay cobbly beaches become more abundant (Fig. 2.6).

2.5.3 Stream inputs

Very little information is available on stream water inputs and sediment loads into either Owen Sound or Colpoy's Bay. Two large streams (the Sydenham River and the Pattawatomi; Fig. 2.8) drain into Owen Sound through the city of Owen Sound, and several other streams drain into the sound from either shore. The most prominent streams enter the sound north of Squaw Point, south of Vail's Point and at Balmy Beach (Fig. 2.8).

Colpoy's Bay has fewer stream inputs than Owen Sound. The largest ones lie south of Colpoy's Bay Village, at Wiarton and south of Oxenden. There are no streams entering Colpoy's Bay from the western shore north of Colpoy's Bay Village; a possible explanation could be the proximity of the Niagara Escarpment to the bay.

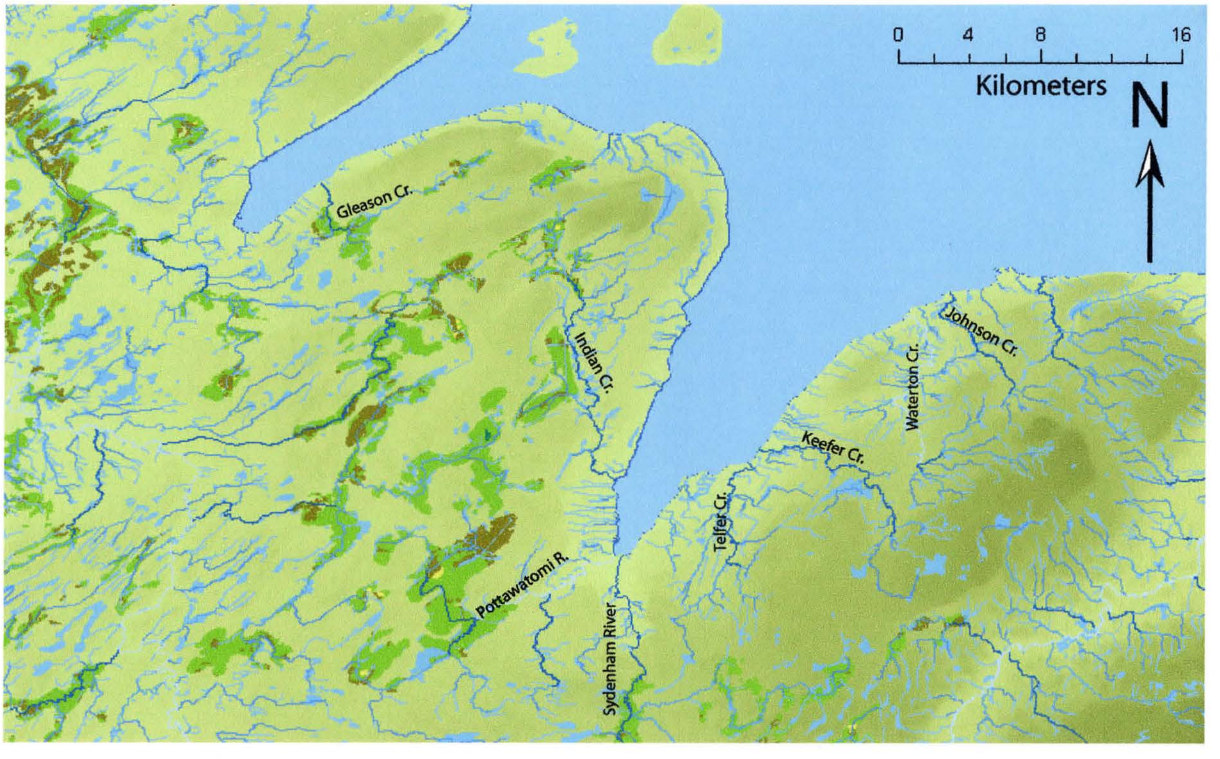


Figure 2.8: Map showing the distribution of surface water bodies and the location of stream inputs to Owen Sound and Colpoy's Bay (modified from MNR unpublished map, 2005).

CHAPTER 3: SIDE SCAN SONAR AND SUB-BOTTOM SEISMIC TECHNIQUES

3.1 Introduction

In order to determine substrate sediment characteristics and their distribution in Owen Sound and Colpoy's Bay, side scan sonar data and sub-bottom seismic data were collected during the summer of 2004. The sub-bottom seismic data were the focus of an undergraduate thesis (Radomski, 2005) and are only used here to validate interpretations of surface sediment type made from side scan data and to establish the age of surface sediment units. This thesis focuses on the side scan data and its use in identifying and delineating substrate types in the study area.

The study area consists of Owen Sound and Colpoy's Bay in southern Georgian Bay, with a total surface area of approximately 150km^2. During the months of June and July, 2004 a database of more than 100km "CHIRP" high-resolution sub-bottom seismic profiles of lake floor sediment and 500km of side scan data of lake floor topography, substrate type and structure were collected. The research vessel, Ontario Rocks, used for field work is a customized 25-foot steel haul Stanley, equipped with a generator, several cable spools and rigs for towing equipment, a computer console and advanced differential GPS navigation system (Fig. 3.1). Each of the geophysical methods used to collect data will be discussed below.

Figure 3.1: Research vessel "Ontario Rocks", a customized 25 foot steel haul Stanley boat equipped with differential GPS system, computer console and rigs for tow equipment deployment. Here seen being prepared for a survey of Owen Sound, in Owen Sound Marina.

3.2 Side scan sonar

Side scan sonar technology has been widely used for commercial applications since 1958 (Flemming *et al.*, 1982), and the development of new and improved systems is on-going. The basic elements of a side scan sonar system are still the same as 40 years ago, but refinements of modern systems make them capable of producing high-resolution sonographs of the sea or lake floor that closely resemble the quality of aerial photographs (Flemming *et al.*, 1982; Mazel, 1985). In order to identify the nature of the surface sediment cover on the floors of Owen Sound and Colpoy's Bay a side scan survey was conducted in the summer of 2004.

Information on the basic operation and image formation of a side scan system is widely scattered in the literature; Flemming *et al.*, (1982) and Mazel (1985) recognized this problem and each provide a detailed summary and comprehensive overview of this information. This chapter will rely heavily on these two references as they are a key source of information on side scan sonar. An overview of side scan systems and processes used in image interpretation is presented below.

3.2.1 Side scan sonar systems

The modern side scan system has a straight forward set-up and an ease of use that is virtually unparalleled in any other sea- or lake-bottom imaging system. The basic elements of a sonar system that are common to all systems, from a simple one-dimensional depth sounder to a more sophisticated side scan sonar, are shown in Figure

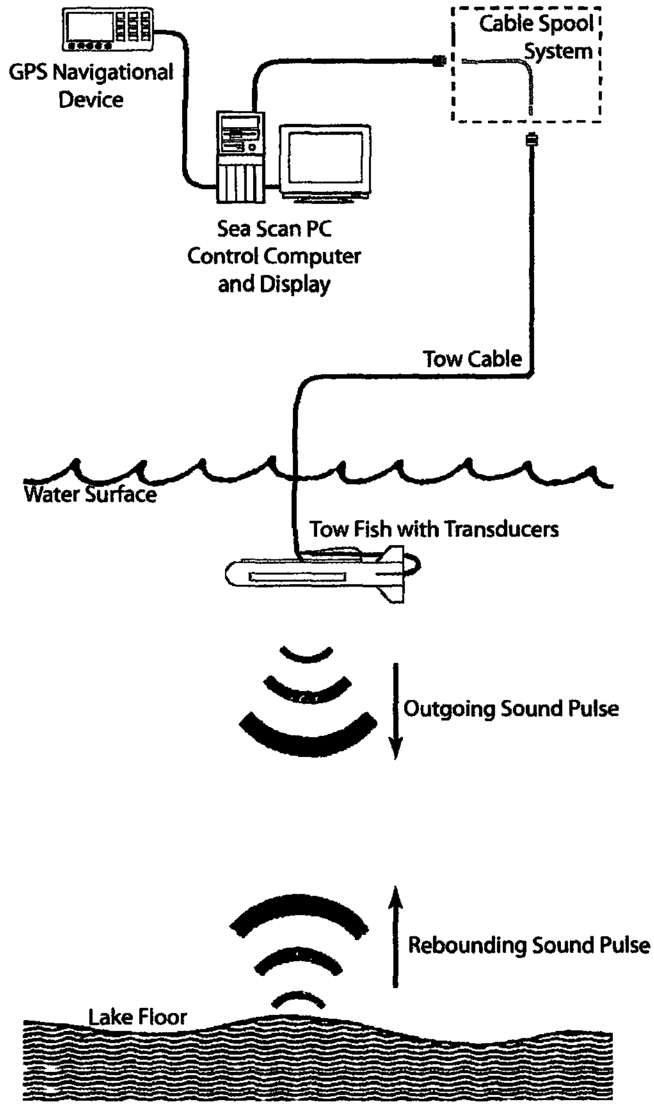


Figure 3.2: The basic elements of a side scan system: the computer acts as a control and display unit that synchronizes the timing of the elements of the system. A transmitter in the computer produces electrical currents that are transformed into sound pulses by the transducer located in the tow fish. These sound pulses travel through the water column and are reflected off surfaces they encounter. Sound echoes are picked up by the transducer and converted back to electrical currents and received through the receiver at the computer. The system is linked to the navigational system of the boat to acquire positional information which is integrated with the side scan imagery (modified from Mazel, 1985; Marine Sonic Technology Ltd. 2001).

The entire system is controlled by the computer which is in continuous two-way communication with the tow fish and regulates the precise timing required for the various elements to synchronize their operations (Marine Sonic Technology Ltd., 2001).

Data received by the computer from the tow fish are directly recorded on the computer's hard drive and integrated with the GPS information received from the boat's navigation system. Data are also displayed in real-time on the computer screen, allowing adjustments to be made to the recording parameters as the survey progresses (Marine Sonic Technology Ltd., 2001).

A side scan system is distinguished from other sea-bottom imaging systems by four characteristics that it must possess: a sideways look angle, the two energy emitting channels on either side of the tow fish, the narrow, symmetrical fan shaped sound beam emitted and the necessity to use a towed body, or tow fish (Fig. 3.3; Mazel, 1985). The sideways look concept means that the energy pulse emitted by the tow fish is directed to the sides of the unit, rather than vertically down. This look angle provides a view of a number of echoes from objects along the lake bed or in the water column, rather than just a single echo from a discrete target under the tow fish. The two sonar channels, one located on each side of the tow fish, effectively double the coverage of a single overpass with the survey vessel, as the energy beams are pointed to both sides of the survey line. The sideways look angle and the two channel operation create the "swath" of the sonar, or the width of the survey line that can be imaged with one overpass (Fig. 3.3). The narrow beam in the horizontal plane achieves the high resolution of a typical side scan survey, as the narrower beams have a better resolving power (Flemming *et al.*, 1982).

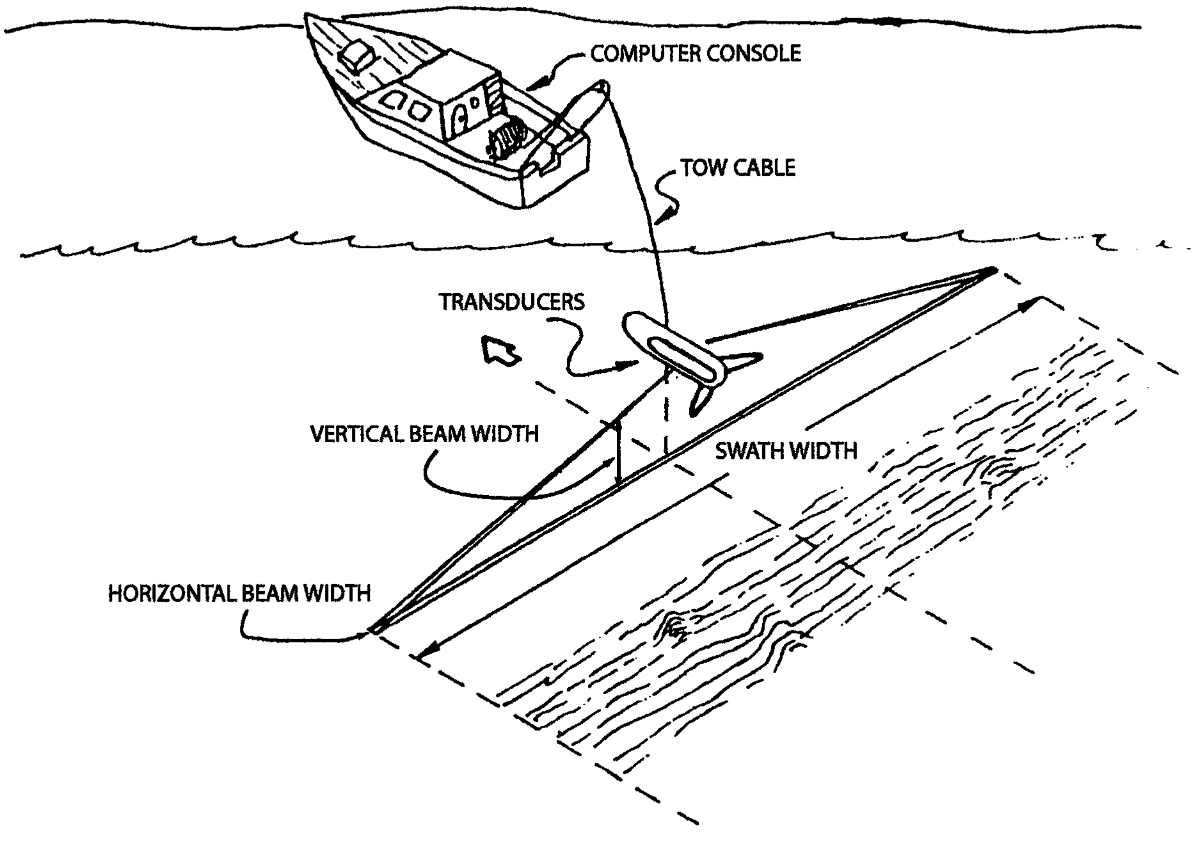


Figure 3.3: Set-up of the side scan survey where a tow vessel is towing the tow fish underwater with a tow cable. The tow fish houses the sonar equipment that emits sound pulses to either side of the tow line, creating a swath. The computer equipment is located on the boat and all operations of the system can be controlled from the computer console (modified from Mazel, 1985).

3.2.2 Side scan sonar geometry

A simplified plane view of the right side channel of a side scan survey is shown in Figure 3.4A, and a sample record corresponding to the plane view is shown in Figure 3.4B. The start time on the display image is when the transmission of the sonar pulse commences and is shown on the sonar image as the output pulse (Fig. 3.4B). The sonar measures the acoustic returns at the tow fish, and thus the tow fish becomes the spatial reference point for interpretation of the display (Flemming *et al.*, 1982; Mazel, 1985; Zehner and Thompson, 1996).

The first signal to be recorded is the outgoing pulse from the tow fish itself. This is shown as a very strong signal and is displayed as a dark line. The outgoing signal marks the start of the display for both channels (only one channel is shown in Figure 3.4B). Following this is a period of time during which the sonar pulse is traveling through the water column and no returning echoes are created. This produces a blank or light area on the record (Fig. 3.4B), unless something such as a school of fish is blocking the sonar pulse in the water column (Flemming *et al.*, 1982; Mazel, 1985).

The next two strong return signals will be from the water surface and the lake floor. These echoes are the strongest received signals as they bounce perpendicularly off the water or lake bottom surface, and not at an angle, reducing the amount of energy lost at the contact (Mazel, 1985). The order of which arrives first depends on the height of the tow fish above the lake floor (Fig. 3.5); in Figures 3.4A and 3.4B the first return will be of the water surface as the tow fish is closer to it than the lake floor.

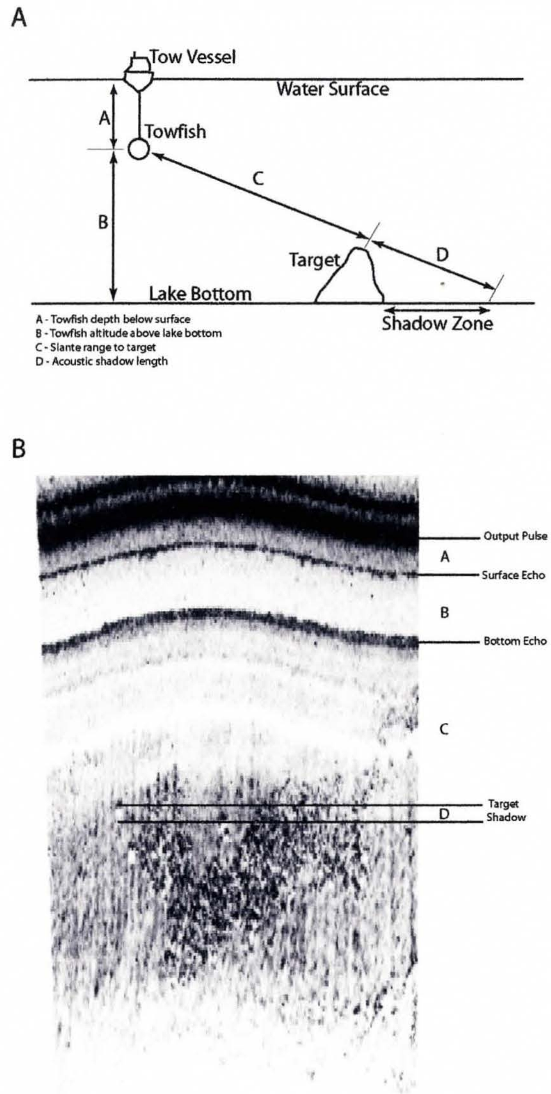


Figure 3.4: (A) Side scan sonar geometry where the tow fish is towed closer to the water surface (distance A) than the lake bottom (B). The sonar measures the two-way travel time of the sound pulse along the slant ranges (C) and (D). The distinct target will produce an acoustic shadow behind itself (adapted from Mazel, 1985). **(B)** A sample image that shows the elements of this geometry on the output image. The output pulse is seen near the top of the image. The first reflection (dark line) seen under (A), is from the water surface (Surface Echo); the second dark line, after (B) (Bottom Echo) is the first lake bottom reflection. The target is seen after (C); the target shadow zone is (D) on the output image.

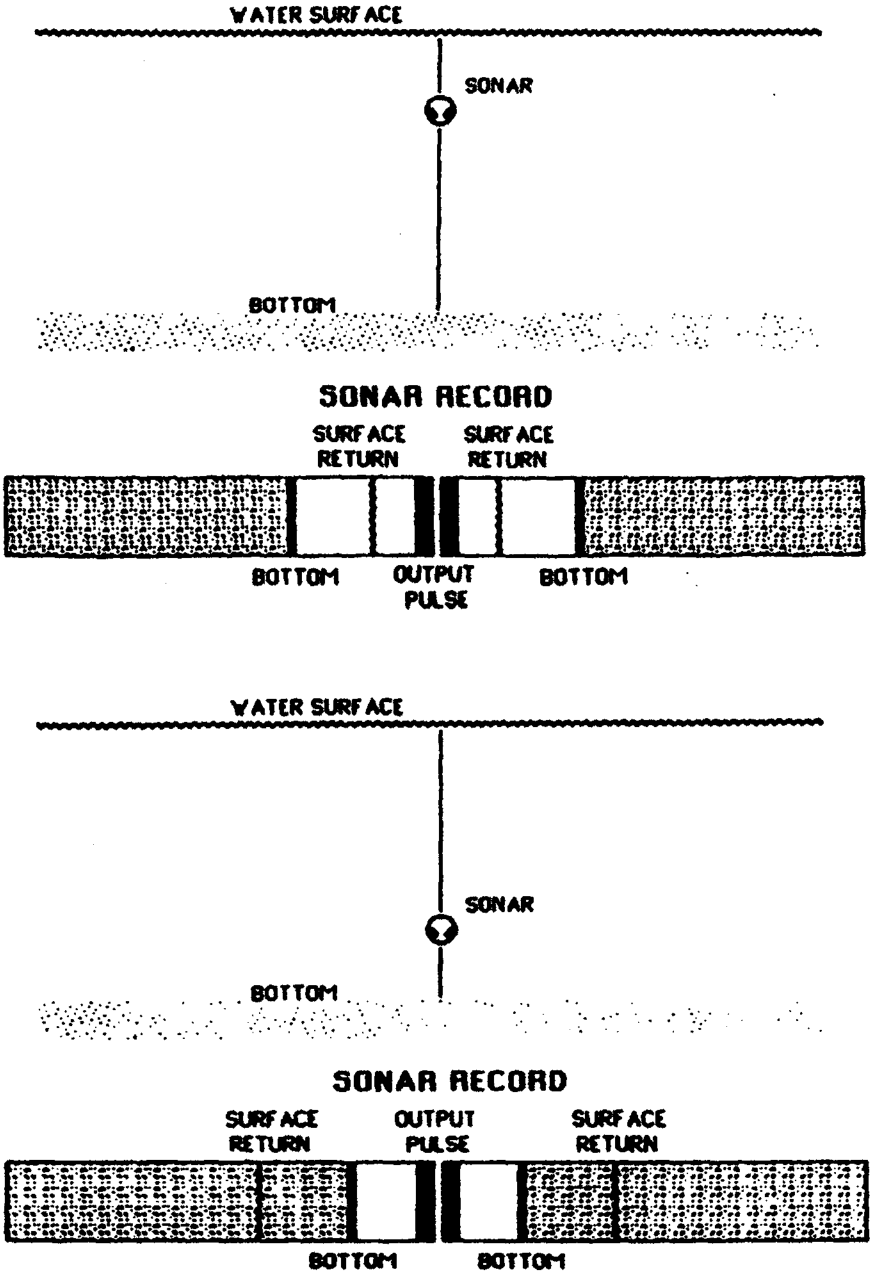


Figure 3.5: Depending on the altitude of the tow fish either the water surface echo or the lake bottom echo will be recorded first. On the upper image the tow fish is closer to the water surface, thus the first return will be from the surface, on the lower image the tow fish is closer to the bottom and the bottom return is recorded first. Notice that on the lower image the surface return is superimposed on the useful image portion of the bottom echoes (Mazel, 1985).

Often it is difficult to differentiate between the two returns based on the display only, but there are several ways to do this. The fastest and simplest way is to find where continuous returns from the lake floor start; in an ideal situation these returns should follow right after the first bottom return. Another way is to determine the height of the tow fish in the water column and calculate whether it is being towed at a shallower or deeper depth than one-half of the total water depth. Finally, the tow fish can be lowered or raised and based on the relative movement of the strong linear returns it can be deduced which return belongs to the water surface and which to the bottom (Flemming *et al.*, 1982; Mazel, 1985).

Immediately following reception of the initial strong lake bottom echo, a series of returns from the lake floor at successively increasing distances from the tow fish are recorded. These returns are the main focus or target of any lake- or sea-bottom study. As the sonar measures the two-way time of the echoes, the distance displayed in a raw display are slant ranges and do not represent the actual horizontal distance of the points on the bottom away from the tow fish. The two-way travel time of the sound corresponds to the slanted distance between the tow fish and the target (e.g., Lines C and D, Fig. 3.4A; Mazel, 1985). The true horizontal offset can be calculated with simple trigonometric calculations, and is done automatically in modern systems, such as the one used in this study (Marine Sonic Technology Ltd. 2001).

3.2.3 Side scan sonar resolution

The term 'resolution' refers to the ability of the system to distinguish between two closely spaced objects (Mazel, 1985). The side-scan sonar system used for this study has a resolution of 29cm, which means that objects spaced 29cm or more apart will be shown on the output image as two distinct objects; however, if they are spaced closer together they will appear as one object. The 'detectability' limit of a system refers to the ability to see a target at all on a sonar record; this limit is usually less than one centimeter; meaning that a single object with a diameter of less than one centimeter can be identified on an output image, provided it is at least 29cm away from any other objects (Flemming *et al.*, 1982; Mazel, 1985).

Two different resolution types can be differentiated for side scan sonar systems: across-track, or range resolution, and along-track, or transverse resolution. The former deals with objects located in a line perpendicular to the tow fish path, the latter with objects that lie in a parallel line to the survey path (Mazel, 1985). The resolution of the system will depend on a number of survey design factors, such as outgoing pulse length, beam width, beam patterns and directivity and frequency. Furthermore, resolution is affected by external factors, such as tow speed, water temperature variations, salinity variations (Mazel, 1985) and tow fish motions (Zehner and Thompson, 1996).

Generally speaking the range or swath width (Fig. 3.3) of a side scan sonar system becomes smaller as the resolution increases, and vice versa (Flemming *et al.*, 1982; Mazel, 1985; Marine Sonic Technology Ltd., 2001). The design of any side scan sonar system thus involves a trade-off between resolution and range. In practice, a sonar system must be designed to have high enough resolution to image the desired targets whose approximate scale is known or estimated. For example, if sunken ships with unknown locations are the target of a survey, a low resolution system can be used, which will have a long range; this set-up will speed up operations as a larger area can be covered in a given time. When closely spaced wreck debris is to be mapped however, a short range, high resolution system is required to image individual particles.

