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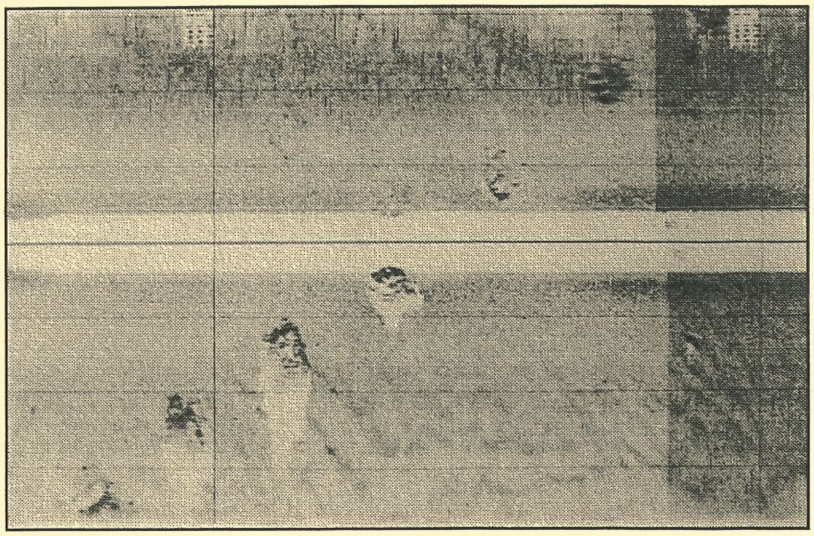
Demonstration Report No. 4F

Lake Champlain
Basin Program

Bottom Morphology and Boundary Currents of Southern Lake Champlain.



May 1995

Prepared by Hollistir Hodson

for Lake Champlain Management Conference

PUBLICATION SERIES

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This demonstration report is the fourth in a series of reports prepared under the Lake Champlain Basin Program. Those in print are listed below.

Lake Champlain Basin Program Demonstration Reports

1. Case Study of the Town of Champlain, Yellow Wood Associates, October 1993.

2. (A)Demonstration of Local Economic/Other Community Impacts, Community Case Studies for Economic Plan Elements. The City of Vergennes, Vermont. Economic and Financial Consulting Associates, Inc. October 1993.
(B)Demonstration of Local Economic/Other Community Impacts. Community Case Studies for Economic Plan Elements. Appendix. The City of Vergennes, Vermont. Economic and Financial Consulting Associates, Inc. October 1993.

3. The Archeology of the Farm Project. Improving Cultural Resource Protection on Agricultural Lands: A Vermont Example. Jack Rossen. May 1994.

4. (A)The 1992 Fort Ticonderoga-Mount Independence Submerged Cultural Resource Survey. Executive Summary. Arthur Cohn. May 1995.
(B)The 1992 Mount Independence Phase One Underwater Archaeological Survey. Kevin Crisman. May 1995.
(C)The Great Bridge "From Ticonderoga to Independant Point". Arthur Cohn. May 1995
(D)Geophysical Reconnaissance in the Mount Independence Area: Larrabee's Point to Chipman Point. Patricia Manley, Roger Flood, Todd Hannahs. May 1995.
(E)Ticonderoga's Floating Drawbridge; 1871-1920. Peter Barranco, Jr. May, 1995.
(F)Bottom Morphology and Boundary Currents of Southern Lake Champlain. May 1995. Hollistir Hodson.

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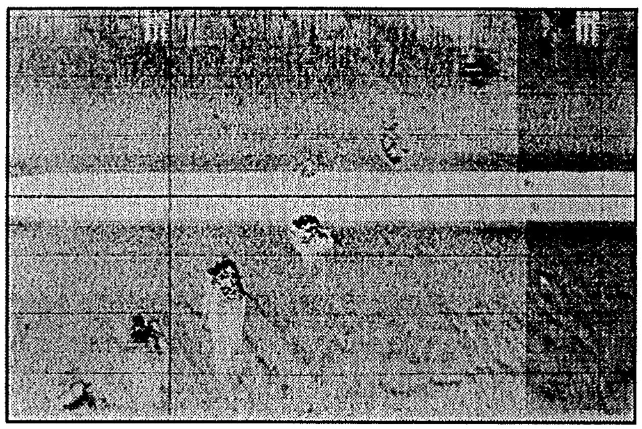
Bottom Morphology and Boundary Currents of Southern Lake Champlain.



Prepared by Hollistir Hodson

Hodson, Hollistir S., 1993, Bottom Morphology and Boundary Currents of Southern Lake Champlain: Larabee's Point to Chipman Point: Unpublished senior thesis, Department of Geology, Middlebury College, Middlebury, VT 05753

ABSTRACT

In May 1992 Lake Champlain Maritime Museum and Middlebury College imaged a six square kilometer section of southern Lake Champlain with a high resolution, dual frequency side-scan sonar system. These side-scan sonar profiles were used to identify the sediment bedforms and submerged cultural artifacts present south of Larabee's Point to Chipman Point. Several bottom morphologies including sediment waves, lineations, sediment furrows, and linear groups of pockmarks were recorded and mapped.

Most of the sediment waves are found in conjunction with the cultural artifacts beneath Lake Champlain's surface that disturb the bottom current, creating sediment waves. These waves are classified into two distinct groups by their size, orientation, and asymmetry. The height of the waves ranged from several centimeters to 0.5 meters, and the wavelength varied from 1 to 12 meters. The two groups had orientations of 65^{o} and 175^{o}. Around the inside bends of the lake surrounding Buoys 37 and 38, fields of sediment furrows have developed . They are approximately 15 to 50 cm deep, 2 meters wide, up to 600 meters long, and have an average spacing of 10 to 20 meters. Furrows are evidence of either a strong, stable bottom current in those regions or an strong, episodic current that erodes the bottom sediment. The pockmarks are located along a linear trend on