3.2.3.1 Frequency

A major factor that affects working range and both across-track and along-track resolution is the frequency of the emitted sound pulse. As with other factors, frequency choice is a trade off between maximum attainable range and resolution, where higher frequencies allow for shorter pulse lengths (affecting across-track resolution, Section 3.2.3.2) and narrower beams (affecting along-track resolution, Section 3.2.3.3), resulting in better resolution (Mazel, 1985). The range however will decrease with increasing frequency, as higher frequencies attenuate faster in a medium (Flemming *et al.*, 1982).

3.2.3.2 Across-track resolution

Across track resolution is the ability to image closely spaced objects that lie perpendicular to the survey line path. The major factor affecting across-track resolution is pulse length. The sound pulse generated by the transducers in a tow fish is of a fixed length which can be changed with certain units, but in most systems it is a factory pre-set length (Marine Sonic Technology Ltd. 2001). In general, a shorter outgoing sound pulse length will yield better resolution, but a longer pulse has a narrower bandwidth, and is less sensitive to outside noise, increasing the performance of the unit at long range. Commercial units are pre-set to maximize the range of the system, while maintaining resolving power (Flemming *et al.*, 1982; Marine Sonic Technology Ltd. 2001).

If two objects are closer together than the across-track resolving power of the side scan sonar system, then the returning echoes from the two objects will overlap and they will blend together as one target on the record (Fig. 3.6). Theoretically, the minimum separation distance between objects is ½ of the physical pulse length, but the actual resolution achieved is always less than the theoretical limit. This is due to the fact that the "footprint", or the extent of the arriving sound energy on the bottom at any time, is always larger near the sonar, or tow fish, due to the angle of incidence of the energy wave on the bottom (Fig. 3.6; Mazel, 1985). The further the sound pulse travels from the sonar, the closer the bottom footprint approaches the actual pulse length in the water, increasing the across-track resolution (Mazel, 1985). This is only theoretically true however, as other factors diminish the resolving power of the sonar at distance from the source.

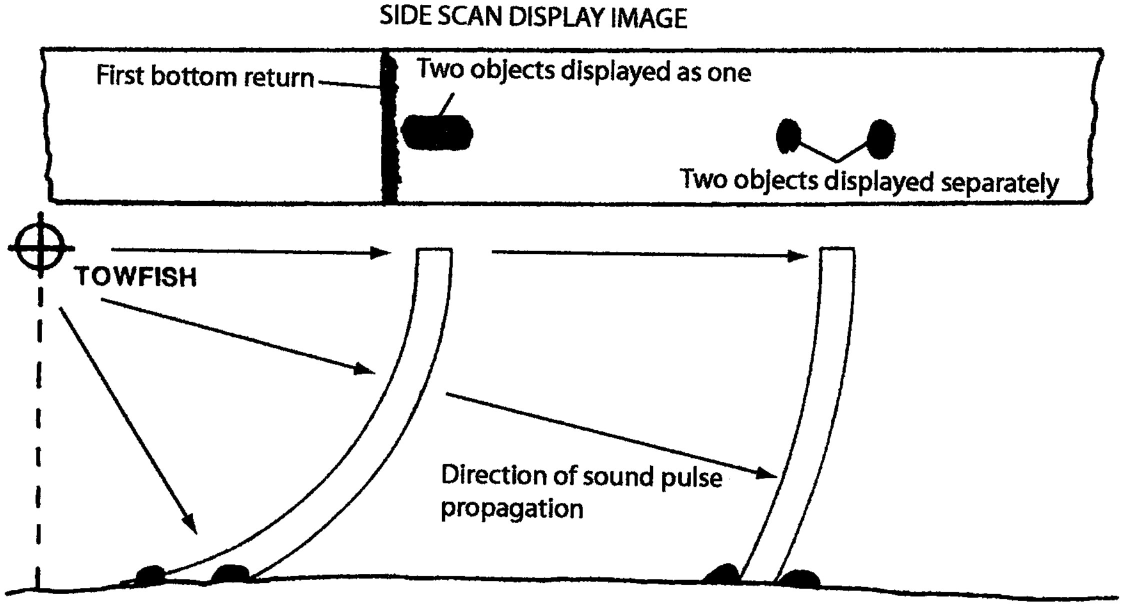


Figure 3.6: Across-track resolution of the sonar is dependent on pulse length and distance from the tow fish. Theoretically a shorter pulse length will increase resolution. The angle of incidence narrows the "footprint" of the sound pulse on the lake floor further away from the sound source, resulting in an increase in resolution at a distance from the tow fish (modified from Mazel, 1985).

3.2.3.3 Along-track resolution

Along track resolution refers to the ability of the sonar to distinguish between two closely spaced objects that lie parallel to the survey line path. The along-track resolution of a side scan sonar system is largely dependent on the sound pulse beam pattern, or beam shape, that the sonar emits. The pattern of the beam emitted by the sonar is the result of transducer design and is fixed for each unit. The side scan transducer consists of a line array of crystal elements, where each point on the faces of the crystals acts as a sound radiator. As the sound waves travel through the water they create pressure disturbances which add (amplify) or subtract (mute) each other, depending on the phase they are in. The net effect of these amplifications produces a distinct sound beam pattern characteristic for each instrument (Mazel, 1985).

The typical beam pattern in the horizontal plane of a side scan sonar has a strong central main axis with weak side lobes, meaning that most of the sound energy is focused in a narrow line perpendicular to the sonar. Because the transmitters also function as the receivers, the receiving beam pattern is the same as the transmitting pattern. For an active sonar these beam pattern effects add up, narrowing the two-way beam width, which enhances resolution (Fig. 3.3). An additional advantage of a narrow beam width to enhanced resolution is that it helps to reject background noise coming from all directions in the water column (Mazel, 1985).

The vertical beam width is significantly different from the horizontal one. The beam is much wider, which explains why a signal is received from both the water surface and the lake floor beneath the sonar (Fig. 3.3). On most systems the main axis of the beam is angled about 10 degrees down from horizontal, so that most of the energy is directed toward the bottom, where it is needed to image targets on the lake floor. Unlike the horizontal beam pattern, there are no distinct energy peaks in the sound beam; this ensures that the sound reaching the bottom is even and no light or dark bands are on the record (Flemming *et al.*, 1982; Mazel, 1985).

The maximum attainable along-track resolution with a given system is strongly dependent on the horizontal beam width of the sonar (Fig. 3.3). If two objects lie closer together than the spread of the sonar beam at that range, then during the entire time the objects are being passed by the tow fish, one or both will be illuminated at all times and seen as a single, larger object (Fig. 3.7; Mazel, 1985). At closer ranges the beam is narrower and the along-track resolution will be better, in contrast to across-track resolution where the reverse is true.

3.2.4 Tow fish stability

The side scan sonar system is a high-resolution sound sensor, and as with any high-resolution system, motion perturbations of the actual sensor platform can cause degradation of the quality of the images produced. The amount of degradation or damage to the images is dependent on the type and nature of the motion disturbance, and it is important in the interpretation of the images to account for any deformation caused by unwanted tow fish motions (Zehner and Thompson, 1996).

In an ideal situation the tow fish is moving in a straight line forward through the water column at a constant height above the sea or lake bottom. Due to towing set-up,

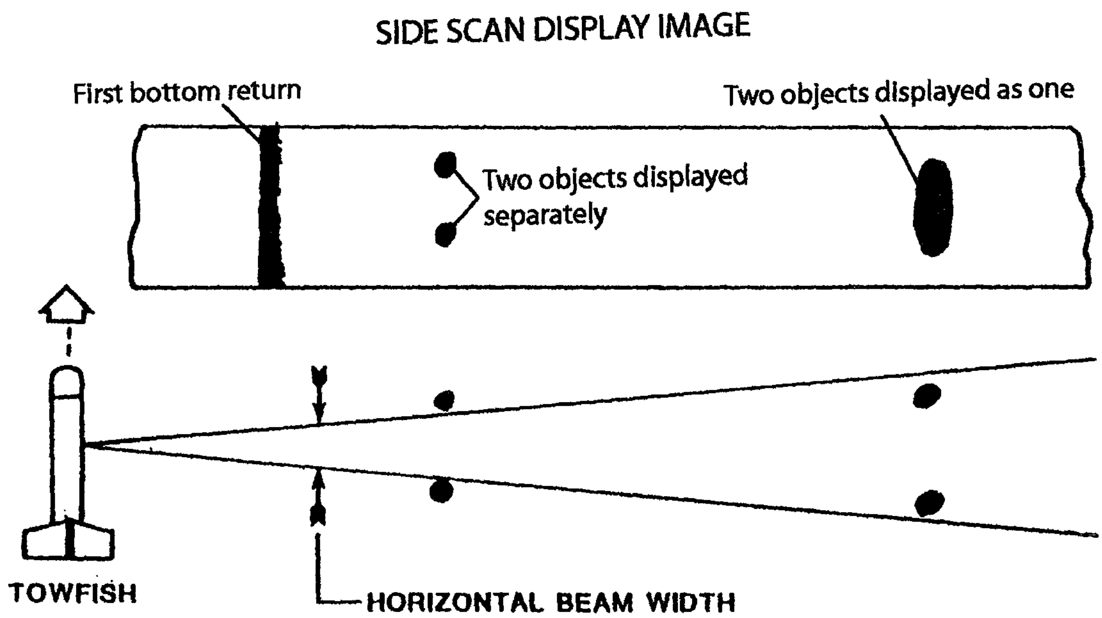


Figure 3.7: The along track resolution of a side scan sonar system is heavily dependent on the horizontal beam width which widens as distance from the tow fish increases. Resolution is best with a narrow beam width which occurs close to the tow fish (modified from Mazel, 1985).

weather or current effects this ideal situation is rarely achieved and some disturbances in tow fish motion are experienced. Six motion disturbances can be identified as significant in sonar image quality degradation, each of which will have a different effect on the final image. These six are roll, pitch, yaw, velocity changes in along-track, across-track and vertical directions, or a combination of any of these (Fig. 3.8; Mazel, 1985; Zehner and Thompson, 1996).

With any of the motion disturbances the symmetrical fan shaped sound beam of the side scan sonar (Fig. 3.3) is disturbed or re-oriented in an unwanted direction, leading to an over-sampling in one area of the image and an under sampling in another, and in more severe cases image distortion can occur. Under ideal conditions the scan lines of a single sound pulse, or scan, are V-shaped in plan view due to the forward motion of the tow fish. Successive scans line up in parallel straight lines to produce an even sampling pattern (Fig. 3.9A; Zehner and Thompson, 1996).

Changes to the sampling pattern show where over or under sampling, or distortion, takes place in a side scan picture. Figure 3.9B shows the sampling pattern where the tow fish experiences a change in along-track velocity. The scan lines remain parallel and straight, but where the tow fish moves faster, under sampling takes place, and when it moves slower, over sampling occurs (Zehner and Thompson, 1996). Fortunately with modern systems, as the one used in this survey, this error is largely corrected with the aid of the navigational data received from the boat's GPS system by controlling the number of pulses emitted per second, and the remaining error due to the "jerking" of the tow fish is negligible (Marine Sonic Technology Ltd., 2001). In this

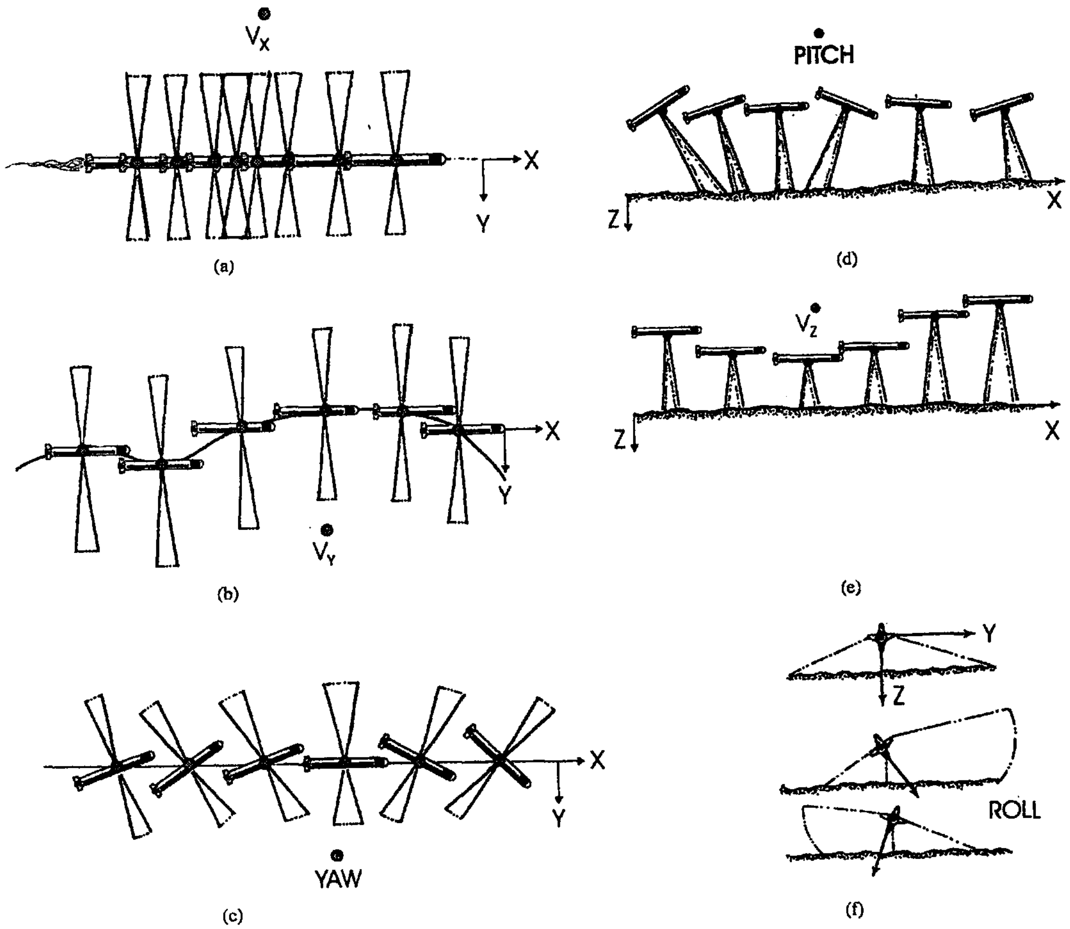


Figure 3.8: Motion perturbations of the tow fish can degrade the quality of the sonar image. Six different motion types can be distinguished:

(A): along-track speed changes

(B): cross-track speed and position changes

(C): yaw

(D): pitch

(E): vertical or altitude changes

(F): roll

(Zehner and Thompson, 1996)

survey this type of error was only seen when the survey track line was directly head on with large storm waves.

Figure 3.9C shows the effects of tow fish movement to the sides, or cross-track movements, where the tow fish nose is still pointing forward. This motion rarely is experienced by itself, and will result in a locational error in the output images and in severe cases some shearing of the target image (Zehner and Thompson, 1996).

Altitude changes of the tow fish will result in the sampling pattern shown in Figure 3.9D. The biggest effect an altitude change will have is in the short-range areas of the image and mostly affects the length of the acoustic shadows cast by targets on the lake bottom (Zehner and Thompson, 1996). As the tow fish is lowered toward the bottom the shadow of any object will become longer, just as shadows elongate during sunset when the sun is lower on the horizon. This error is easily identifiable on a side scan image by the varying distance of the first bottom return to the output signal (Mazel, 1985). This type of error was often seen in the survey of Owen Sound and Colpoy's Bay as the survey line approached shore. The steep bathymetry of both bays made it difficult to accurately control the altitude of the tow fish.

Tow fish roll has a negligible effect on the location of sampling points, however as the sonar rolls to one side, that side can experience severe over sampling and the other side severe under sampling. This can result in the loss of useful acoustic shadow information as the signal can become too weak on the under sampled side (Zehner and Thompson, 1996). This error is also readily identifiable by a "scalloped" appearance of the side scan image and can, to a certain extent, be corrected by gain changes to either channel. This error was encountered when the survey line was perpendicular to the dominant wave direction and both the boat and the tow fish rolled from side to side.

Pitch effects are illustrated in Figure 3.9E. This error is similar to errors caused by along-track velocity changes, but can be distinguished by the slight errors in cross-track sampling locations (Zehner and Thompson, 1996). In other words, the scan lines do not stay parallel, as is the case where only the along-track velocity changes. This effect occurred rarely when the boat rolled over large rolling waves and the tow fish suddenly lurched forward and up.

Figure 3.9F shows the effects of yaw, which has the most severe degrading effect on image quality. This is due to the combination of a long range and narrow beam width with which the side scan system operates. When the tow fish turns, the inside of the turn is over sampled, while the outside of the turn is severely under sampled; this error cannot be corrected as the data are simply not available from the under sampled areas (Zehner and Thompson, 1996). This type of error is readily visible on the locationally corrected images taken as sharp turns were made by the boat, where the inside of the track line is over sampled, and the outside turn is missing of data.

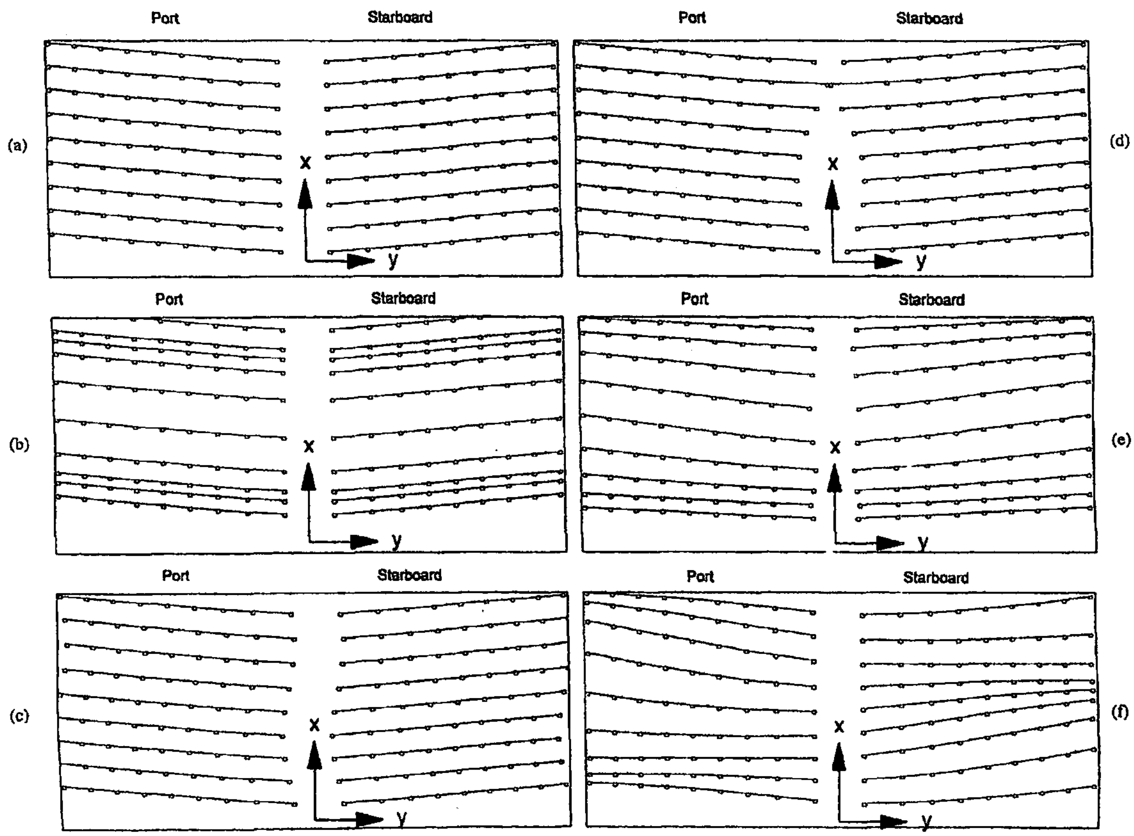


Figure 3.9: Motion changes disturb the sampling positions of the sonar.

(A) shows the sampling pattern of a sonar under ideal conditions. The sampling patter is even with parallel lines in a slight V-shape.
(B) the effects of along-track velocity changes.
(C) the effects of cross-track velocity changes
(D) the effects of altitude changes
(E) the effects of pitch disturbances
(F) the effects of yaw
(Zehner and Thompson, 1996)

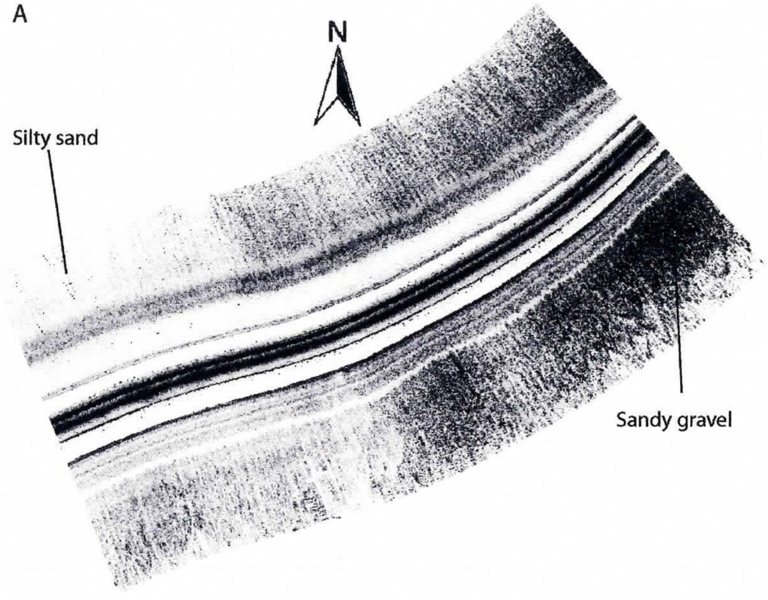
3.3 Side scan image interpretation

The sound pulse that travels away from the tow fish interacts in different ways with the objects it encounters. How this sound is reflected back to the sonar will ultimately determine the characteristics of a sonar image. This Section will outline how various targets and lake or sea floor materials affect and reflect the incident sound pulse, and how these reflection characteristics aid in target identification.

3.3.1 Lake or sea floor materials

Different lake or sea floor materials can be distinguished on a side scan sonar image due to the effects of backscatter, or bottom reverberation. The lake floor always has some distinctive texture based on the grain size of the sediments, which causes backscattering of sound energy from grains comprising the bottom sediment. The irregular surface, or 'roughness' of sediments on the lake floor allows sound energy to be scattered in various directions, and the portion that returns to the sonar is recorded. Sediment types with different grain sizes, such as sand, clay, mud, silt and gravel, will scatter a different proportion of the sound energy back toward the tow fish and will be represented by different textures and shades of grey on the recorded image (Mazel, 1985; Edsall *et al.*, 1989; Boss *et al.*, 1999). For example, a relatively fine-grained substrate consisting of silty- sand will reflect a relatively small amount of sound energy back toward the tow fish and will appear as a light coloured area (Fig. 3.10). In contrast, coarser grained sediment, such as gravel, will backscatter more of the sound energy due to the increased surface roughness of the sediment and will produce a darker coloured image.

The smoother the surface of the lake floor, the more sound energy will be reflected away from the tow fish (Fig. 3.11; Mazel, 1985). Smooth surfaces formed by flat-lying bedrock or compacted clay will reflect most of the energy away from the tow fish and produce the lightest areas on the sonar image (Fig. 3.11A) and can be differentiated with the use of sub-bottom profiler imagery (see Section 3.6). Coarser grained sediment types produce darker and more 'textured' images (Fig. 3.11B) and when grain size increases above the resolution of the tow fish, individual grains can be identified as targets with distinct acoustic shadows. The side scan sonar survey conducted in Owen Sound/Colpoy's Bay has a resolution of 29cm, allowing any objects that are located more than 29cm apart to be picked out as individual targets, and objects closer together be imaged in textural form. Objects that are larger than 29cm will be imaged individually, no matter the spacing between them (Marine Sonic Technology Ltd., 2001). Bedrock ledges can be identified by a distinct dark and light banding on the output images. The dark bands are created at the faces of the ledges as they reflect nearly all sound energy back to the tow fish, while on the tops of the ledges most of the energy is reflected away to produce white bands on the image (Fig. 3.11C).



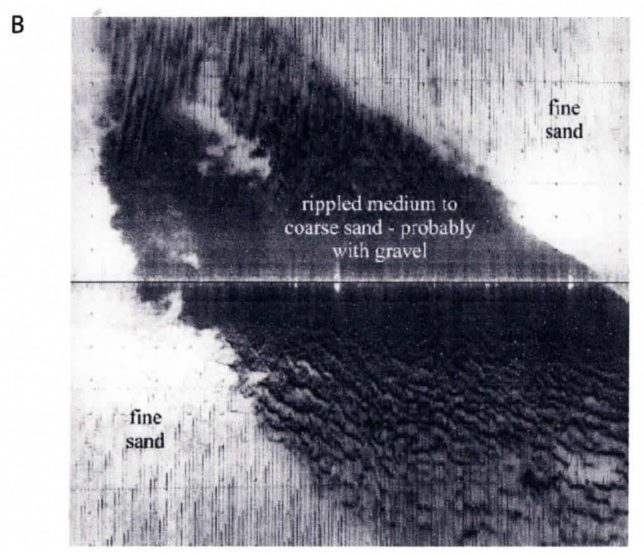


Figure 3.10: (A) Different bottom materials will backscatter different amounts of acoustic energy. On the left side of the image silty-sand reflects less energy and is shown as a lighter color, on the right sandy-gravel reflects more of the incident sound energy and is shown as a rougher textured, darker area. **(B)** Image taken from Boss *et al.* (1999) showing a similar light and dark reflection pattern for fine sand and coarse sand with gravel respectively.

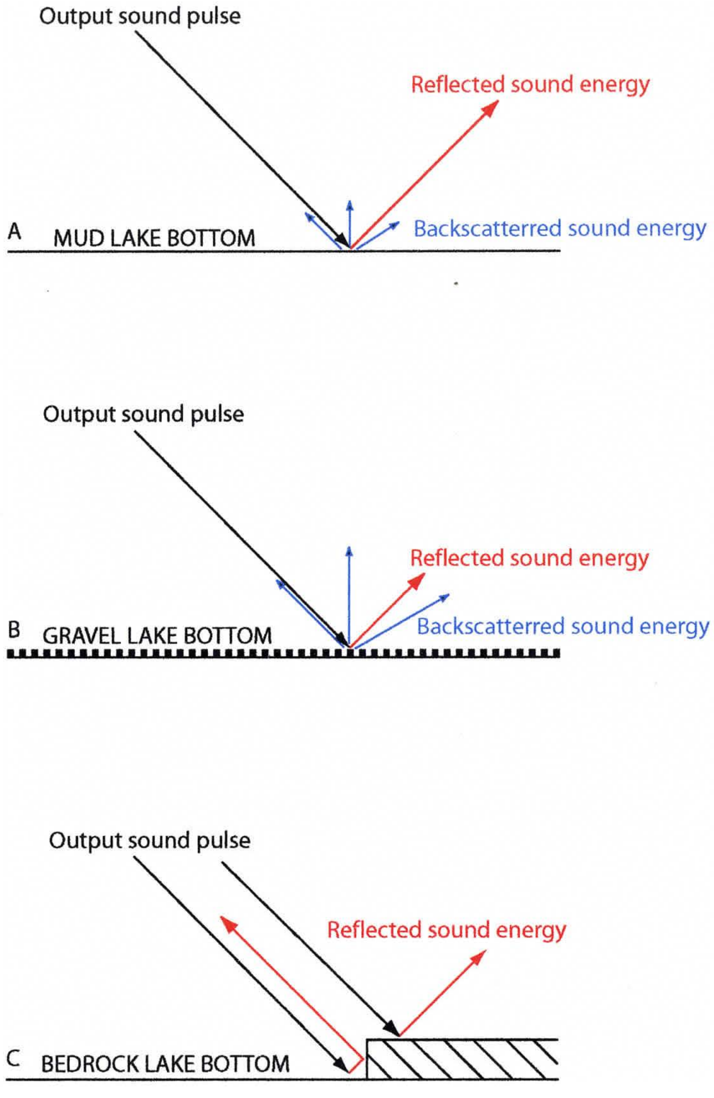


Figure 3.11: (A) a muddy lake bottom is relatively smooth and will reflect most of the incident sound energy away from the tow fish. Some of the energy will be backscattered to produce a light gray area on the output image. **(B)** a gravelly lake bottom will backscatter a larger portion of the incident sound energy due to its greater surface roughness, producing a darker area on the output image. **(C)** bedrock surfaces are smooth and will reflect nearly all of the incident sound energy. The angle of reflection will depend on the slope of the bedrock surface. A submerged bedrock outcrop that has ledges, as shown in this image, will produce dark and white bands on the output image, as some areas reflect almost all of the sound energy back to the tow fish, while other areas reflect most of the energy away from the tow fish.

3.3.2 Shadows

Objects that project above the lake floor or are suspended in the water column will reflect a large portion of the acoustic energy, and block it from reaching the lake floor, creating an acoustic shadow behind themselves. This acoustic shadow zone appears as a light area on the sonar record (Mazel, 1985).

Acoustic shadows often show more detail than the direct reflections off a target as they create a complete outline of the target and may be used to help interpret side scan sonar records. Man-made objects commonly have sharp, distinct shadows (e.g., masts and decks on shipwrecks), while natural features tend to be more rounded (Mazel, 1985). With simple trigonometric calculations that can be automatically done on the computer, the size of an acoustic shadow can be used to calculate the height of the target (Marine Sonic Technology Ltd. 2001). The position of the acoustic shadow will also identify whether the target is on the lake floor or suspended in the water column. If the shadow is directly attached to the target on the side scan image then the target is lying on the lake floor, but when the target is suspended in the water column the acoustic shadow will be at a distance away from the object on the image (Fig. 3.12).

Due to the large vertical beam width of the side scan sonar, reflections can be received from objects anywhere in the water column or even from the water surface. This means that an object in the water column can be seen anywhere on the sonar image, depending on the relative positions of the lake floor, the tow fish and the object. Because the sonar only measures the two-way travel time of the sound pulse, an object suspended in the water column can appear on the lake floor part of an image, but can be

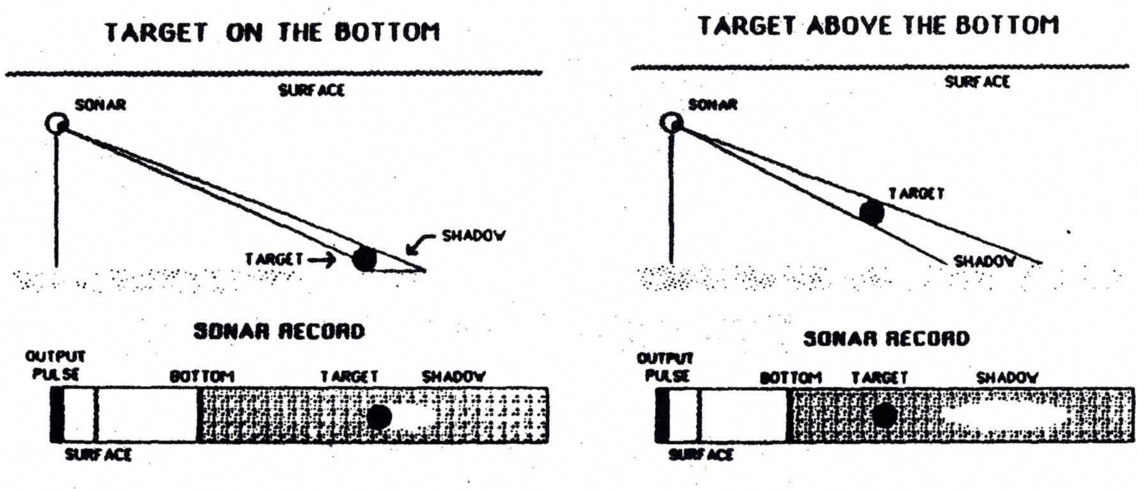


Figure 3.12: A target on that lies on the lake floor will cast an acoustic shadow immediately behind itself (left), while an object some distance above the lake floor (right) casts a shadow some distance away from the target (Mazel, 1985).

differentiated from an object actually located on the bottom by the lack of an acoustic shadow (Mazel, 1985). In the study conducted in Owen Sound/Colpoy's Bay this was often encountered as the survey passed through the wake of other vessels. The resulting sonar image shows a linear dark band that could be mistaken for different bottom materials or vegetation (Fig. 3.13).

3.3.3 Projections and depressions

From the relative positioning of the acoustic shadow and reflection it is possible to differentiate between a target on the lake floor that is a projection and one that is a depression. If the target protrudes above the surrounding area, it will return a strong echo to the sonar producing a dark mark, followed by a light acoustic shadow (Fig. 3.14; Mazel, 1985); a depression will record as a light area followed by a dark mark. Lake floor features such as dunes (projections) and scours (depressions) can be identified on sonar images in this way (Fig. 3.15).

3.3.4 Sloping lake bottom

Because this study focuses on lake trout and whitefish spawning habitats that are found in relatively shallow water, the side-scan sonar track lines are often run parallel to the shoreline along bathymetric contours. This often results in a situation where the lake floor is sloping perpendicular to the track lines (Fig. 3.16). The sloping lake floor will have two effects on the reflected sound energy, and the resulting image.

The first effect is that the side of the sonar image closer to shore becomes darker as this side is shallower and the lake floor faces the sonar. A larger proportion of the sound energy on this side will be reflected back to the sonar, resulting in an overall darker appearance of the image, even if the same lake bottom material is present. This effect is alleviated to a great degree by the automatic gain setting of the Sea Scan software package, but care should be taken when interpreting images where one side is consistently darker than the other.

The second effect is a distortion of the image due to the shortened travel time of the sound pulse on the shallow side of the image. This results in an apparent shortening of acoustic reflections and shadows as the image is effectively "squeezed" together. The severity of this error depends on the slope of the lake bottom, but is usually negligible.

3.4 Data collection in Owen Sound and Colpoy's Bay

In this study, 500km (Fig. 3.17) of side scan data were collected in Owen Sound and Colpoy's Bay using a Marine Sonic Technology Sea Scan system with a 300 kHz tow fish (Fig. 3.18) and Sea Scan software. A single 20µsec sound pulse was emitted by the sonar and the range used for this survey was 100m on either side of the tow fish, producing images with a total resolution greater than 29cm (Marine Sonic Technology

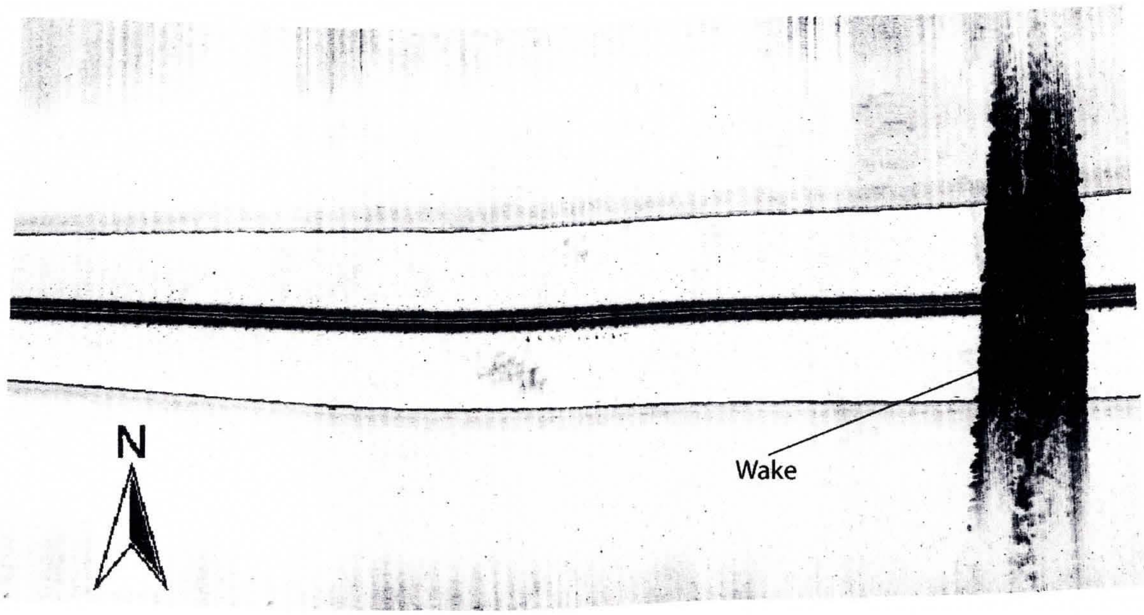


Figure 3.13: Image taken near the western shore of Owen Sound. The linear dark band on the right side of the image is the remnant wake of a boat that passed in front of the research vessel. Notice the lack of acoustic shadow corresponding to the wake.

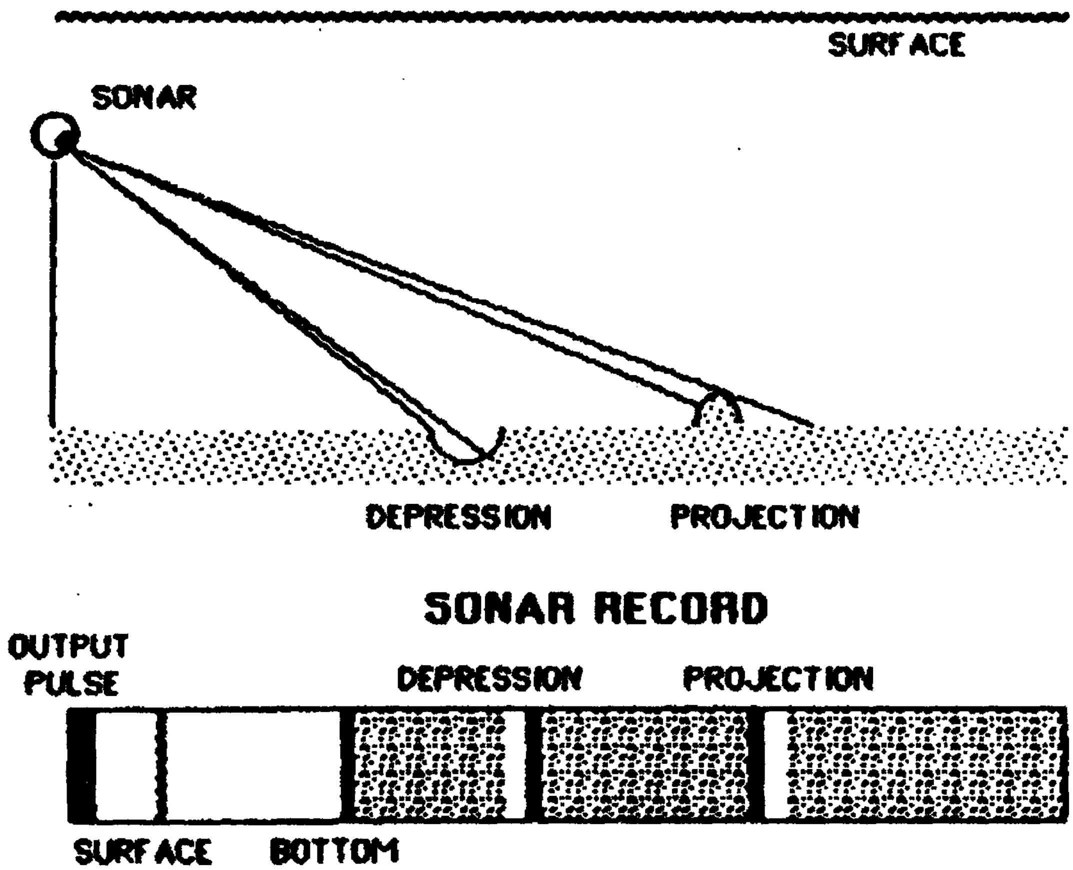


Figure 3.14: A depression on the lake floor can be characterized by a lighter acoustic "shadow" followed by a darker mark. A projection above the lake floor however will have a dark mark first, followed by the light acoustic shadow. This is a quick way to tell whether the imaged feature is a depression or projection (Mazel, 1985).

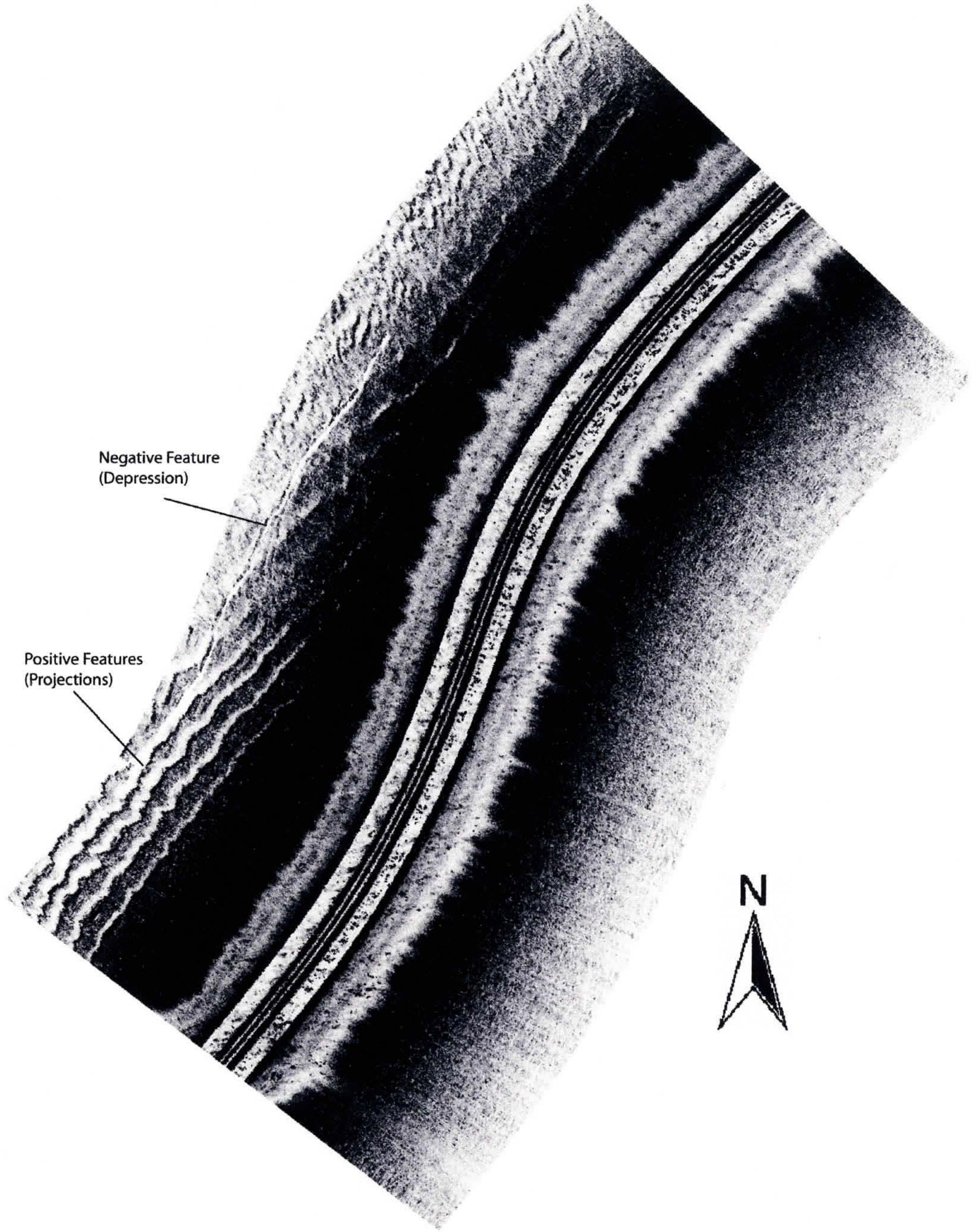


Figure 3.15: Sample image from the east shore of Owen Sound showing examples of both depressions and projections on the lake floor. The linear features on the lower left side of the image are projections on the lake floor, interpreted as dunes. Above the dunes a thinner linear feature can be seen with light-dark band characteristic and is possibly a scour in the sediments produced by an anchor dragging on the lake floor.

Ltd., 2001). The maximum possible range of the tow fish is 200m, but in order to increase the resolution and thus enhance sediment classification potential, a smaller range was chosen for this study.

The Sea Scan software automatically corrects for speed variances and slant range effects, and integrates the side scan data with GPS data received from the boat's navigational system. Because the tow fish is towed at some distance behind the boat, a set-back value is also used to correct for the positional error that would occur if the navigational GPS data were to be used directly. The software package displays individual side scan images which are each made up of 1000 individual scans and stores each image as a separate file; after the images have been corrected for location, a mosaic of a number of images can also be created and displayed (Marine Sonic Technology Ltd., 2001).

3.5 Sub-bottom seismic profiling

In order to obtain data regarding sediment thickness and stratigraphy in Owen Sound and Colpoy's Bay, a series of sub-bottom seismic profiles with a total length of 100km were also collected during the summer of 2004 (Fig. 3.17; Radomski, 2005). Sub-bottom seismic data were acquired using an Edge Tech X-Star FM high resolution digital sub-bottom profiling system operated at 2-15 kHz (Fig. 3.1). The vertical resolution of this system is 8cm and penetration ranges from several meters in sand up to 60m in clay. This system uses standard seismic reflection methods and emits a highly repeatable seismic pulse that travels through the water column and is reflected back to the surface off various reflectors on the lake floor and subsurface (the 'CHIRP' system). The

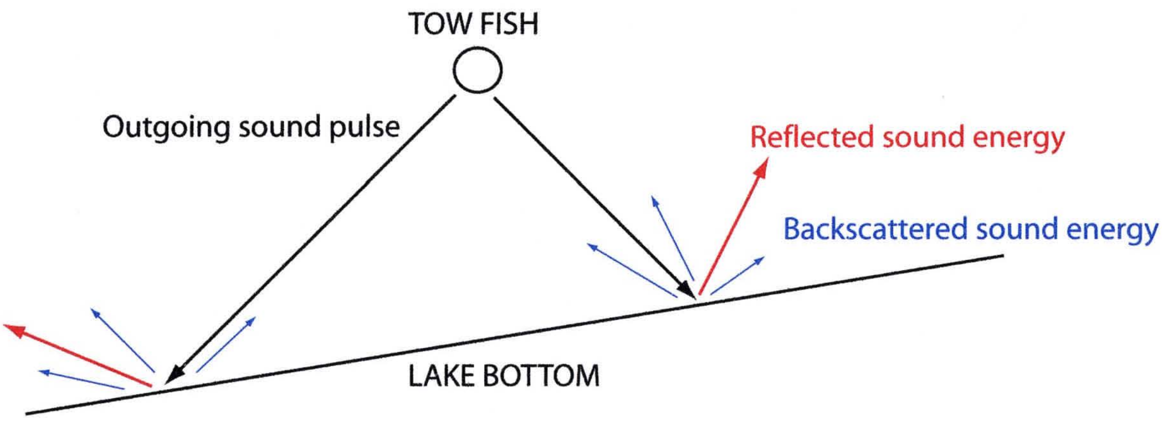


Figure 3.16: During the survey of Owen Sound and Colpoy's Bay the track lines were often following bathymetric contours, resulting in a situation where the lake bottom is sloping perpendicular to the track line under the tow fish. This will result in a relative darkening of the image on the right and a lightening of the image on the left in the above illustration.

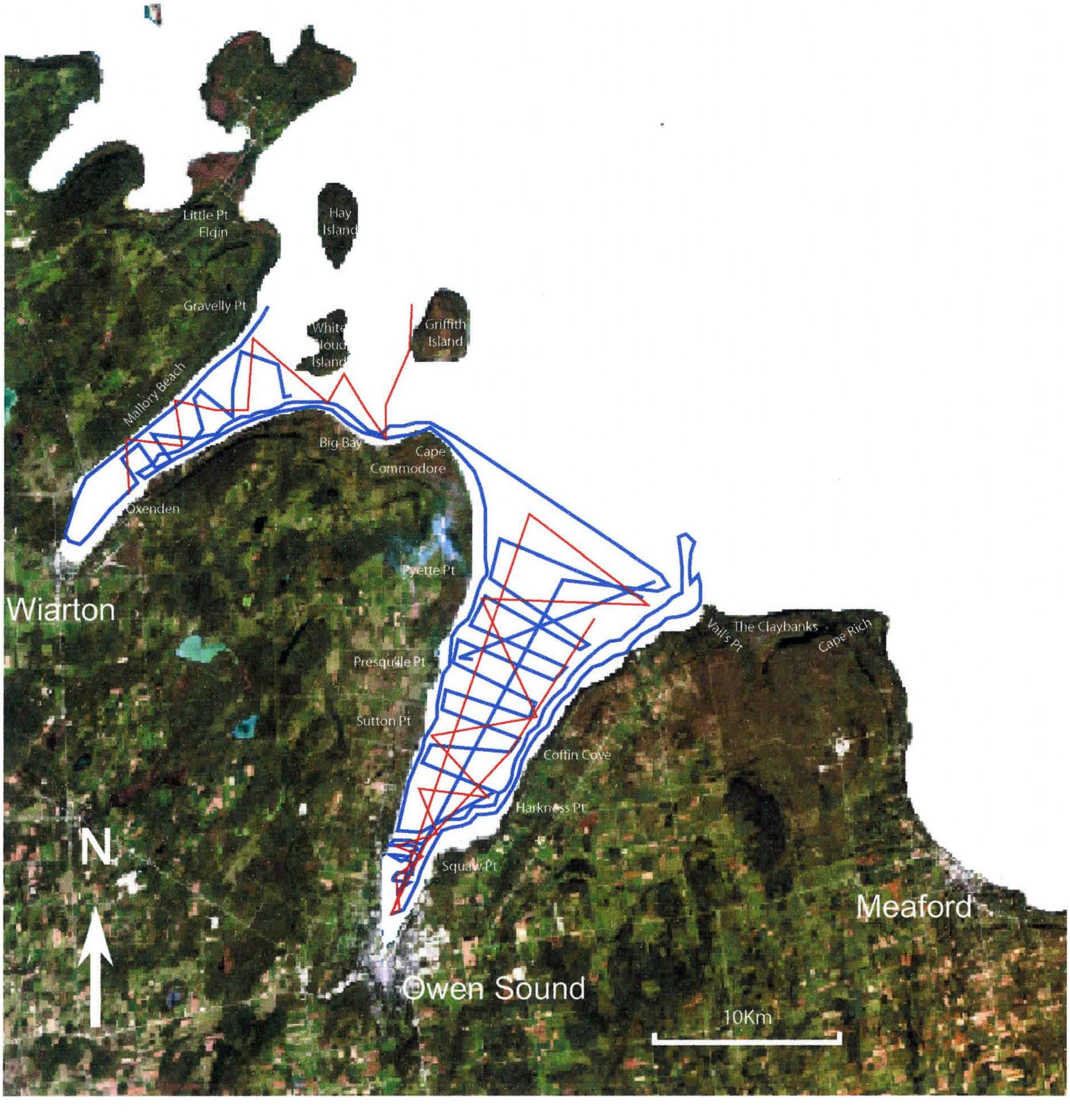


Figure 3.17: Blue lines show side scan sonar track lines and red lines show sub-bottom seismic lines collected during the summer of 2004. In total 500km of side-scan sonar and 100km of seismic data were acquired and processed.

Figure 3.18: The side scan system used in the survey. Pictured are the tow fish, tow cable, and computer (Marine Sonic Technology Ltd., 2004).

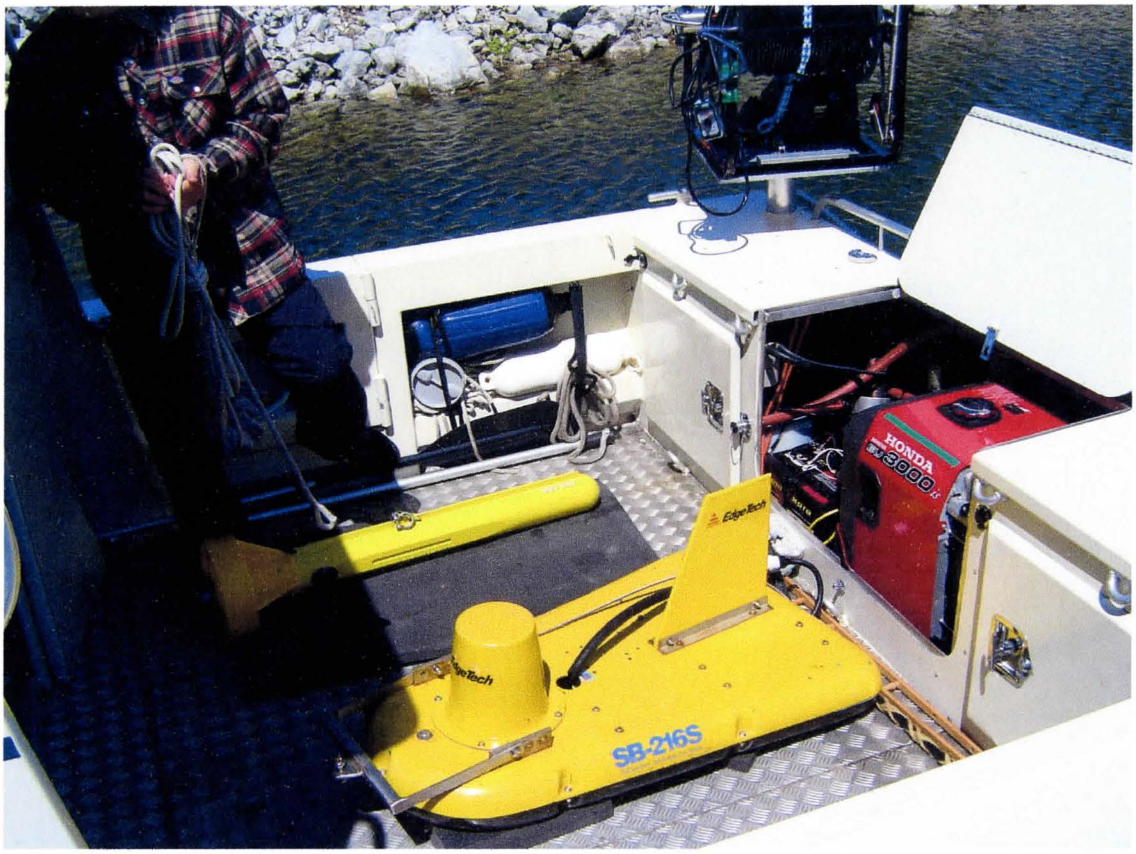


Figure 3.19: The EdgeTech sub-bottom seismic tow vehicle (foreground) and the Marine Sonic side scan sonar being prepared for deployment on the deck of research vessel "Ontario Rocks", Owen Sound Marina, 2004.

CHIRP system used in this study consists of three major components: a tow vehicle, which contains the seismic pulse generator (transducer) and receivers (hydrophones), a Full Spectrum Processor which has two-way communication with the tow vessel at all times, and a PC computer running seismic software, which has two-way communication with the Full Spectrum Processor (EdgeTech, 1998).

The sub-bottom tow vessel, which contains the seismic pulse generator and receivers, is towed behind the research vessel at a constant water depth of approximately 5 meters. This system works at a relatively low frequency which allows for penetration of sound energy below the lake floor to a maximum depth of 30m, depending on sediment types and bedrock burial depth, while maintaining a high-resolution output for imaging strata in the sub-bottom (EdgeTech, 1998).

Seismic track lines were oriented along and across the main axis of both Owen Sound and Colpoy's Bay in order to achieve maximum survey coverage (Fig. 3.17). This survey method allows for establishing data cross-check points where the track lines cross each other. Data from the differential GPS system used on the boat for navigation purposes are integrated with the digital seismic data to provide spatial coordinates along each recorded profile line. The seismic data received from the tow vessel are simultaneously recorded on a magnetic tape storage device and printed on a thermal plotter to produce a permanent paper record.

Sub-bottom data are used to identify the thickness and distribution of Holocene sediment that has accumulated since deglaciation of the region and older glacial lacustrine sediment deposited in Glacial Lake Algonquin. These sub-bottom data provide the key dataset with which the approximate age of the substrate can be determined (Eyles *et al.*, 1993; Eyles *et al.*, 2000, Eyles *et al.*, 2003).

The sub-bottom dataset is a valuable source of information on sediment distribution and grain size and is used here to cross validate interpretations of the side scan dataset. Seismic data were especially useful in differentiating between areas underlain by a uniform mud-covered substrate and a coarser grained sandy substrate (Fig. 3.21); these types of substrate can appear very similar on side scan images.

3.6 Sub-bottom seismic image interpretation

Lake floor sediments can be broadly classified according to mean grain size based on their acoustic characteristics (Halfman and Herrick, 1998). Clay-rich sediments are highly permeable to high frequency seismic waves and allow energy to travel through without reflecting, producing a very weak seismic signature (Eyles *et al.*, 2003). The internal structure of clay units is thus often difficult to resolve on seismic profiles. Most sediment accumulating in the deeper parts of the modern Great Lakes basins consists of fine-grained Holocene mud and is represented by an acoustically transparent unit immediately below the lake floor on seismic images (e.g., Fig. 3.20).

Coarser grained (silt-rich) sediments are resolved more clearly on seismic profiles as they allow deep penetration of seismic energy but are sufficiently reflective at bed contacts to create strong seismic records. Well-bedded silty-clay units form an 'ideal' substrate type to image with the CHIRP system, as they allow for deep penetration of the signal, while showing clear internal reflector surfaces (Fig. 3.20; Eyles *et al.*, 2003). In

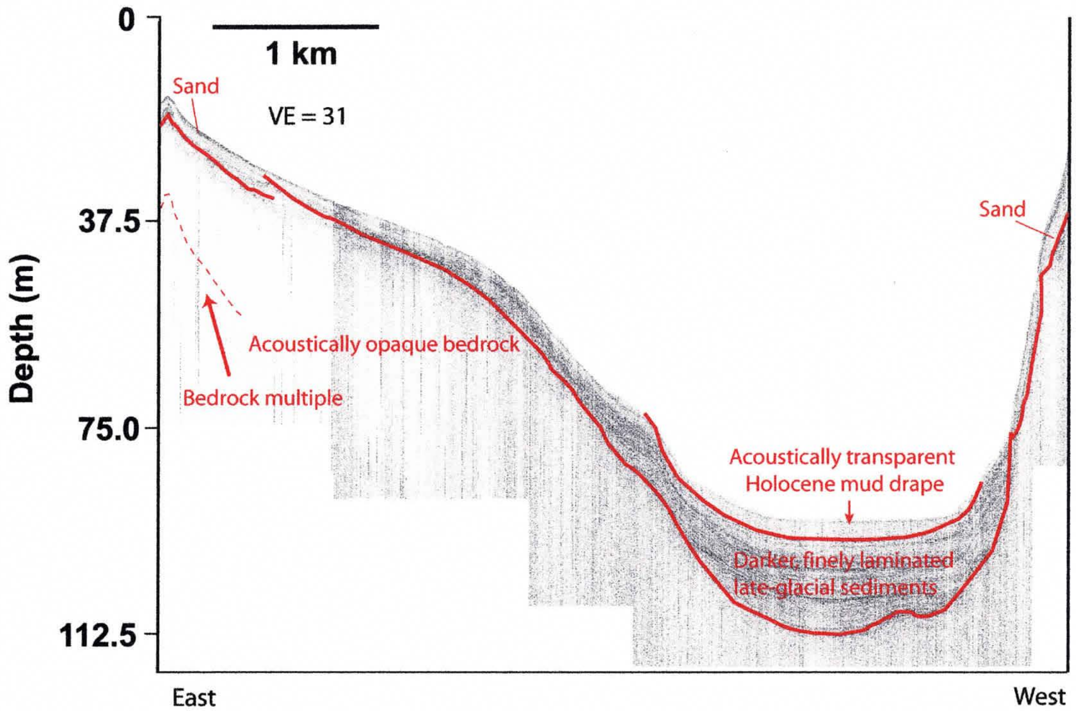


Figure 3.20: Seismic profile across Owen Sound showing a sandy bottom near and an infill of late-glacial sediments in the deeper areas. A Holocene mud drape in the deeper parts of the profile covers the late-glacial sediment. Bedrock underlies all units, but is especially clearly imaged near the eastern shore, where an acoustic multiple of the bedrock can also be seen.

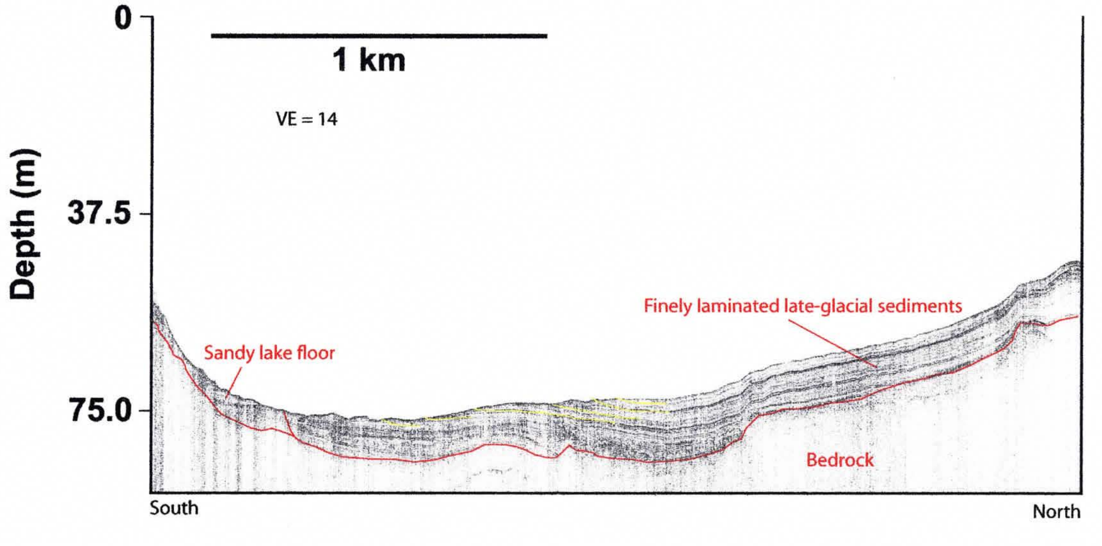


Figure 3.21: Seismic profile running south-north between White Cloud and Griffith Islands showing a sandy bottom near shore (south), and laminated late-glacial sediments in the offshore parts of the profile. The laminated unit is truncated at the lake floor, indicated by yellow lines.

contrast, sand-rich substrates do not allow deep penetration of the seismic impulse and the internal structure of sand beds is often poorly resolved on seismic profiles (Eyles *et al.*, 2003). One of the most distinctive contacts recognized on lake floor seismic images is the sediment/bedrock contact as the relatively high frequency seismic impulses generated by the CHIRP system do not penetrate bedrock (Eyles *et al.*, 2003). On seismic profiles the bedrock surface usually appears as a high-amplitude reflector below which no reflections can be seen.

Seismic images can be complicated by the presence of 'multiples' which are signatures resulting from the rebound of reflected energy between any strong reflector and the water surface. Multiples are commonly created occur coarser grained substrates and bedrock are imaged (e.g., Fig. 3.20). When acoustically more transparent sediments, such as clay and silt are imaged, multiples are not usually created as the sediments transmit rather than reflect most of the seismic energy. One way to identify multiples is to visually trace them across a seismic profile; they should have the exact same shape as the original reflected layer, but will occur at double the return time on the profile.

CHAPTER 4: SIDE SCAN DATA ANALYSIS

The main objective of this study is to establish a sediment classification system using side scan sonar imagery that is easy to use and can be implemented for future investigations of substrate types and potential fish spawning grounds in the Great Lakes. During the survey of Owen Sound and Colpoy's Bay in the summer of 2004, 945 individual side scan images were collected and subsequently analyzed in detail. Raw side scan data were recorded in separate files that were numbered sequentially as the survey progressed. Each file contains 1000 individual scans of the lake floor. Using the GPS data recorded during the survey, and the set-back distance (the distance that the tow fish was behind the boat during the survey), the images were corrected for geographic location and GeoTIFF files created using SeaScan software. These GeoTIFF files are compatible with any ArcGIS software package and can be displayed in their correct geographic positions. For ease of use and quick reference to specific images a Microsoft Excel© spreadsheet was set up tabulating image number, interpretation and color coding later used on compilation maps (Appendix 1).

Analysis of the side scan images allowed seven different facies or substrate types to be identified; the seven substrate types were described and coded with numbers 1 through 7 (Facies 1 through 7; Table 4.1). The numbers correspond to (1) mud, (2) sand, (3) sand with ripples, (4) sand with dunes, (5) sand with boulders, (6) boulders and (7) bedrock. Additionally, vegetation was identified, and where present a "v" was added to the substrate number code; for example mud with vegetation is coded as "1v". Vegetation

Table 4.1: Substrate facies types identified on side scan sonar images from the study area.

Side-scan sonar facies:	**Description:**	**Interpretation of substrate type:**
1: Low relief, muddy substrate	Identified by a low and uniform reflectivity off the lake floor. Image is light gray colored. Occurs in water depths between 30 and 40 meters.	Fine grain size (<sand), flat bed on lake floor.
2: Low relief, sandy substrate	Identified by a medium and uniform reflectivity off the lake floor. Image is medium gray colored. Occurs in water depths of 0 to 40 meters.	Sand size sediment, flat bed (or very small ripples) on lake floor.
3: Sandy substrate with ripples	Identified by medium reflectivity (similar to Facies 2) ornamented with small linear, wave-like high reflectors with small acoustic shadows. Occurs in water depths of 5 to 30 meters.	Sand size sediment with surface ripples (possibly wave or current formed) on lake floor.
4: Sandy substrate with dunes	Identified by medium reflectivity (similar to Facies 2) with relatively large linear or wave-like high reflectors oriented parallel to shore. Large acoustic shadow can be seen behind these reflectors. Occurs in water depths of 10 to 20 meters.	Sand size sediment with surface dunes (> 8cm amplitude). Dunes possibly wave formed.
5: Sandy substrate with surface boulders	Identified by medium reflectivity (similar to Facies 2) with point reflectors scattered across the image. Occurs in shallow waters with depths under 10 meters.	Sand size sediment with scattered large clasts (cobbles/boulders) on lake floor. Clasts may be lags, current transported or ice rafted.
6: Cobble/boulder dominated substrate	Image dominated by single point reflectors with acoustic shadows. No significant patches of uniform reflectivity can be seen between the point reflectors. Occurs in shallow waters with depths under 10 meters.	Cobbles/boulders on lake floor without intervening areas of finer-grained sediment.
7: Bedrock	Alternating high and low reflectivity bands forming linear patterns on image. Usually occurs along the edge of an image in relatively shallow water.	Irregular bedrock surface exposed on the lake floor. Linear features represent strike of closely spaced dipping beds.
V: Vegetation	Irregular, dark patches on image without preferred shape or orientation. Can be superimposed on any of the previous 7 facies types.	Aquatic vegetation.

can grow on many different substrate types, and the facies classification scheme was designed to include the presence of vegetation on any sediment type (see Appendix 1). A numerical coding system was also implemented for use with GIS software where the vegetated areas were reclassified and the facies numbering continued up from 10. Thus, the GIS the classification of mud with vegetation changed from 1v to 10, sand and vegetation from 2v to 11 and so on.

4.1 Description and interpretation of side scan images

Several criteria were considered when a side scan image, or part of a side scan image was assigned to one of the seven substrate types identified in the study area: strength of the acoustic return, presence of point reflectors, and features such as the size and shape of acoustic shadows. Each of the side scan facies types is described and interpreted below together with a description of the spatial distribution of each facies in the study area. Reference will be made to Figure 4.1 (and the larger version of this map included as inset Map 1), which shows the distribution of facies types in the study area, throughout this chapter. Compilation of this map will be discussed in more detail in Chapter 5. Some of the limitations of interpreting lake floor sediment types from side scan images are also discussed at the end of this chapter.

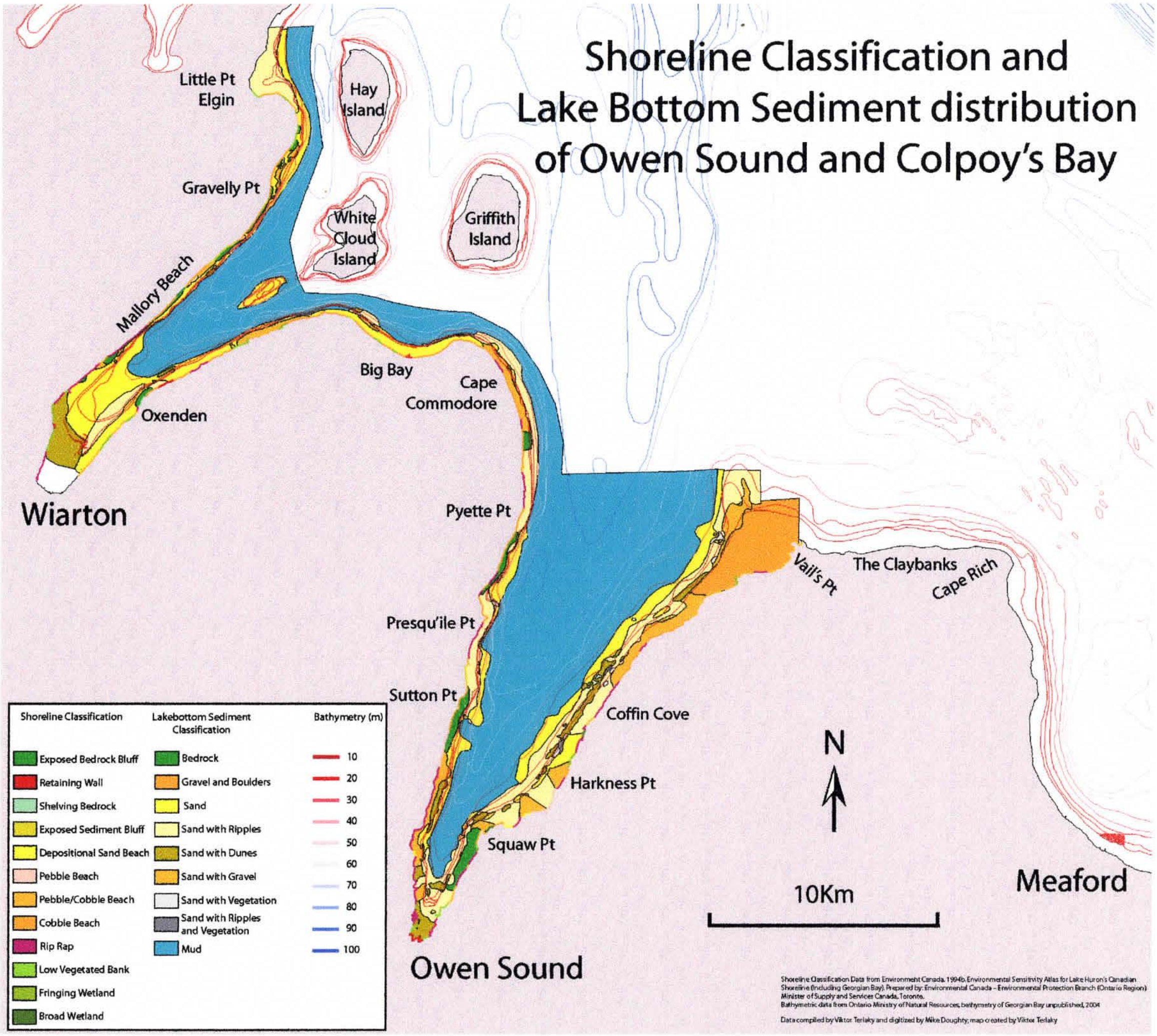


Figure 4.1: Sediment distribution map for Owen Sound and Colpoy's Bay created manually from interpretation of substrate point data, bathymetric and shoreline classification data (Fig. 2.6). The map was initially hand-drawn and later digitized to produce the digital format map shown here; this map is also presented in larger format as inset Map 1.

4.1.1 Facies 1: low relief, muddy substrate

Side scan Facies 1 (Table 4.1; Fig. 4.2) is characterized by a relatively weak acoustic return producing a uniform, light gray to white sonar record. This facies is the most common type identified on the side scan images and is usually encountered in water depths of over 30 meters (Fig. 4.1), although it also occurs in shallower areas south of Sutton Point and to the west of Big Bay. The uniform texture of the image indicates a relatively smooth lake floor with no surface features greater than several centimeters amplitude. The pale appearance of the image is created by low backscattering of the acoustic pulse and suggests that the surface materials are fine-grained, possibly mud. Similar side scan signatures with low back-scatter were described by O'Brian (1993) in the Gulf of Mexico and by Bronikowski (2004) in the Gulf-Coast Estuary, Lavaca Bay, Texas and were interpreted to represent mud or clay-rich sediments. Boss *et al.* (1999) described similar facies on the central North Carolina shelf and interpreted as these as representing a fine sand substrate.

Comparison of side scan images with sub-bottom seismic profiles from the deeper parts of Owen Sound and Colpoy's Bay shows that Facies 1 corresponds to the acoustically transparent upper sedimentary unit (Fig. 3.20) interpreted as the Holocene mud drape (Radomski, 2005). Side scan Facies 1 also corresponds to an acoustically highly penetrable laminated layer in shallower areas (Figs. 3.20, 3.21); this laminated layer generally underlies the transparent upper unit and is interpreted as consisting of silt-rich deposits formed in Glacial Lake Algonquin (Radomski, 2005). Acoustic penetration

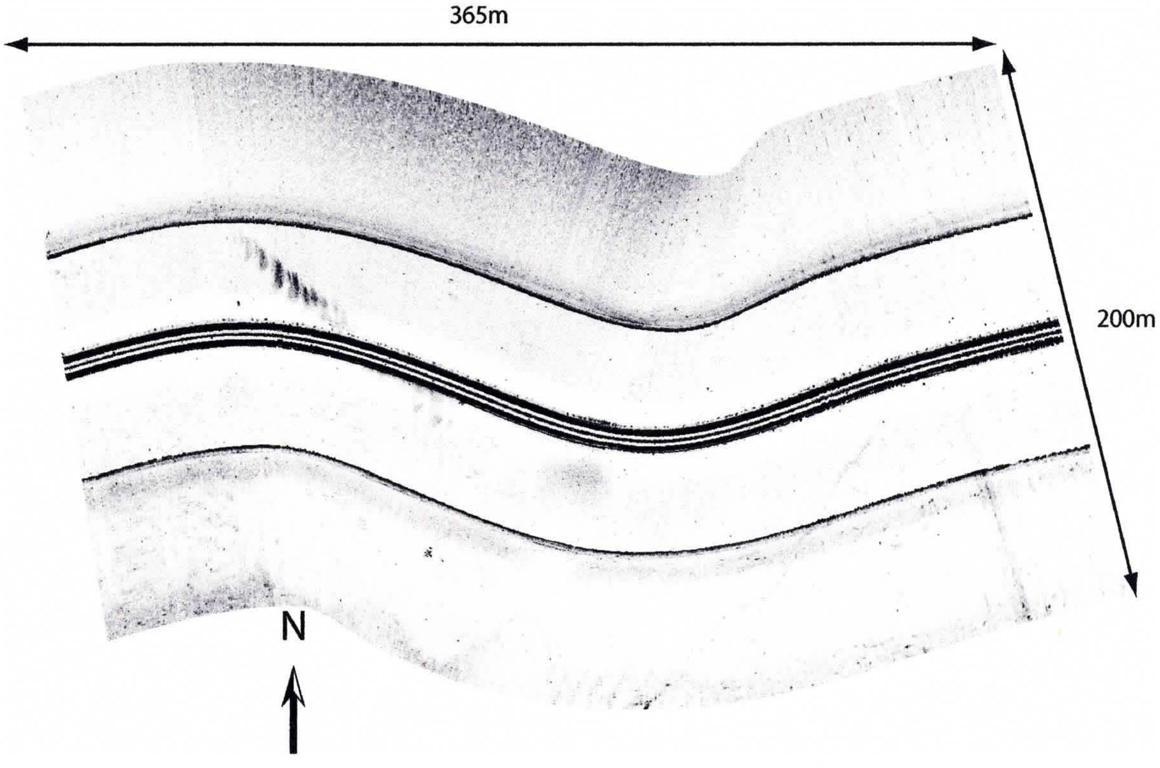


Figure 4.2: Side scan image showing Facies 1, a low relief, muddy substrate, characterized by a uniform white to light gray sonar image. Image from the "inner bay" area of Owen Sound, south-west of Squaw Point (see Figure 4.1 for location).

through both units is over 30 meters and bedrock is usually encountered before the penetration limit of the sub-bottom signal is reached.

Integration of side scan and seismic data thus suggests that side scan Facies 1 can be interpreted to represent relatively flat areas of the lake floor underlain by fine-grained, muddy sediment. The spatial distribution of this fine-grained sediment indicates that it is either accumulating in deeper water areas (as part of the Holocene mud drape) or is older sediment exposed by erosion in relatively shallow areas.

4.1.2 Facies 2: low relief, sandy substrate

Side scan Facies 2 is identified on the images by areas of uniform, medium intensity, medium to dark gray reflectors (Fig. 4.3); the images are darker and more grainy than the images of Facies 1, but are similarly featureless. Facies 2 is most commonly seen in water depths of between 30 and 40 meters, but is also observed in shallower areas. Similar side scan facies have been described in shallow marine environments by Twichell and O'Brian (1993), Wever *et al.* (1997), Bornhold (2002) and Bronikowski (2004) and are interpreted to represent featureless sand sheets; a similar interpretation is adopted here.

Close to the eastern shore of Owen Sound Facies 2 appears to form a transition zone between the muddy substrates of Facies 1 found in deeper water areas and rippled and dune-covered sandy substrates of Facies 3 or 4 in the shallower waters (Fig. 4.1). A similar distribution of substrate types is seen in Colpoy's Bay where a large area of Facies 2 near Oxenden separates the deeper water Holocene mud cover (Facies 1) and the

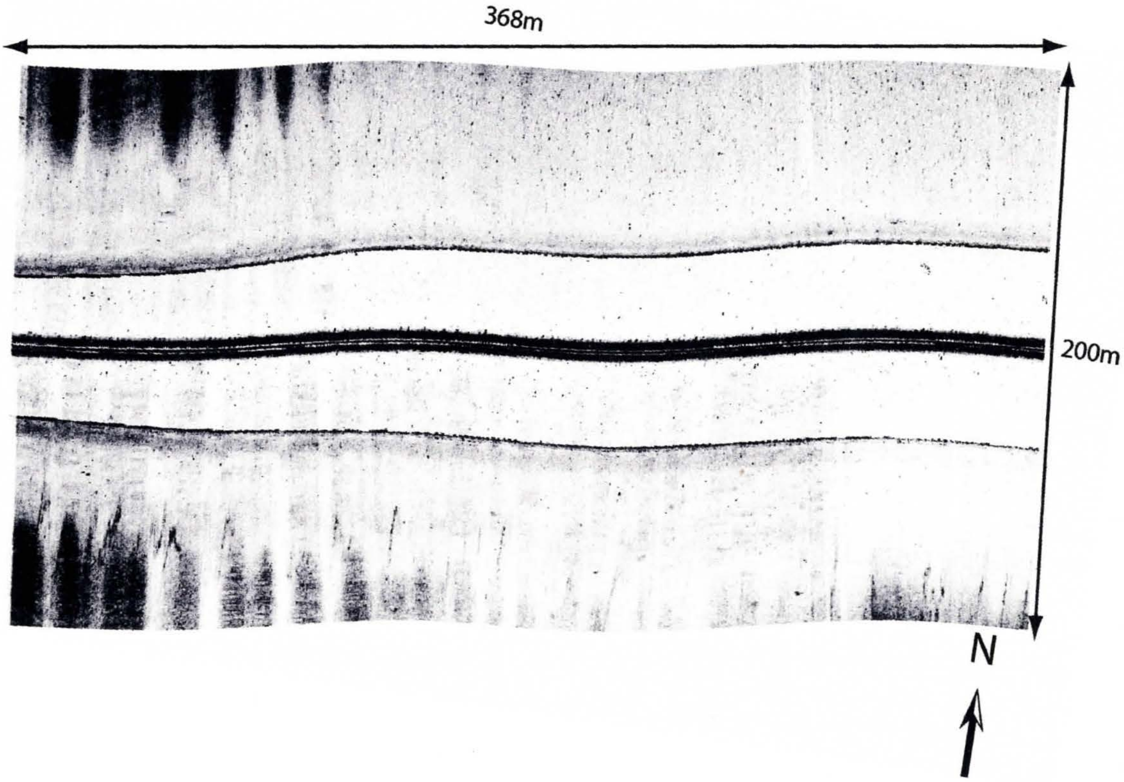


Figure 4.3: Side scan image showing Facies 2, a low relief, sandy substrate, characterized by a uniform medium to dark gray sonar image. Image from the "inner harbor" area of Owen Sound, near the western shore (see Figure 4.1 for location).

rippled and dune covered lake floor (Facies 3 and 4) in shallow areas (Fig. 4.1). One exceptional occurrence of Facies 2 is in the middle of Colpoy's Bay, where a shallow shoal lying south-west of White Cloud Island is sand covered in contrast to the surrounding mud covered substrate (Fig. 4.1).

Side scan Facies 2 is correlated with a largely acoustically impermeable sub-bottom seismic facies encountered in water depths of between 30 and 40 meters in both Owen Sound and Colpoy's Bay (Fig. 3.21). The seismic signal penetrates this facies to a depth of several meters, but no internal structure is seen; a weak acoustic multiple below the lake floor is also seen on the seismic images.

The uniform, relatively high reflectivity seen on side scan sonar images and a near acoustically impermeable signature on seismic records indicate that Facies 2 consists of sand sized sediment that forms a flat bed on the lake floor. Sandy lake floor substrates are generally indicative of some form of current activity on the lake floor (Wever *et al.*, 1997). These currents may be responsible for the creation of small, closely spaced bedforms, such as ripples, which are under the resolution limit of the sonar (Wever *et al.*, 1997; Clay and Medwin, 1977).

4.1.3 Facies 3: sandy substrate with ripples

Side scan Facies 3 has similar reflectivity characteristics to Facies 2, producing a medium to dark gray image, but differs in that it is ornamented by small, linear or wave-like high reflectors with small acoustic shadows (Fig. 4.4). The orientation of these features is variable. When asymmetric ripples are encountered one side of the side scan

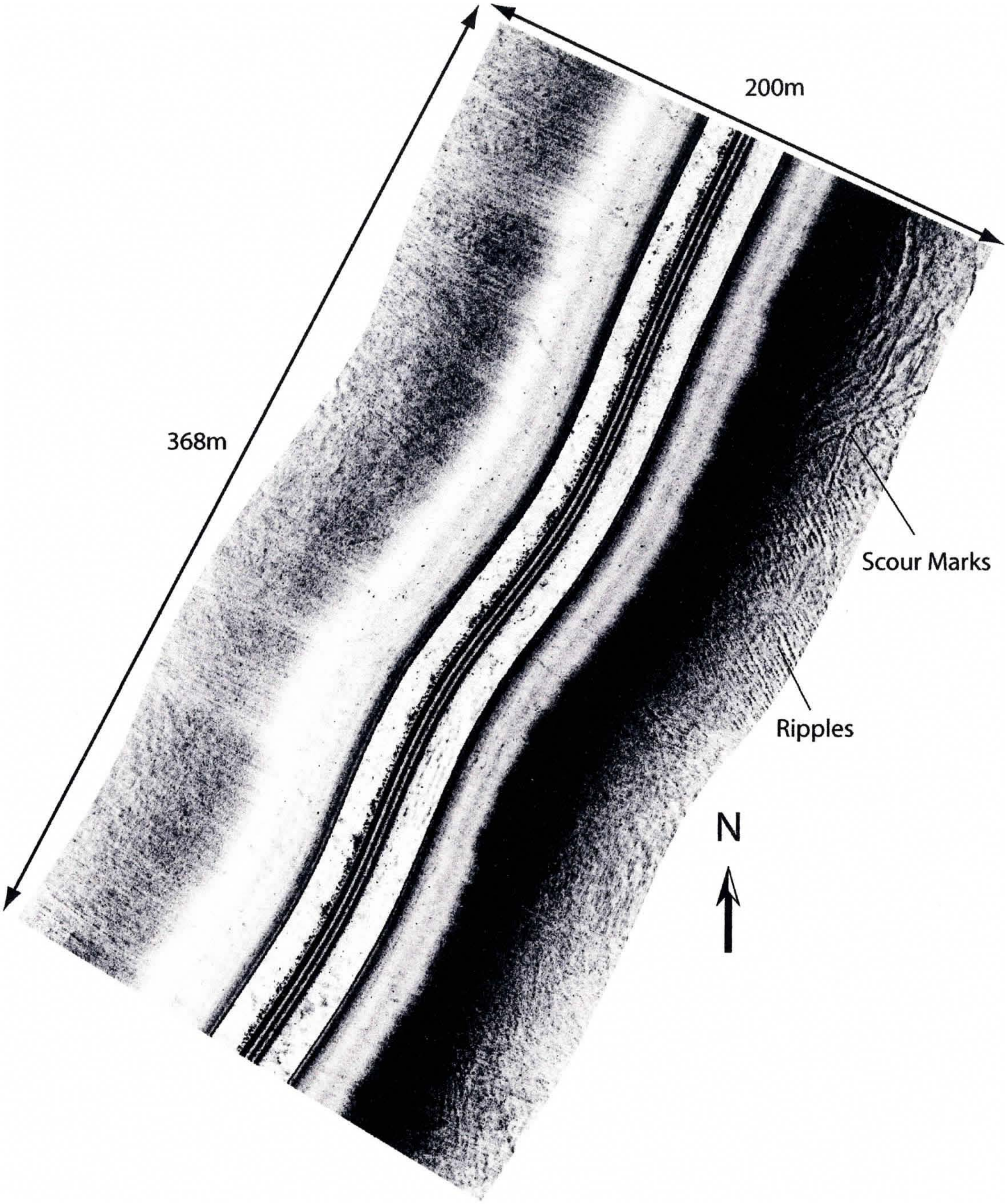


Figure 4.4: Side scan image showing a sand substrate with ripples (Facies 3), characterized by a medium to dark gray sonar image with wave-like high reflectors that cast narrow shadows The longer linear negative features on the right of the image are interpreted as scour marks that are the result of ice dragging along the lake floor during ice rafting. Image from Coffin Cove (see Figure 4.1 for location).

image might show ripples while the other only shows a rough lake bottom. This is due to the view angle of the tow fish; when ripples are seen parallel to the track line, they will cast acoustic shadows, while if ripples are perpendicular to the track line, they will not cast shadows and only cause the image to be darker than a flat bedded sand. Facies 4 is most commonly seen in shallower waters with water depths below 20-30 meters; it can be identified along the entire shoreline of Colpoy's Bay with the exception of a 7km long gap south of Sutton Point (Fig. 4.1). In Colpoy's Bay, Facies 3 is only encountered near Oxenden, at Little Pt. Elgin, and some minor patches occur near Mallory Beach. On side scan images this facies type is sometimes superimposed on Facies 4. Side scan Facies 3 has a similar seismic characteristic to Facies 2 with little seismic signal penetration and no internal structure. The linear/wave like structures are not seen on the seismic images as their amplitude is below the resolution limit of the seismic system (8cm).

Side scan Facies 3 is interpreted to represent sandy substrates, similar to those of Facies 2, with surface ripples large enough to be discriminated by the imaging system, but less than 8cm in amplitude. Ripple crests have between 30cm and 1m spacing; ripples spaced closer together cannot be imaged individually as they fall below the resolution of the system but can be identified as relatively dark and rough areas on the output image (Clay and Medwin, 1977). Side scan facies similar to Facies 3 have been described by Boss *et al.* (1999) from shallow marine environments on the central North Carolina shelf and were also interpreted to represent rippled coarse sandy substrates.

4.1.4 Facies 4: sandy substrate with dunes

Side scan Facies 4 is characterized by medium to high reflectivity and produces a similar medium to dark gray image to that of Facies 2 and 3 but in this case the surface is ornamented by relatively large linear or wave-like high reflectors with large acoustic shadows (Fig. 4.5). These reflectors have a preferred orientation parallel to the shoreline, but are sometimes observed trending in different directions. Facies 4 is encountered in water depths of between 10 and 20m and in the shallow areas near the head of both bays (Fig. 4.1). Similar facies were described by Wewetzer *et al.* (1999) in the Tay Estuary, Scotland and were interpreted to represent dunes with a wavelength of 2-10m and a height of up to 0.5m on a sandy substrate.

This facies type has similar seismic characteristics to Facies 2 with little seismic signal penetration and no internal structure. The linear/wave like structures can be identified on seismic images as wave-like features on the surface of the lake floor with a height of up to 30cm.

Side scan Facies 4 is interpreted here to represent a sand covered lake floor with dunes between 20 and 30cm in height and spaced several meters apart. The preferred orientation of the dunes parallel to the shore line, the water depths in which they are found and their size suggests that they have been created by large storm waves that have sufficient energy to build up these large features (Gallagher *et al.*, 1998). Large storm waves of over 2 meters have been recorded at Wendake Beach, Georgian Bay, and are known to produce large bedforms (Greenwood and Sherman, 1984). In some images ripples (Facies 3) are superimposed on dunes, indicating that large after a storm event

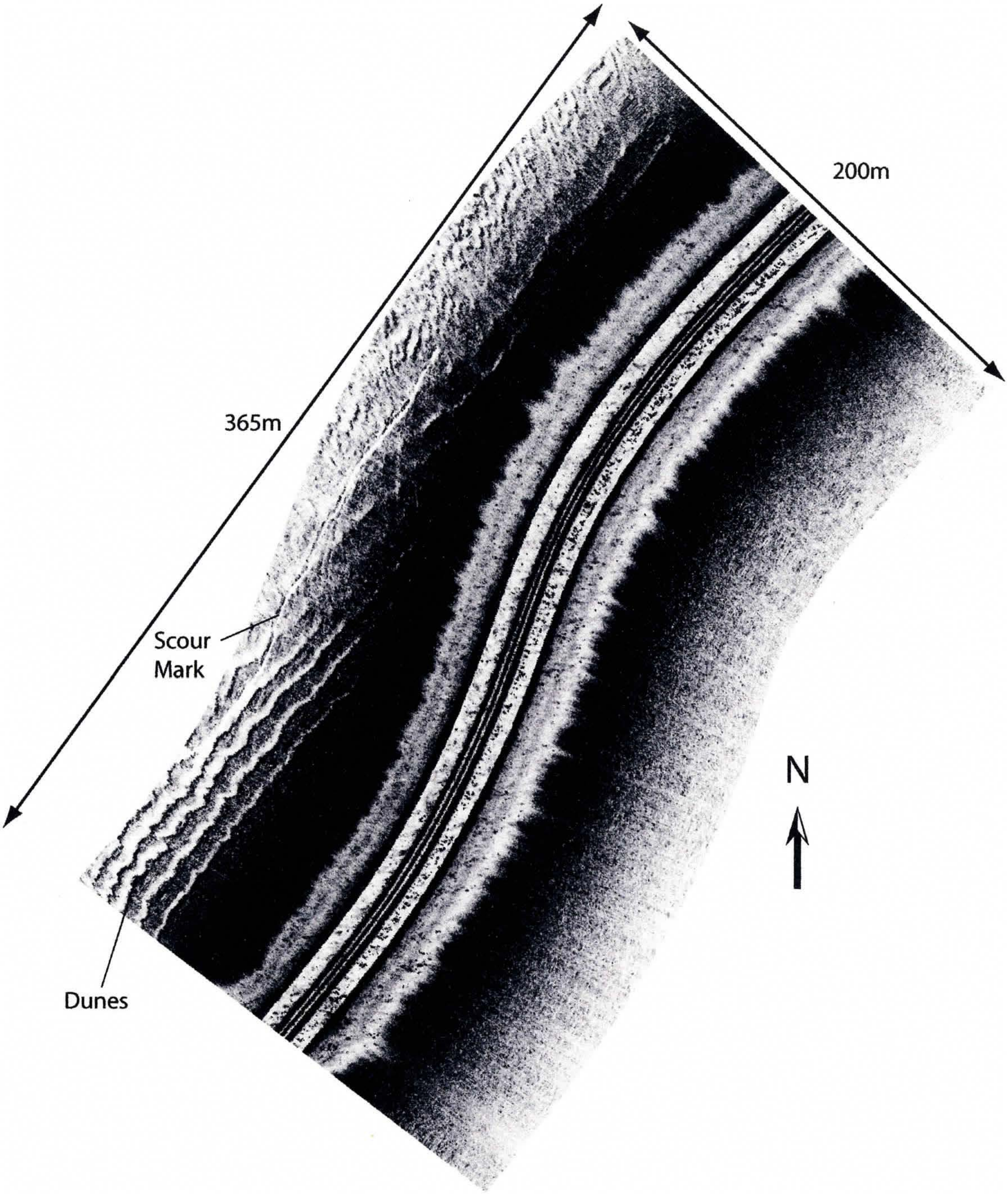


Figure 4.5: Side scan image showing a sand substrate with dunes (Facies 4), characterized by a medium to dark gray sonar image with large linear high reflectors that cast wide shadows. A scour mark can be seen north of the dunes. Image taken near Harkness Point (see Fig. 4.1 for location).

fair-weather wave currents rework the sandy lakefloor slowly destroying dunes and creating a rippled lake floor. The orientation of these ripples are also often different from the dunes, indicating that they are created by different currents on the lake floor.

4.1.5 Facies 5: sandy substrate with surface boulders

Side scan Facies 5 is characterized by a medium to high reflectivity, similar to that of Facies 2, 3 and 4, but also displays point reflectors scattered across the image. These point reflectors have a variable size and shape, ranging from sizes below the resolving limit of the sonar to reflectors with a diameter of 1-2 meters. The larger point reflectors cast acoustic shadows (Fig. 4.6). Facies 5 can be identified in shallow areas of both Owen Sound and Colpoy's Bay near stream inputs (also see Fig. 2.8) and close to gravelly and pebbly beaches (Fig. 2.6). This facies type was not identified on seismic transects.

Similar facies are described by Edsall *et al.* (1989) in northern Lake Michigan and were interpreted as representing sandy substrates with various sizes of boulders and rubble scattered on the surface. The same interpretation is adopted here. Point reflectors represent clasts of a wide range of sizes scattered on the lake floor; the larger clasts cast acoustic shadows and are probably boulders with a diameter greater than 30cm. This facies type is located in areas close to stream inputs and may record input of coarse sediment from fluvial sources; clasts may either be transported by traction currents during flood or storm events or may be rafted by seasonal ice during spring break up (e.g.,

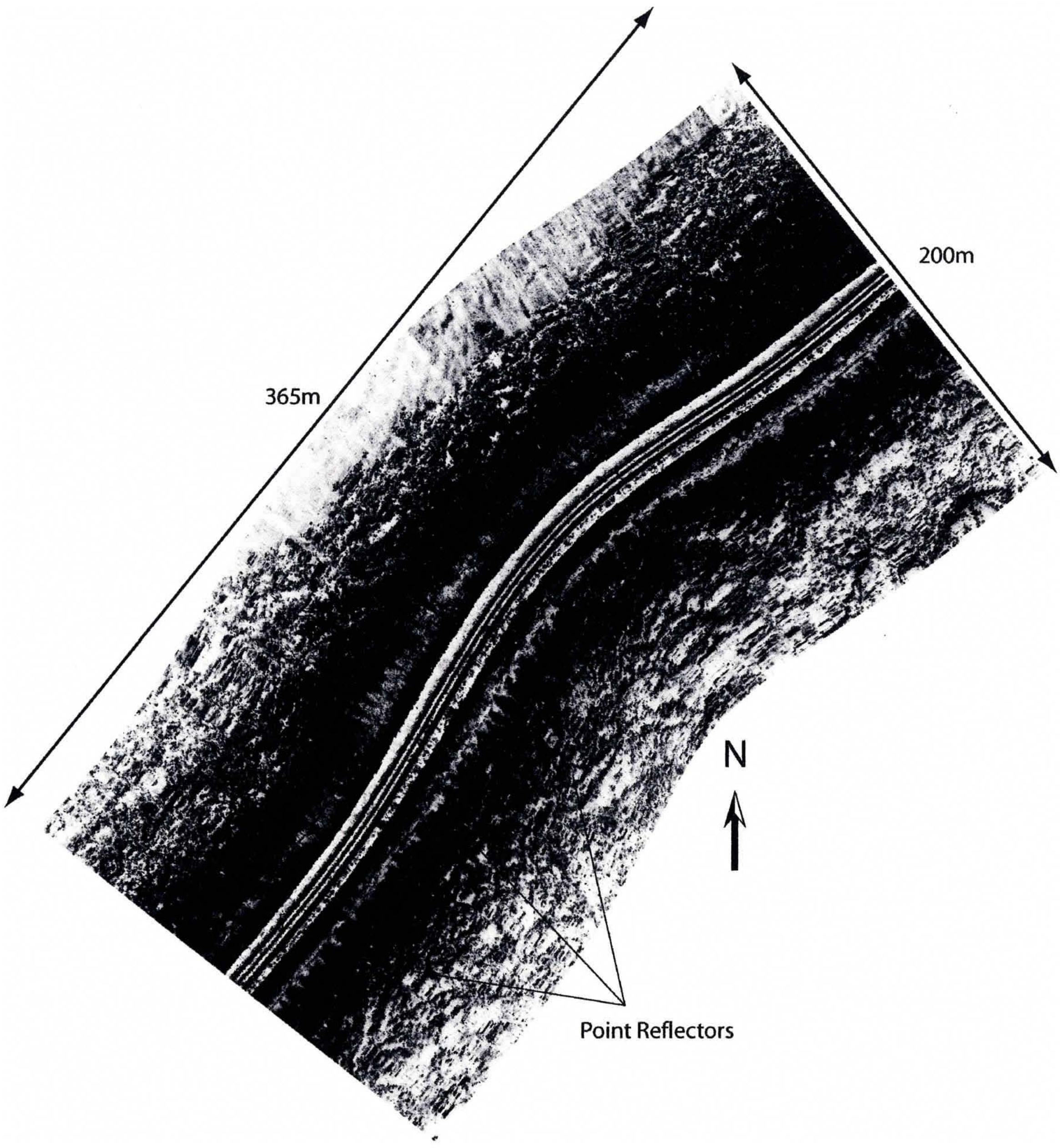


Figure 4.6: Side scan image showing a sand substrate with boulders (Facies 5), characterized by a medium to dark gray sonar image with scattered point reflectors casting acoustic shadows. Image taken approximately half-way between Vail's Point and Coffin Cove near the eastern shore of Owen Sound (see Fig. 4.1 for location).

Dionne, 1993). Side scan Facies 5 is also associated with gravelly and pebbly beaches that occur along high energy areas of the shoreline where bedrock is exposed (Fig. 2.6). Transport of coarse material offshore from these beaches during storms or seasonal ice break up may account for the presence of Facies 5 and 6 in these regions.

4.1.6 Facies 6: cobbles and boulders

Side scan Facies 6 is dominated by single point reflectors that cast distinct acoustic shadows. However, in contrast to Facies 5, no significant patches of uniform reflectivity can be seen between the point reflectors. Point reflectors vary in size and shape, ranging from sizes below the resolving limit of the sonar to reflectors with a diameter of 1-2 meters (Fig. 4.7). Facies 6 is only seen in the area around Vail's Point where a shallow shoal is present with water depths as low as 1 meter (Fig. 4.1).

Similar facies were described from side scan images by Edsall *et al.* (1989) and Bornhold (2002), and were interpreted as representing cobble and boulder substrates with little to no sediment infilling the voids between the large clasts. This facies type could not be identified on seismic transects, but the substrate was visually inspected from the research vessel.

Based on the side scan signature and direct visual observations, Facies 6 is interpreted as a boulder and cobble dominated substrate. The clasts range in size from 10cm to 2m diameter with a mean clast size of 40-50cm; most clasts appear to be sub-rounded to sub-angular from the shape of the acoustic shadows formed on side scan images (Fig. 4.7). This facies is only found on a shallow shoal that forms a spit near Vail's Point, an exposed location open to the high energy currents and storm waves of southern Georgian Bay. The coarse-grained sediment forming this facies may represent a lag deposit created by winnowing and removal of finer grained sediment by current and wave activity; some of the coarse sediments may also have been transported to this location by high energy shoreline processes. Given the large size of some of the boulders in Facies 6, it is likely that it was created at least in part by deposition of seasonally ice-rafted material.

4.1.7 Facies 7: bedrock

Side scan Facies 7 shows alternating bands of high and low reflectivity that create alternating light and dark bands on the output image. This pattern of high and low reflectivity is often observed near the shore-side of an image recorded in relatively shallow water depths and is bounded by a completely white area beyond the banded region (Fig. 4.8). The light/dark bands have sharp edges, and often have a jagged appearance (Fig. 4.8). Facies 7 is always sharply juxtaposed with other side scan facies types indicating an abrupt change in substrate types. Facies 7 was identified along the shores of both Owen Sound and Colpoy's Bay. The most remarkable examples lie south of Squaw Point in Owen Sound and near Oxenden in Colpoy's Bay, where Facies 7 forms extensive shallow shoals (Fig. 4.1). On the western shore of both bays bedrock outcrops above lake level can be correlated with the offshore occurrence of Facies 7 on the sonar images.

Facies 7 is interpreted here to represent Paleozoic bedrock outcropping on the lake floor. The linear banding on the side scan images represents the strike of closely

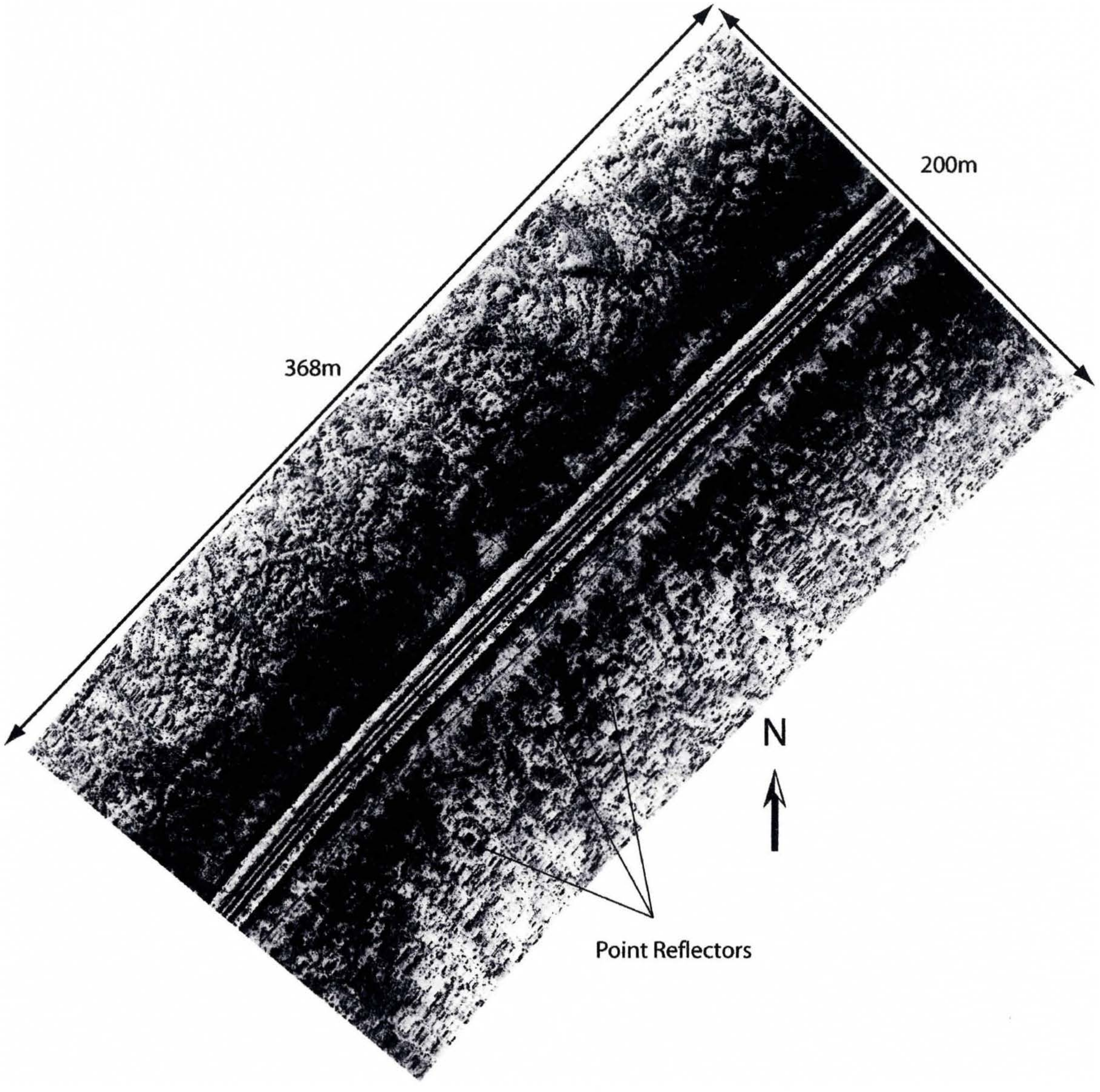


Figure 4.7: Side scan image showing a boulder substrate (Facies 6), characterized by point reflectors casting acoustic shadows with no patches of uniform reflectivity in-between point reflectors. Image taken near Vail's Point (see Fig. 4.1 for location).

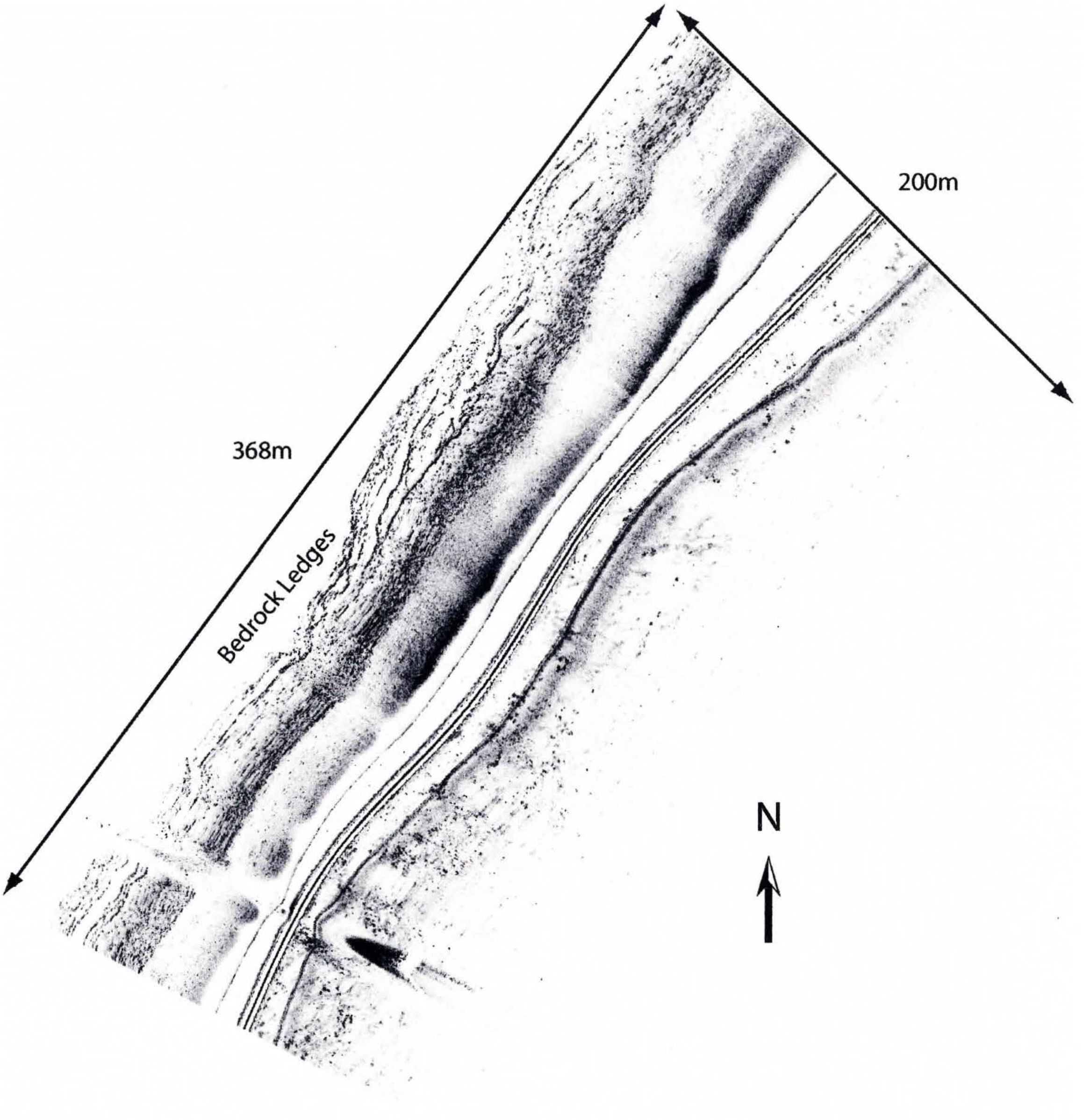


Figure 4.8: Side scan image showing a bedrock ledge (Facies 7), characterized by light and dark banding on the western side of the image. Image taken near Gravelly Point at the western shore of Colpoy's Bay (see Fig. 4.1 for location).

spaced dipping beds of the exposed Georgian Bay shale. The white bands represent areas where the acoustic energy is bounced off the top of bedrock ledges away from the sonar source, while the dark bands indicate where vertical bedrock faces reflect most of the acoustic energy back to the tow fish (also see Fig. 3.11). The side scan signatures recorded in this study correspond well with rock outcrops or bedrock described on side scan images from other locations (e.g., Mazel, 1985; Wever *et al.*, 1997; Bornhold, 2002). On seismic profiles this facies type appears as an acoustically impermeable surface that lies at the surface in shallow water areas, but can also be identified below other sediment types in deeper water. Where it lies close to the modern lake floor and is not masked by a thick sediment cover a strong multiple can be seen on the seismic record (Fig. 3.19).

4.1.8 V: vegetation

Vegetation is identified on a sonar image as a series of high reflectors (dark patches) with no preferred shape or orientation. The edges of these dark patches are often "fuzzy" (Fig. 4.9) and contrast with the sharp edges of large point reflectors such as boulders (Fig. 4.7). These dark patches are most commonly found associated with Facies types 3 and 4 (flat bedded sand and sand with ripples) in water depths of between 10 and 20 meters (Fig. 4.1). The largest patches of vegetation identified on the side scan images occur near the eastern coast of Owen Sound. Similar acoustic returns from vegetation were described by Pasqualini *et al.* (2000) and Siljeström *et al.* (2002) who attribute the high acoustic return from vegetation to air pockets present in the stems and leaves of sub-

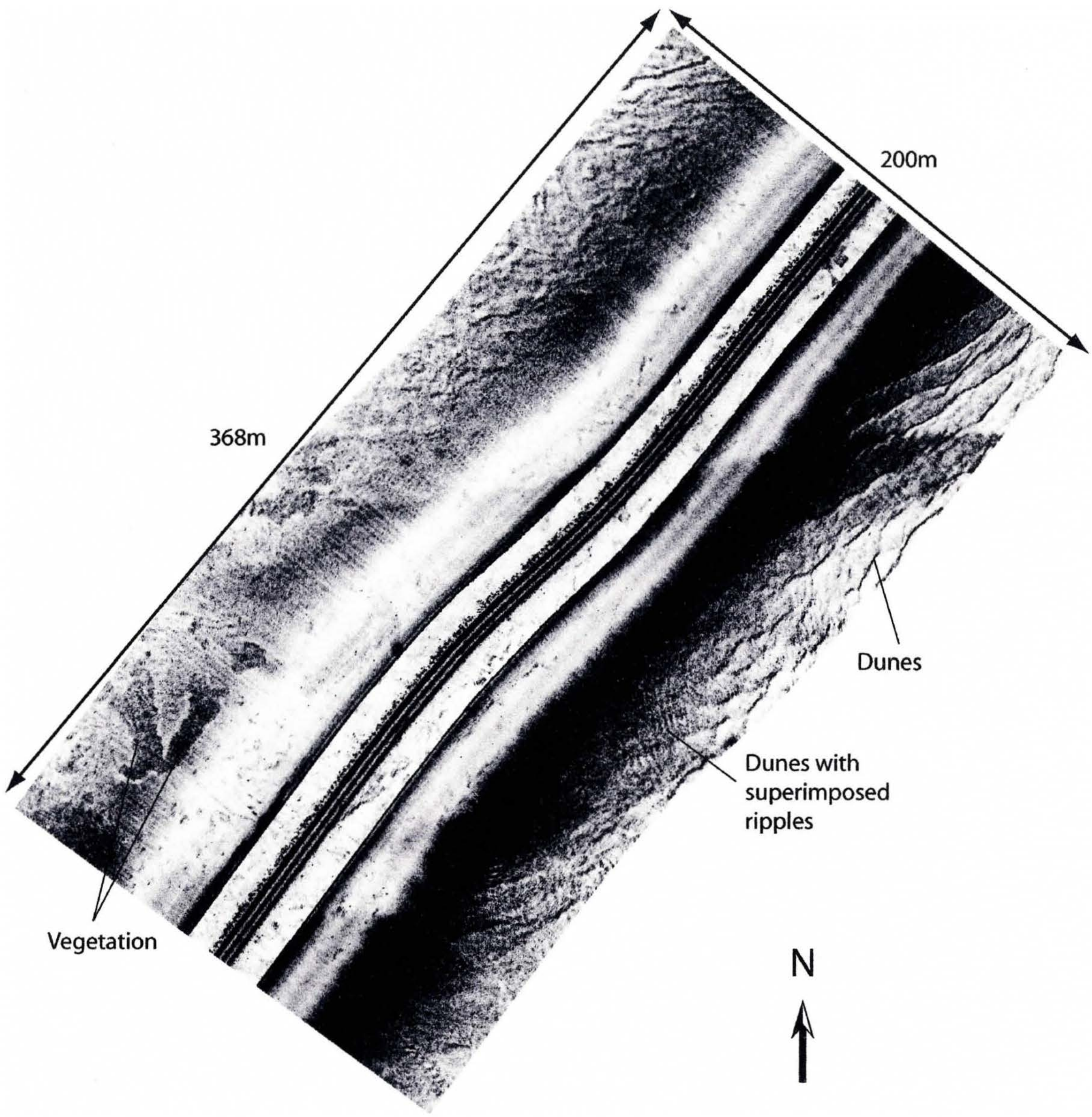


Figure 4.9: Side scan image showing patches of vegetation, characterized by dark patches with irregular shape and "fuzzy" edges near the south-western side of the image. Image taken north of Harkness Point, eastern shore of Owen Sound (see Fig. 4.1 for location).

aqueous plants. These air pockets, not the plants themselves, are responsible for the reflection of the sound energy.

4.1.9 Limitations of side scan data

One of the major limitations to the interpretation of substrate types from side scan sonar imagery is the availability of data for ground-truthing images. Several studies (e.g., Wever *et al.* (1997); Bronikowski, 2004) show that sub-bottom seismic data are complimentary to side scan sonar imagery and can be used as a means of cross-referencing both datasets; seismic data may also be used to validate interpretations of side scan images provided there is a basic understanding of the types of sediment that may be present. In this study, seismic and side scan data were acquired concurrently in order to maximize their cross-validation potential. In addition, visual data of substrate characteristics were acquired where possible, as the clear waters of southern Georgian Bay allowed good visibility of the lake floor to depths of up to 10 meters.

A second limitation to the interpretation of lake substrate types from side scan imagery is the density and spatial distribution of the data. Due to time constraints, collection of data providing full areal coverage of both bays with a 100m wide side scan sonar swath was not possible, and there are thus significant gaps in the available data (also see the track line map, Fig. 3.17). This survey focused on the collection of data from relatively shallow water depths (between 5 and 40m; Fig. 2.6) as these areas are thought to be most significant for fish spawning. To aggravate this problem of incomplete data coverage some of the acquired images were corrupt and thus lost for interpretative purposes. In the areas where gaps exist in the data, substrate type was interpreted based on the known sediment distribution in nearby areas and available bathymetric, shoreline and environmental data (see discussion of map compilation in Section 5.1). In some instances, this lack of data may have resulted in overgeneralization of the substrate type.

A further limitation to the data presented here is that due to time constraints, some of the survey was carried out in less than ideal weather conditions, resulting in unwanted tow vessel and tow fish motions. In some instances tow fish motions were so severe that the survey had to be stopped altogether as the acquired images were unusable. Pitching of the tow fish occurred when the research vessel experienced head-on wave action (Fig. 4.10), while roll and yaw were experienced when the research vessel rolled over waves perpendicular to the track line paths (Fig 4.11). At other times the motions were less severe, but still caused some image quality degradation as described in Section 3.2.4; this degradation of image quality was accounted for during the image interpretation process. An example is Figure 3.6, where the scalloped appearance of the western side of the image is caused by pitch and roll of the tow fish. The identification and interpretation of small scale features, such as small ripples was affected most significantly by these effects as these features are close to the resolution limit of the sonar and are the first ones to be lost if the imaging process is compromised.

Another difficulty with the interpretation side-scan images occurred due to the sloping lake bottom as the track lines followed bathymetric contours. In this situation the shallower side of the image is represented relatively darker than the deeper side (Fig. 3.16 and Fig. 4.12). Care should be taken however when interpreting slope in these images as the darkness of one side of the image might be caused by the presence of ripples on the lake bottom that have crests perpendicular to the survey track line (also see Section 4.1.3).

The final limitation to interpretation of side-scan images was the inconsistency of the greyscale of the images from one survey day to another. The presence of a nearby military radio transmitter blocked the sonar signal to differing degrees on several days during the survey, sometimes resulting in extremely light images, such as Figure 4.8. For a correct interpretation, these images had to be cross-correlated with images taken on days when the radio transmitter was not blocking the sonar signal.

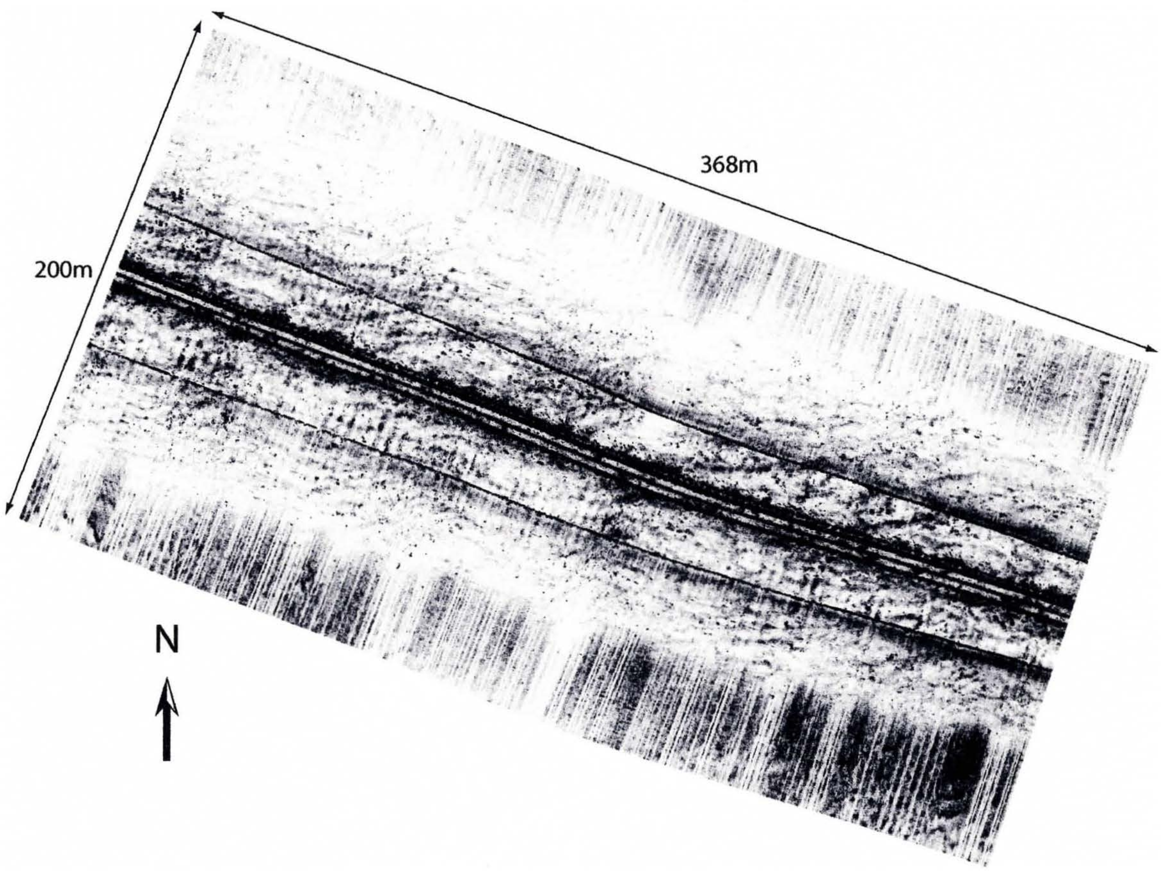


Figure 4.10: Image showing the effects of head-on wave action. The narrow dark and light banding perpendicular to the track line are due to the pitching of the tow fish.

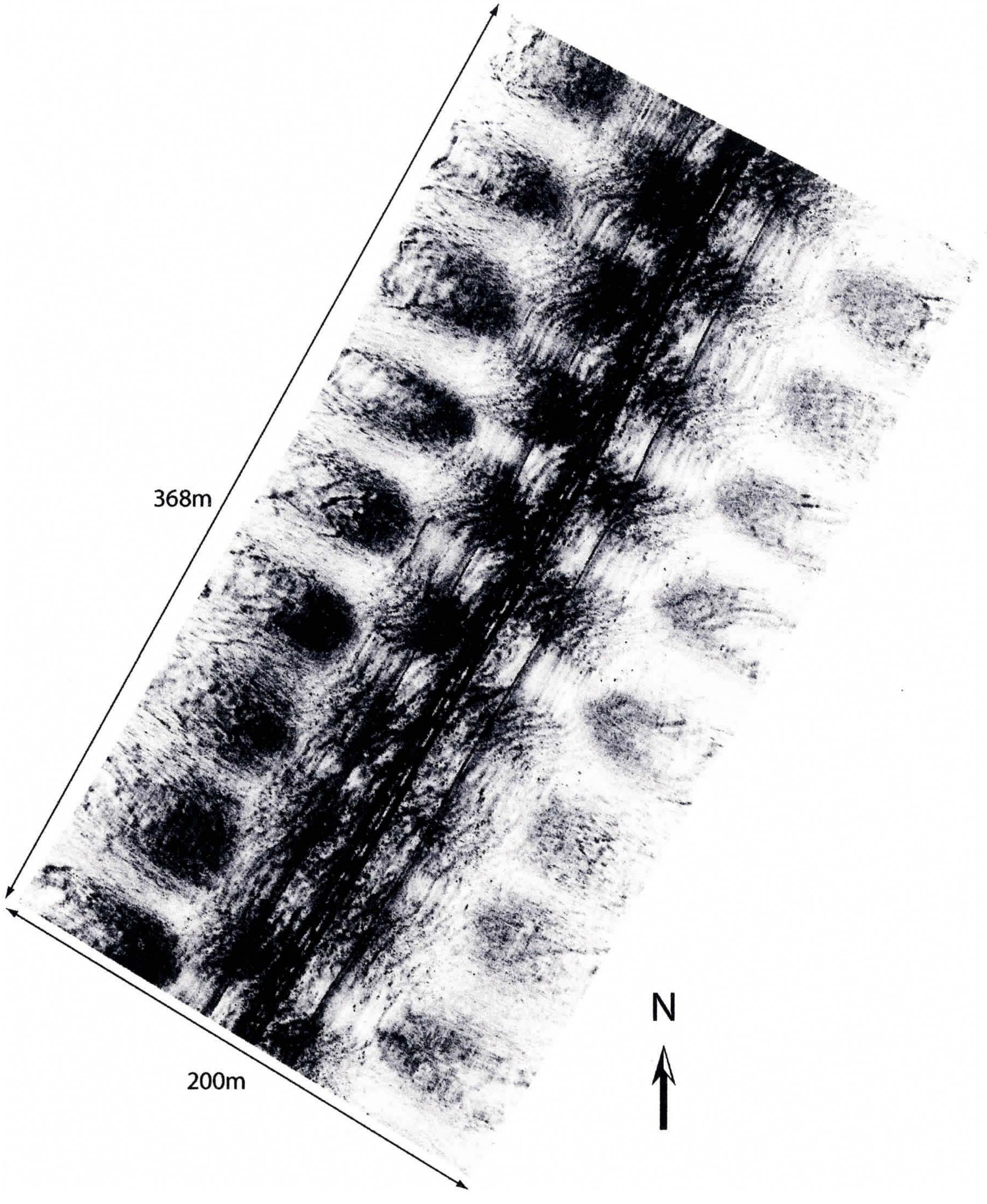


Figure 4.11: Image showing the effects of wave action perpendicular to the track lines resulting in a roll and yaw motion of the tow fish. The scalloped appearance of the image is the result of over- and under-sampling on alternating sides of the track line as the tow fish is moving forward.

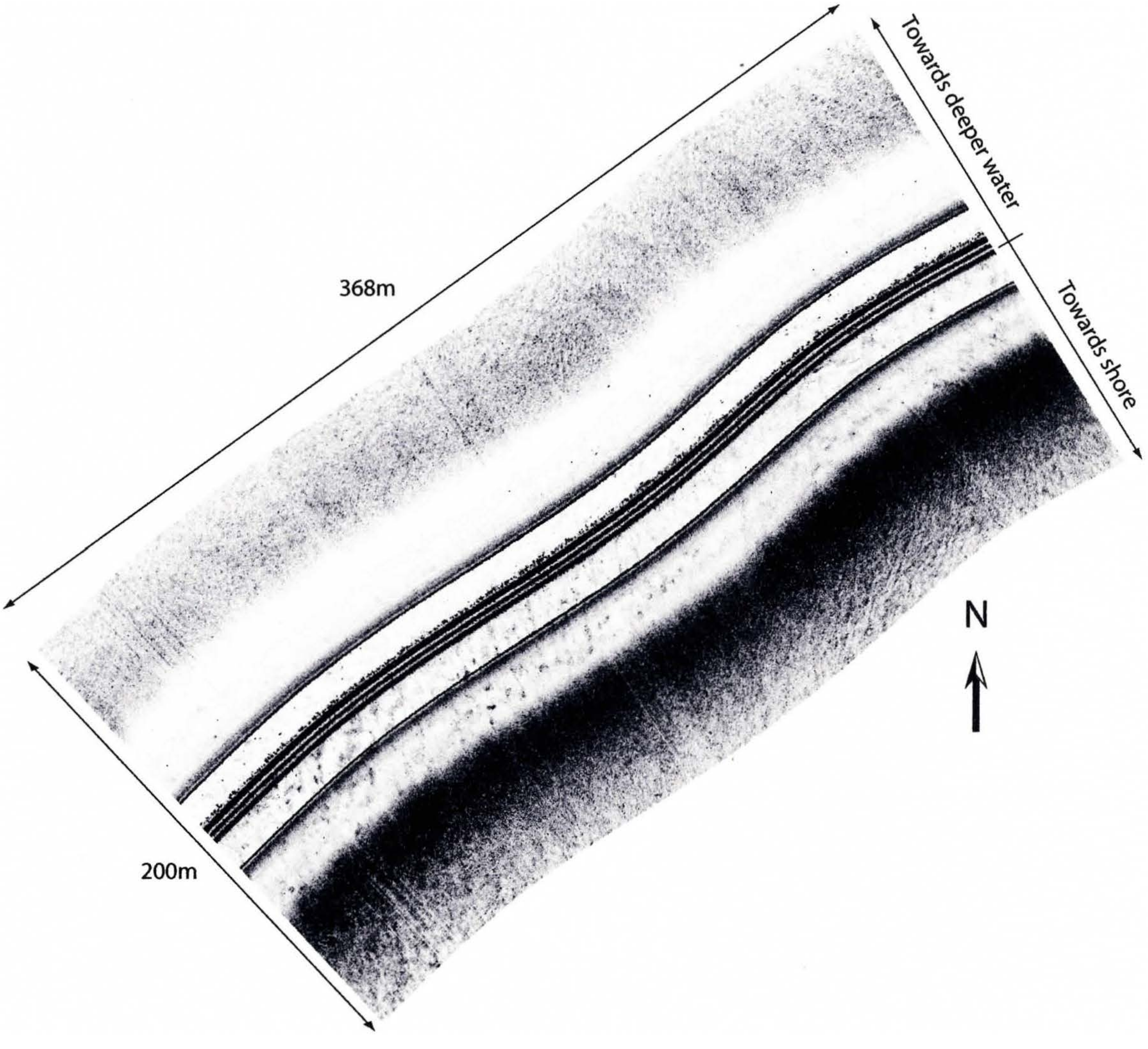


Figure 4.12: Image showing the effects of a perpendicular sloping lake bottom under the tow fish. The right hand side of the image is closer to shore and is shallower water than the left hand side, resulting in an overall darker appearance of the image, even though the substrate type is the same on both sides.

CHAPTER 5: SURFACE SEDIMENT DISTRIBUTION IN OWEN SOUND AND COLPOY'S BAY

A second objective of this study is the creation of a sediment distribution map of Owen Sound and Colpoy's Bay region of southern Georgian Bay that is not only useful for the fisheries studies conducted by the Ontario Ministry of Natural Resources, but is also time efficient to produce. The creation of maps showing the spatial distribution of sediment types on lake and ocean floors from linear swaths of side scan data is, however, not an easy task. In other studies, sediment distribution maps have been compiled using a number of techniques. In situations where the areal coverage of the survey is almost 100% and there are no significant spatial gaps in data coverage, it is usual to draw the map directly from the side scan images either by hand or digitally (e.g., Edsall *et al.*, 1989; Scheirer *et al.*, 2000; Bornhold, 2002; Eittreim *et al.*, 2002). Unfortunately, due to time constraints, 100% survey coverage of the study area was not possible in this study, and significant gaps exist between individual track lines (Fig. 3.17). Sediment distribution maps were therefore created by the interpolation of data between track lines, an approach used in several other studies (e.g., Boss *et al.*, 1999; Bronikowski, 2004). Two approaches were used to create maps in this study; one involving visual interpolation of digitized data points and manual delineation of unit boundaries and the other using a GIS-based ArcMap mapping program.

5.1 Data input

In order to translate the data shown on the side scan images into a format that could be used for the visualization and spatial analysis of substrate types across the entire study area, the images were imported into ArcView and data points with specific sediment classification information were created on each of the images (Fig. 5.1). Each data point was located in the centre of the area characterized by a specific substrate type and any one image could contain up to 8 of these numbered points, depending on how many facies types were identified on the image. In total, 3038 points containing relevant sediment classification information were created on the images collected from Owen Sound and Colpoy's Bay. These points were overlain on the pre-existing bathymetric data set obtained from the Ministry of Natural Resources and printed on a 4x4ft size sheet.

In this study, a point system that was created in ArcView was used to classify substrate data interpreted from side scan images. Vector data can be created in ArcView in either point, line or polygon form. As the aim of the work was to create a map showing the areal extent of substrate types, line data was not considered to be suitable. Point form data creation was also selected over polygonal data creation. The use of points, rather than polygons, to interpolate the available dataset facilitated data screening for errors in substrate classification; this was especially useful when two or more side scan images overlapped and interpretation of substrate characteristics varied from one image to

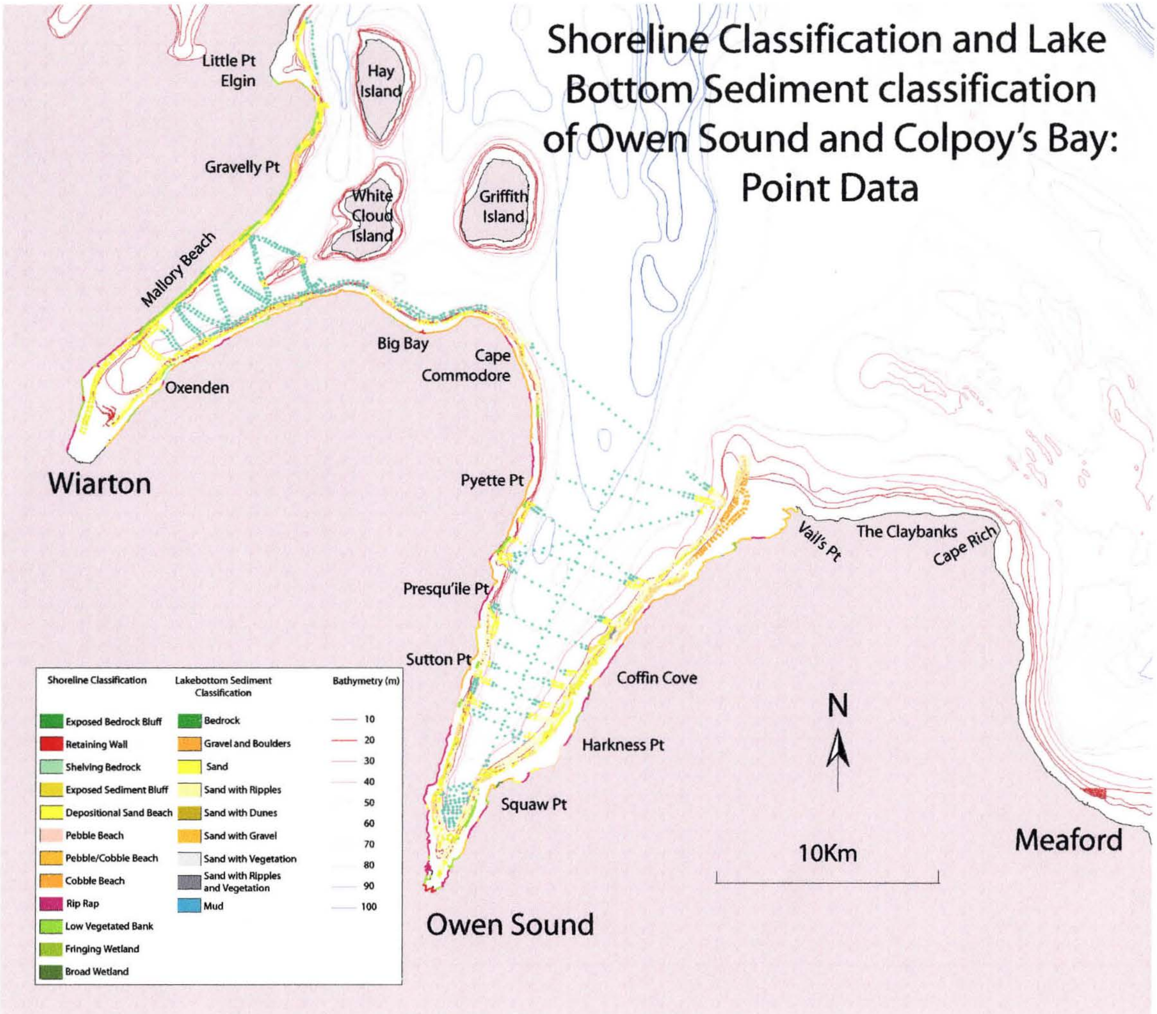


Figure 5.1: Map showing shoreline classification, bathymetry and the location of 3038 data points recording lake floor sediment characteristics as interpreted from side scan images collected in Owen Sound and Colpoy's Bay. The shoreline classification and bathymetry data are used to help create the sediment distribution map shown in Figure 4.1 from the substrate point data. Bathymetry map from the Ontario Ministry of Natural Resources (2004), shoreline classification data from Environment Canada (1994b).

another. This situation was encountered on parts of the lake floor covered by sand where one image might display a flat lake floor (Facies 2), and a second image of the same location taken on a different day (after a storm for example) might show certain areas covered with ripples (Facies 3). If bedforms such as ripples were observed on an image, then that portion of the image was always classified to recognize the bedforms; the presence of bedforms provides significant information regarding depositional processes and was therefore important to include on the substrate map. In this example, point data allowed closely spaced areas on an image to be given different classifications, one for Facies 2 and one for Facies 3; grouping of these classifications as mappable units occurred during the subsequent map creation process and took into consideration other factors such as bathymetry and shoreline type. In most cases the bedform ornamented substrates took precedence over flat beds as they are important in the interpretation of depositional processes and the controls on the system. If polygons had been used initially to classify substrate type then both the flexibility of the data input process and the accuracy of the map created would have been reduced. Thus, establishing an initial system of point data from the side scan images allowed the later creation of polygonal data by hand or by computer and facilitated the most comprehensive interpretations of sediment distribution to be made during the map creation process (Fig. 5.2).

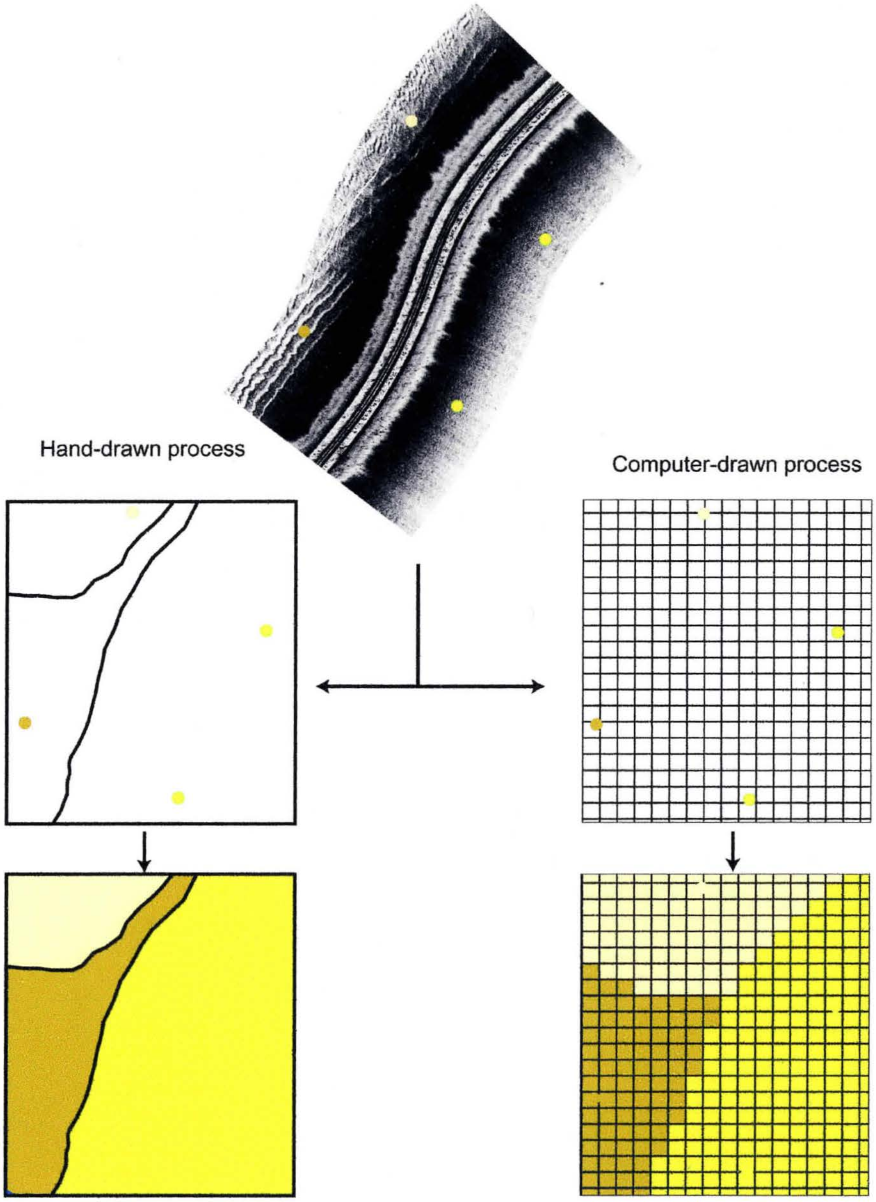


Figure 5.2: Image illustrating the hand-drawn and computerized map creation processes. The three colors represent different facies types: yellow for flat sand, faded yellow for sand with ripples and brown-yellow for sand with dunes. Left side: the hand-drawn process is shown where sediment distributions are interpolated from side scan data taking into consideration other data, such as bathymetry, shoreline sediments and environmental controls. The black lines represent the delineation of substrate types. Right side: computerized process only uses the data points classified from side scan sonar image for the interpolation of a grid. With this process ArcMap's distance/allocation function first creates a blank grid over the point dataset and subsequently assigns grid cell values based on the nearest point in a straight line.

5.1.1 Creation of maps from data points

The coded points identified on the side scan images were used to manually create a sediment surface cover map based on their spatial distribution, and their relationship to bathymetric features (Fig. 5.1), the nature of shoreline materials and known environmental conditions. Consideration of bathymetry and shoreline type was considered important in the interpretation of side scan data points for the manual creation of the lake floor sediment cover map as these can exert a great amount of control on the sediment distribution in lakes (Johnson, 1984). The initial hand drawn map was subsequently digitized to create a GIS database of sediment cover of Owen Sound and Colpoy's Bay (Fig. 4.1, inset Map 1).

The same dataset of coded points obtained from the side scan images was also converted into a grid in ArcMap. The sediment classification data are coded as nominal thematic data (see Chapter 4) and thus cannot be processed in a mathematical sense, since they do not represent an absolute or relative value, but a distinct sediment facies type. A process has to be chosen that creates a grid of the available data points without treating the data as continuous nominal data (Heywood *et al.*, 1998). The surface distribution map was created with ArcMap's distance/allocation function in the spatial analyst toolbox (Fig. 5.3).

This method of spatial analysis of input data builds a blank grid, or raster, on the base map and identifies the closest classified point in a straight line to each cell in the

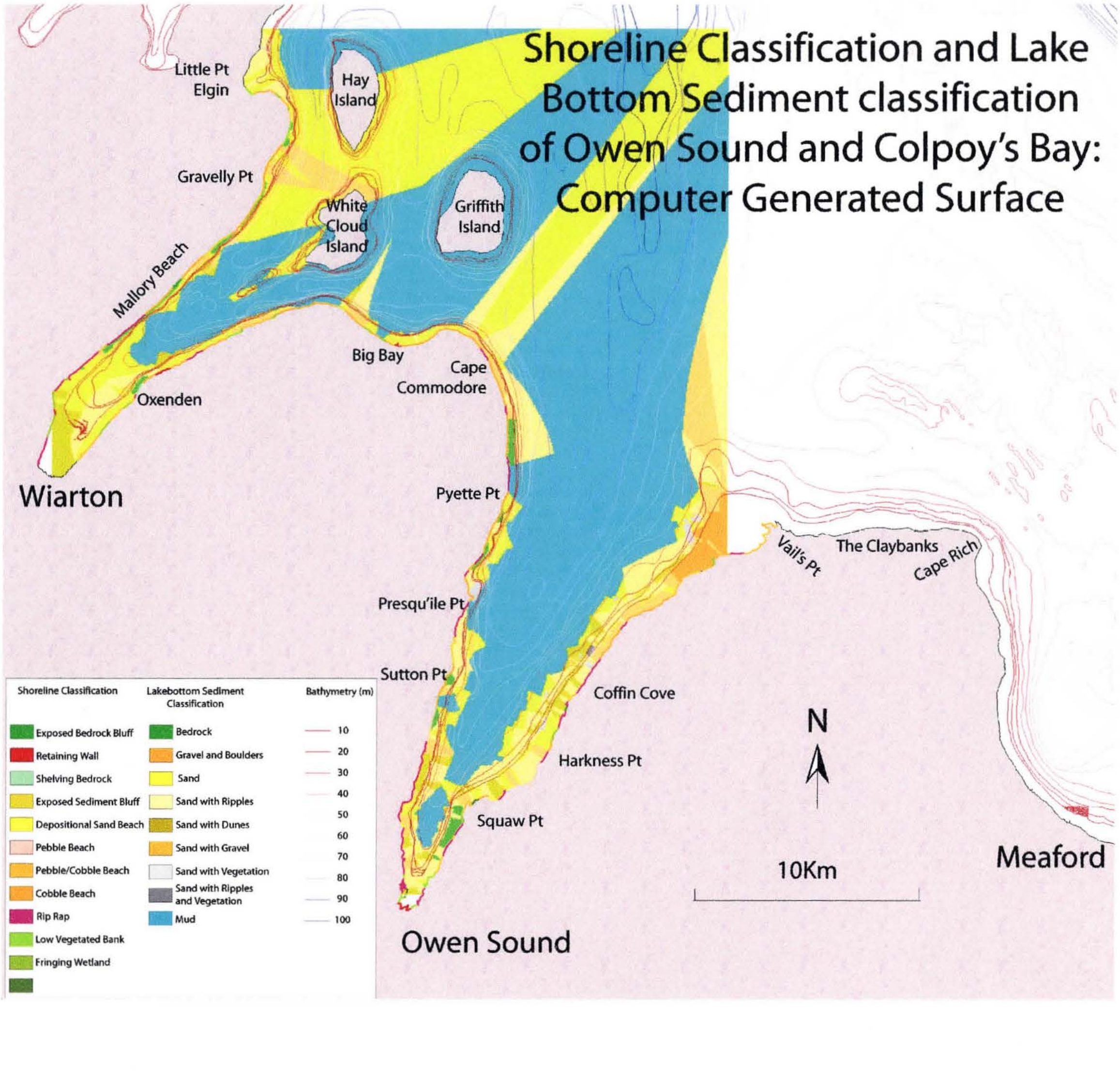


Figure 5.3: Sediment distribution map created with the Spatial Analyst toolbox in ArcMap. Note linear boundaries created between different substrate types and unrealistic extrapolation of data to the outer boundaries of the modeled area.

output grid. Each cell in the output grid receives the value, or classification, of the closest classified point. These grid cells have the same value as the point data they were created from. Thus, where a number of points with the value 1 are close to each other and no points with other values lie between these points, a continuous area with value 1 is created that incorporates all points with value 1. The area will extend the half-distance to any point with a different value than 1. This process is illustrated in Figure 5.2. A grid cell size of 5m was used in this study in order to produce a map with sufficient resolution for screen display or letter size printouts. The sediment distribution map created from this process is shown in Figure 5.3.

The two sediment surface cover maps (Figs. 4.1 and 5.3) were compared and their effectiveness and accuracy in portraying a realistic sediment distribution for Owen Sound and Colpoy's Bay was evaluated. The hand-drawn map was used as the basis for discussion of substrate facies distribution and interpretation provided below and the reasons for selecting this map are presented in Section 5.3.

5.2 Facies distribution and controls on sediment distribution

The spatial distribution of the 7 side scan facies types identified in this study identifies three broad zones of substrate characteristics in the Owen Sound/Coploy's Bay study area (Fig. 5.4). The first substrate zone consists of low–relief muddy substrates of Facies 1 and is encountered in water depths greater than 30-40 meters (Fig. 4.1). The second substrate zone is characterized by sandy substrates with various surface textures (Facies 2, 3 and 4), and is encountered in water depths of less than 30 to 40m (Fig. 4.1).

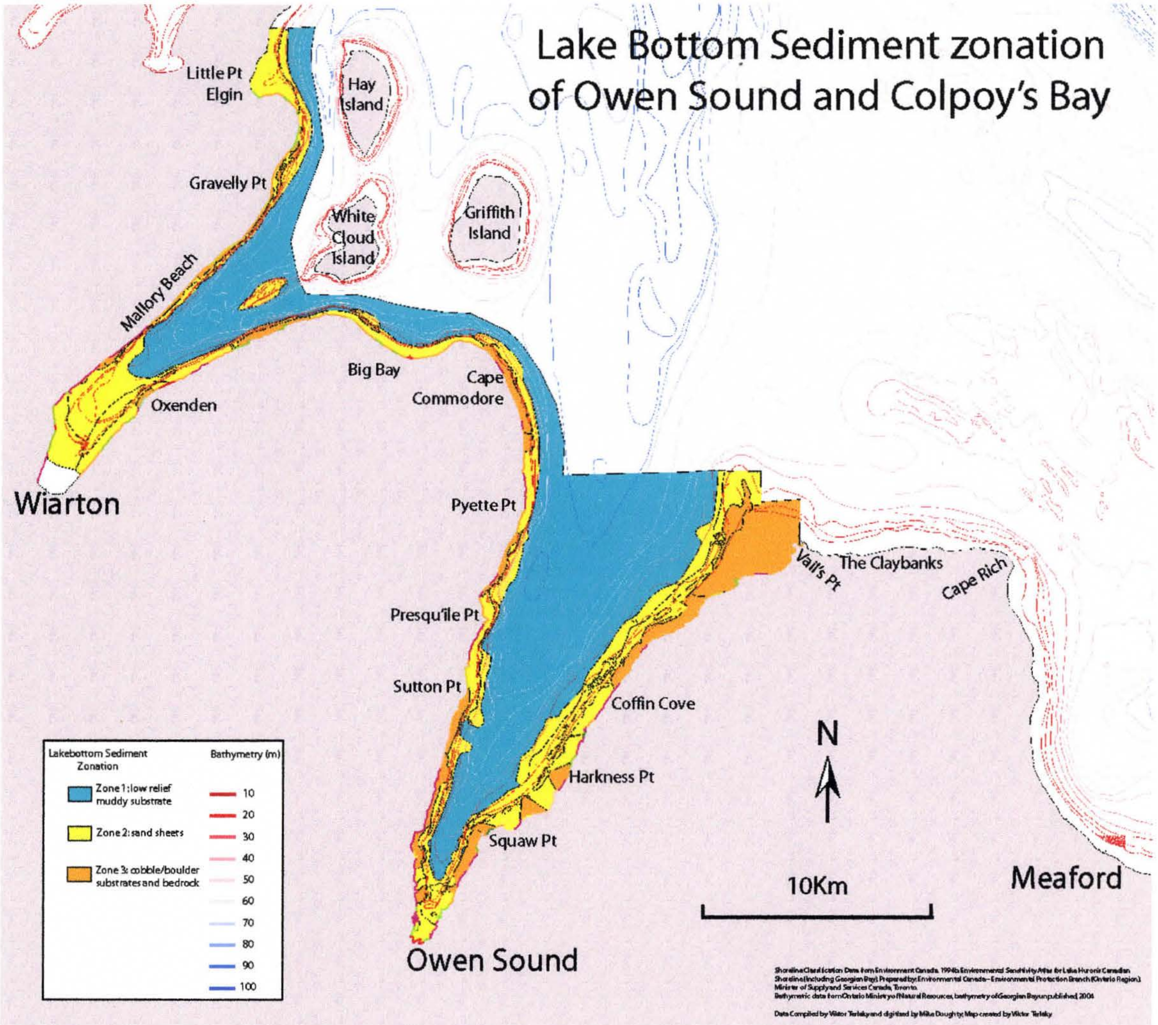


Figure 5.4: Map showing the distribution of the 3 main substrate zones identified. The areas in orange (zone 3, cobble, boulder and bedrock rich areas) are the most suitable fish-spawning habitats.

The third substrate zone is the most important for identifying potential fish spawning habitats and comprises coarse-grained substrates consisting of cobbles, boulders and bedrock (Facies 5, 6 and 7); these coarse-grained facies are encountered in shallow waters of less than 15 meters depth (Fig. 4.1). The spatial distribution of each of these substrate zones, and the factors that control their distribution will be discussed below.

5.2.1 Zone1: low relief muddy substrates (Facies 1)

The deeper areas of Owen Sound and Colpoy's Bay (in water depths greater than 30 to 40m; Fig. 4.1) are covered with a surface veneer of muddy sediment, but this fine-grained sediment cover does not form a uniform thick blanket across the bays. Seismic profiles show that the modern muddy sediment cover is generally thin and restricted in extent, probably due to the lack of substantial sediment inputs into southern Georgian Bay. Local streams and rivers do not carry large amounts of fine-grained sediment as the area is characterized by hard, erosion-resistant limestone and dolostone bedrock (see Chapter 2) overlain by a relatively thin cover of Quaternary sediments (Fig. 2.6). The lack of substantial suspended sediment load entering southern Georgian Bay is also evidenced by the great clarity of water in the study area. Low rates of modern sediment accumulation have been noted for other areas of Lake Huron (e.g., Thomas *et al.*, 1973) and Georgian Bay (e.g., Kemp and Harper, 1977).

Compounding the effects of low rates of suspended sediment supply, energetic storm waves can also prevent fine-grained sediment accumulation in water depths of less than 100m (e.g., Johnson, 1980). In southern Georgian Bay, storm waves with a crest height of over 2 meters have been observed, and historic data show that wind set-up can reach 0.5 meters in Owen Sound (Weather Guide for Pleasure Crafts, Georgian Bay, 1992). Storms passing over large lakes set up standing waves (seiches) both on the lake surface and along the pycnocline of a stratified lake (Johnson, 1984). When a lake is sufficiently large, the Coriolis effect causes waves to rotate (Mortimer, 1974) and strong bottom currents can be generated in association with these waves. Bathymetric features can focus these currents causing localized erosion of the substrate even in water depths of several hundred meters (Dell, 1976; Johnson *et al.*, 1980). Bottom currents generated by storm activity are of sufficient velocity and duration to prevent deposition of fine-grained sediment in relatively deep water and are also capable of eroding older sediment exposed on the lake floor. Such storm-generated currents may be in part responsible for the thin and variable cover of Holocene mud characteristic of substrate Zone 1 in Owen Sound and Colpoy's Bay.

In the deeper offshore portions of the study area, lateglacial sediment is identified on seismic profiles at the lake floor by the presence of truncated units of well-defined parallel and high frequency reflectors interpreted as finely-laminated 'varve-like' deposits (Radomski, 2005); these deposits are also recognized as Facies 1 on side scan images (Figs. 3.20 and 3.21) The presence of truncated lateglacial deposits at the lake floor surface indicates that the modern lake floor is being actively eroded in places, probably by storm-generated currents. Erosion of substrate materials during the post-Algonquin low water phase of Georgian Bay around 8000 years before present can also be recognized on seismic profiles as truncation surfaces cutting across older (underlying) lateglacial sediment that are draped by a veneer of Holocene mud (Radomski, 2005). The identification of modern and post-Algonquin erosion surfaces in the Owen Sound/Colpoy's bay study area is consistent with other studies conducted in the Great Lakes (e.g., Blasco *et al.*, 2001).

Mud-rich sediments of substrate Zone 1 are not suitable for whitefish spawning and should not be included in rehabilitation efforts in the study area.

5.2.2 Zone 2: sandy substrates (Facies 2, 3 and 4)

Sand-rich substrates occur in relatively shallow water of less than 30m depth and form a continuous belt around the shoreline of both bays (Fig. 4.1). Bathymetry seems to be a primary control on the grain size distribution of sediments in the study area, with coarse-grained sediment generally extending from shore to water depths of between 30 and 40 meters. In areas with water depths of over 20 meters, flat bedded sand (Facies 2) forms the most common substrate type. In shallow waters, between a depth of 25 and 5 meters, first ripples are encountered in the near 25 meter depth sections, then dunes are encountered, followed once again by ripples close to shore in shallow areas (Fig. 4.1). The presence of both ripples and dunes on the sand sheet indicate an active substrate created by the operation of strong oscillatory and traction currents produced below fair-weather and storm waves (Gallagher *et al.*, 1998; Nichols, 1999). Large dunes are created in water depths of between 5 and 30 meters by large storm waves, but can be partially destroyed in shallow waters by fair weather waves after a storm event. This can explain the presence of large dunes on sand sheets in water depths of 10-20 meters and smaller ripples closer to shore, and the presence of ripples superimposed on larger dunes.

The sand sheets of substrate Zone 1 appear to be very dynamic environments and may rapidly change form under storm conditions. Aagaard and Greenwood (1995) report that offshore sediment bars in Lake Huron migrated as much as 25m offshore during a 10 hour storm period, and caused sediment erosion to a depth of 0.92m at the former bar crest. In another study at Wendake Beach, Georgian Bay, Greenwood and Sherman (1984) show that offshore bars can also migrate towards the shoreline during a storm, and may also show some alongshore movement. Some studies suggest that offshore sand bars might be completely formed and destroyed as conditions change during storms (e.g., Bowman and Goldsmith, 1983; Aagaard and Greenwood, 1994). All of these studies suggest that in high energy systems such as those represented by the sandy substrates of substrate Zone 2, sediment may migrate significant distances and bedforms change considerably under storm and fairweather conditions. This has implications for fish rehabilitation studies as mobile sand sheets might cover known spawning areas from one year to another, or due to the transport of sand a cobble rich lag might be exposed in other areas. This might suggest that fish spawning locations are not rigid, but migrate under the influence of environmental controls.

5.2.3 Zone 3: cobble/boulder substrates and bedrock (Facies 5, 6 and 7)

Storm generated current activity not only causes erosion in deeper areas of Owen Sound and Colpoy's Bay and affects the form and mobility of shallow water sand sheets, but also helps create exposed bedrock ledges, cobble and boulder substrates in shallow areas (substrate Zone 3) which are ideal fish spawning sites. Sediment stripping by waves and currents is known to create lag deposits of coarse-grained sediment in high energy environments (Johnson, 1984).

Areas of coarse-grained sediment, such as boulder and cobble fields are seen near the shoreline of both Owen Sound and Colpoy's Bay in water depths of less than 15 meters (Fig. 4.1). These coarse-grained deposits may have been derived from the in-situ reworking of bouldery glacial sediment such as outwash, moraines and drumlins, which are common on the surrounding landscape (Fig. 2.6) and were likely present in and around the shorelines of Owen Sound and Colpoy's Bay. Currents in the basins created by wave and wind action can strip these areas of finer sediment exposing larger clasts such as boulders and clasts on the lake floor. The area near Vail's Point forms the most extensive boulder field in the study area where a shallow shoal with water depths as shallow as 1m extends several hundred meters into the mouth of Owen Sound (Fig. 4.1). This shoal is well exposed to the high energy current and wave action of southern Georgian Bay, and consequently very little fine sediment is observed in this area. Boulder-rich surfaces may also be created by ice-rafting of coarse debris by seasonal ice (e.g., Dionne, 1993) formed along rivers and the coastal areas of southern Georgian Bay.

Coarse-grained substrates characteristic of substrate Zone 3 also occur close to the mouths of streams entering Owen Sound and Colpoy's Bay (Figs. 2.8 and 4.1). This coarse material probably represents a lag deposit formed on the shoreline as finer-grained materials were removed by nearshore wave and current activity. Some of the streams, such as Telfer Creek and Keefer Creek entering Owen Sound (Fig. 2.8) flow over till and mud plains and carry a load consisting predominantly of clays, silts and cobbles/boulders derived from till. The fines are probably removed by current activity leaving the coarser grained materials close to the stream mouth. Flood events might also provide a mechanism for large clast transport during the spring snow melt season.

Coarse-grained sediments of substrate Zone 3 form ideal fish spawning grounds and future fish monitoring and rehabilitation programmes by the Ontario Ministry of Natural Resources should predominantly focus on these areas.

5.3 Comparison of hand-drawn and computer generated maps

The map production methods outlined in Section 5.1.1 produced maps that each showed considerably different surface sediment distributions for Owen Sound and Colpoy's Bay (Figs. 4.1 and 5.2). The maps will be compared on the basis of two criteria: the accuracy with which the maps represent the sediment distribution in the study area and the amount of time it takes to produce either map. It should be noted that a common dataset, consisting of over 3000 data points containing substrate classification information, was used to create each version of the map; any differences between the maps were due to the map compilation processes applied in each case.

5.3.1 Accuracy

The major difference between the two map production processes is that with the hand-drawn process the delineation of sediment distribution in the study area is not only based on the sediment classification data, but bathymetric, shoreline, sub-bottom seismic and environmental datasets are also taken into consideration. The computerized process used here relies solely on the point data containing sediment classification information, and does not incorporate any information from other datasets. As shown in Section 5.2 bathymetry, in combination with prevalent wind directions and other environmental factors can exert a strong control on current direction and speed in large lakes. This means that the distribution of lake floor sediment types can be closely related to bathymetry and will tend to form predictable spatial patterns (Johnson, 1984). Similarly, the distribution of relict sediment deposited when lake levels were either higher or lower is also controlled by a combination of bathymetry and paleoclimatic conditions.

The nature of sediments exposed along lake shorelines can also provide valuable information regarding offshore sediment types as the shoreline may be affected by similar processes to those operating on the adjacent lake floor and shoreline materials can provide a significant source of sediment to deeper areas of the lake. Hence, consideration of bathymetry and shoreline type was considered important in the interpretation of side scan data points for the manual creation of the lake floor sediment cover map.

The computer generated map shows the distribution of individual sediment types as rectangular or triangular areas with sharp, angular boundaries (Fig. 5.3), in contrast to the irregular distribution with smooth boundaries created on the hand drawn map (Fig.

4.1). Sediment distributions with geometric shapes and angular boundaries are extremely rare in nature (e.g., patterned ground in permafrost regions) and have not been described in lacustrine systems.

Differences between the two maps are especially noticeable in areas with sparse side scan data coverage. In these areas the computerized method simply extends the sediment classification of the closest point to the areas without pre-existing point data, producing unrealistic sediment distributions. A clear example is shown near Squaw Pt. in Owen Sound, where a sand sheet is extrapolated to stretch all the way across the bay by the computerized process (Fig. 5.3). Sub-bottom images show that in this area acoustically permeable sediments exist, thus Facies 1 would be the correct interpretation of substrate type for the deeper areas near Squaw Point. The spatial extent of the sand sheet is restricted on the hand-drawn map, where the deeper areas near Squaw Pt. are interpolated to be a muddy substrate (Fig. 4.1).

In conclusion, the advantage of using a manual system to create the sediment distribution map is that factors affecting sediment distribution can be incorporated in the decision-making process and all available data are taken into consideration when interpolating between data points to establish unit boundaries. The hand-drawn map (Fig. 4.1) is thus more likely to present a realistic representation of the actual sediment distribution in the study area than the computer generated map (Fig. 5.3). Other computer based mapping programs with the ability to incorporate additional data sets in the analysis of sediment distributions may be available but were not used in this study.

5.3.2 Time

The manual map production process took much longer than the computerized process. After the preliminary point data map was printed, the distribution of surface sediment units was drawn and colored on the map manually. The hand-drawn map was then digitized for later analysis with GIS software and was subsequently imported into ArcView and checked for errors, such as missing polygons that were omitted during the digitization process. The last processing step is the creation of the final map with the aid of CorelPhoto Paint 12.0, Adobe Photoshop 7.0 and Adobe Illustrator CS. The total time for this map creation process totaled 6 days.

The computerized map creation process is considerably faster. A grid with sediment distribution data can be created directly without any previous processing steps by using the distance/allocation function in the spatial analyst toolbox. The time taken to create the grid depends on the required resolution of the grid and the processing capabilities of the computer the GIS software is running on. In this study the grid had a cell size of 5 meters and the computer used was a Pentium 4 with 1GB of RAM and no other software running; the total time for grid creation was about 10 minutes. After the grid is created it was overlain on the bathymetry and shoreline datasets and was ready for final map creation, which takes approximately one day.

CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1 Summary

This thesis reports the results of a study conducted in collaboration with the Ontario Ministry of Natural Resources, Upper Great Lakes Management Unit as part of an ongoing project that seeks to identify limiting environmental factors on whitefish and lake trout spawning in Owen Sound and Colpoy's Bay. Lake floor substrate types are known to be a primary influence on successful fish spawning yet there are few data available on the spatial distribution of substrate types anywhere in the Great Lakes basins. The specific aim of this thesis is to develop and implement a simple, yet effective substrate identification and classification scheme using side scan sonar data obtained in the Owen Sound and Colpoy's Bay region. This scheme is also used to create a substrate distribution map based on the interpretation of side scan images and integration of data from sub-bottom seismic profiles and pre-existing knowledge of bathymetry, shoreline sediment types and environmental factors contributing to the dynamic system of Owen Sound and Colpoy's Bay.

Over 500km of side scan sonar data and 100km of sub-bottom seismic data were collected in Owen Sound and Colpoy's Bay during the summer of 2004 (Fig. 3.17). Analysis of 945 side scan images allowed identification of seven substrate types in the two bays. Side scan Facies 1 consists of low relief muddy substrates and is found primarily in water depths greater than 30 to 40 meters. Side scan Facies 2 consists of low relief sandy substrates found in water depths between 0 and 40 meters. Side scan Facies 3 consists of a sandy substrate that is ornamented with ripples on the surface, and is found in water depths of 5 to 30 meters. Side scan Facies 4 consists of a sandy substrate ornamented with dunes, and is found in water depths of 10 t o 20 meters. Side scan Facies 5 consists of a sandy substrate with cobbles and boulders scattered on the lake floor, this Facies type is found in water depths of under 10 meters. Side scan Facies 6 consists of cobbles and boulders and is found in nearshore shallow waters with a depth under 10 meters. Side scan Facies 7 consists of bedrock and bedrock ledges exposed under water and is found near shore in shallow waters.

Data obtained from the analysis of the side scan images were also used to create lake floor substrate distribution maps using two methods: a computerized technique applying GIS-based analysis of the distribution of data points generated from the side scan images using ArcMap (Fig. 5.3), and a more traditional hand-drawn technique that integrated additional sub-bottom seismic, bathymetric and shoreline data with the side scan data (Fig. 4.1). The maps created differed considerably in their effectiveness of portraying a realistic representation of the spatial distribution of substrate types in the study area. The hand-drawn map was selected for use as the computer-based method applied here did not take into consideration all available factors that could influence sediment distribution and extrapolated data in an unrealistic way.

The sediment distribution map created from the interpretation of side scan, sub-bottom seismic, bathymetric and shoreline data (Fig. 4.1) shows that the lake floor in Owen Sound and Colpoy's Bay can be subdivided into three zones based on substrate characteristics (Fig. 5.4). Zone 1 occurs predominantly in deeper water areas and is dominated by low relief muddy substrates. Zone 2 occurs in a ribbon along the shoreline of both bays and is found in water depths of up to 40 meters. This zone consists of sands with various surface bedforms, such as flat beds, ripples and dunes. Zone 3, consisting of cobble, gravel and bedrock substrates, occurs in irregular size areas around the bays, with the most extensive areas near Vail's Point and near stream inputs on the eastern shore of Owen Sound (Fig. 5.4). Fish spawning is most successful in areas underlain by coarse-grained gravelly substrates characteristics of Zone 3; identification and delineation of these substrate types in Owen Sound and Colpoy's Bay is thus critical for the effective implementation of fish rehabilitation programs proposed by the Ontario Ministry of Natural Resources.

6.2 Contributions of this work

This thesis presents the results of the first side scan sonar study to be conducted in southern Georgian Bay and contributes significantly to our understanding of geophysical techniques that may be used for the rapid and cost-effective assessment of lake floor substrate types in order to identify potential fish spawning sites. The Ontario Ministry of Natural Resources currently determines the location of fish monitoring and restoration sites based on historical high catchment areas and anecdotal evidence from local fishermen. The geophysical methods used in this study have shown to be a rapid, cost-effective and reasonably accurate means to gather information about lake bottom substrate distribution, which is crucial for an accurate delineation of suitable spawning sites. Understanding the spatial distribution of appropriate substrate types will improve the efficiency and effectiveness of fish monitoring and restoration programs by providing a narrow areal focus for these efforts.

A further contribution of this study is in the discussion of issues regarding compilation of lake floor sediment distribution maps from interpretation of a spatially limited database of side scan images. This process is not an easy one and requires appropriate methods of data extrapolation and analysis. The outputs from both computer-based and hand-drawn techniques used in this study were compared and the hand drawn maps were selected for use due to their perceived realism and accuracy. More sophisticated computer mapping and analysis techniques to those used here may be available in other software applications and should be investigated in future studies.

Finally, this study has significantly increased understanding of the nature and spatial distribution of substrate types in relatively shallow areas of southern Georgian Bay. This distribution of substrate types can be used to better understand the many dynamic processes operating in these waters and may have application to the understanding of processes operating in other areas of the Great Lakes basins.

6.3 Future research

With the conclusion of this study a lake floor sediment distribution map and corresponding GIS database for Owen Sound and Colpoy's Bay will be shared with the Ministry of Natural Resources and may be used to plan future fish rehabilitation work in southern Georgian Bay. In particular, the sediment distribution map will be used to guide the location and placement of netting studies in Owen Sound and Colpoy's Bay during the upcoming spawning season. The substrate classification system developed in this study will also be used in future collaborative research between University of Toronto and the Ministry of Natural Resources in other areas of southern Georgian Bay.

The lake floor sediment distributions identified in this study indicate that a highly energetic and dynamic system exists in the study area. The maps produced here provide an image of substrate conditions at only one point in time. Sand sheets typical of substrate Zone 2 may migrate over time and cover areas that were initially identified as highly suitable whitefish and lake trout spawning areas (substrate Zone 3); alternately, coarse-grained sediments covered by sand may subsequently be exposed as a result of storm activity. Multiple side scan sonar and sub-bottom surveys conducted over several years might give a better insight into the actual sediment transport dynamics of the system and the long-term stability of suitable substrates for fish spawning.

Side scan sonar surveys being conducted in the area to the east of Owen Sound during the summer of 2005 have the same objective as this study: to create a substrate distribution map and make recommendations regarding potential fish spawning sites.

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APPENDIX 1:

Microsoft Excel spreadsheet displaying side scan sonar image number, Facies classification and color coding.

Image number		Major facies type	Minor facies type
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29-Jun	60	2	
29-Jun	61	2	
29-Jun	62	2	
29-Jun	63	2	4
29-Jun	64	2	4
29-Jun	65	4	
29-Jun	66	4	
29-Jun	67	4	
29-Jun	68	4	
29-Jun	69	4	2
29-Jun	70	3	2
29-Jun	71	3	2
29-Jun	72	3	2
29-Jun	73	3	2
29-Jun	74	3	2
29-Jun	75	3	2
29-Jun	76	2	7
29-Jun	77	7	2
29-Jun	78	2	3
29-Jun	79	2	
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29-Jun	81	2	
29-Jun	82	2	5
29-Jun	83	2	
29-Jun	84	2	
29-Jun	85	1	2
29-Jun	86	1	
29-Jun	87	1	
29-Jun	88	2	4
29-Jun	89	2	4
29-Jun	90	2	4
29-Jun	91	2	1
29-Jun	92	1	
29-Jun	93	1	
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29-Jun	95	1	
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29-Jun	97	1	
29-Jun	98	1	
29-Jun	99	1	
29-Jun	100	1	
29-Jun	101	1	
29-Jun	102	1	
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29-Jun	108	2	1
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29-Jun	110	1	
29-Jun	111	1	
29-Jun	112	1	
29-Jun	113	1	
29-Jun	114	1	
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29-Jun	116	1	
29-Jun	117	1	
29-Jun	118	1	
29-Jun	119	2	
29-Jun	120	2	
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29-Jun	122	1	
29-Jun	123	1	
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29-Jun	126	1	
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29-Jun	128	1	
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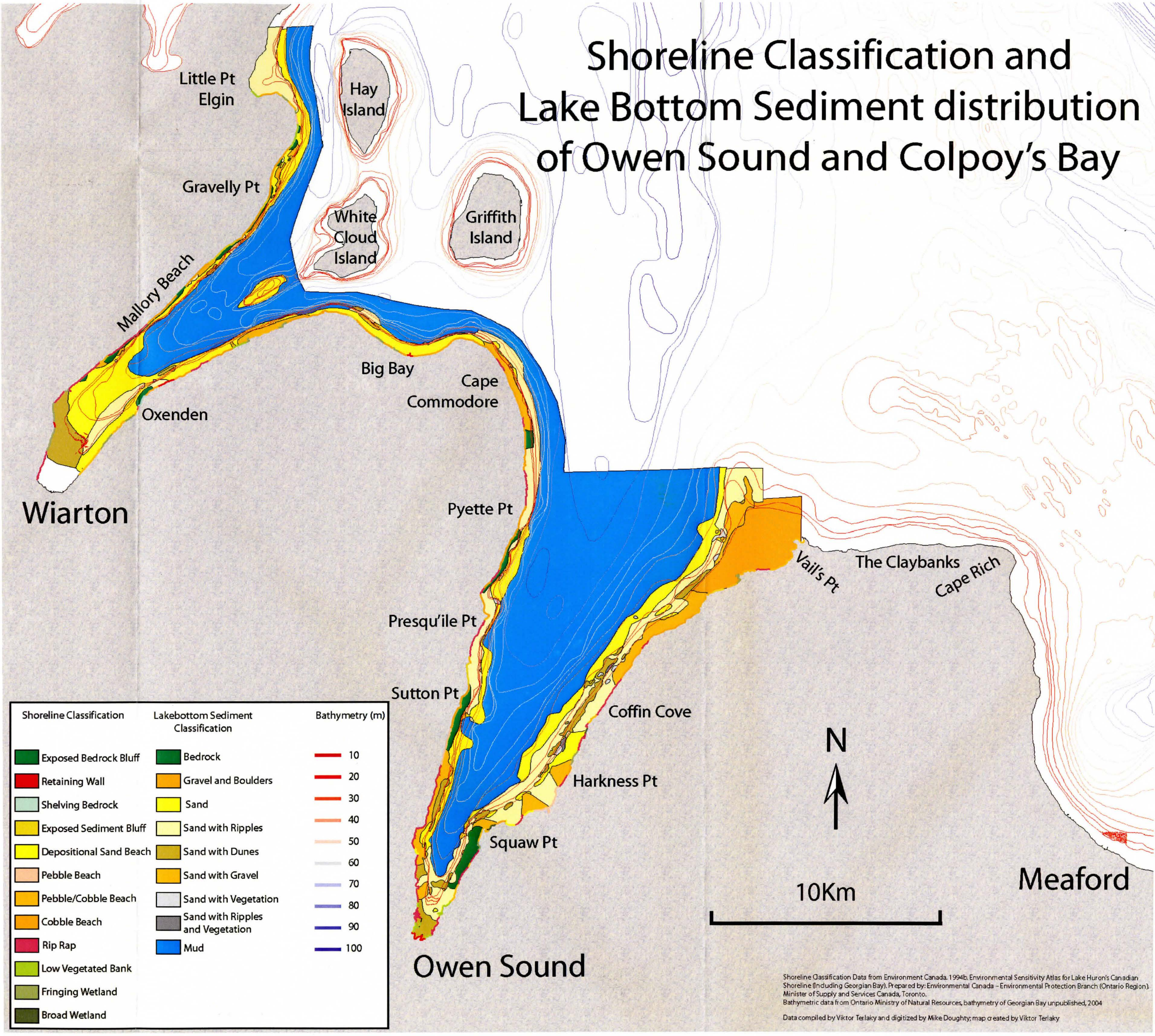
29-Jun	130	1	
29-Jun	131	1	
29-Jun	132	1	
29-Jun	133	1	
29-Jun	134	2	
29-Jun	135	2	
29-Jun	136	1	
29-Jun	137	1	
29-Jun	138	1	
29-Jun	139	1	
29-Jun	140	1	
29-Jun	141	1	


Shoreline Classification and
Lake Bottom Sediment distribution
of Owen Sound and Colpoy's Bay
Little Pt Elgin
Hay Island
Gravelly Pt
White Cloud Island
Griffith Island
Mallory Beach
Big Bay
Cape Commodore
Oxenden
Wiarton
Pyette Pt
Vail's Pt
The Claybanks
Cape Rich
Presqu'ile Pt
Sutton Pt
Coffin Cove
Harkness Pt
Squaw Pt
Meaford
Owen Sound
N
10Km
Shoreline Classification
Exposed Bedrock Bluff
Retaining Wall
Shelving Bedrock
Exposed Sediment Bluff
Depositional Sand Beach
Pebble Beach
Pebble/Cobble Beach
Cobble Beach
Rip Rap
Low Vegetated Bank
Fringing Wetland
Broad Wetland
Lakebottom Sediment Classification
Bedrock
Gravel and Boulders
Sand
Sand with Ripples
Sand with Dunes
Sand with Gravel
Sand with Vegetation
Sand with Ripples and Vegetation
Mud
Bathymetry (m)
10
20
30
40
50
60
70
80
90
100
Shoreline Classification Data from Environment Canada. 1994b. Environmental Sensitivity Atlas for Lake Huron's Canadian Shoreline (Including Georgian Bay). Prepared by: Environmental Canada – Environmental Protection Branch (Ontario Region). Minister of Supply and Services Canada, Toronto.
Bathymetric data from Ontario Ministry of Natural Resources, bathymetry of Georgian Bay unpublished, 2004
Data compiled by Viktor Terlaky and digitized by Mike Doughty; map created by Viktor Terlaky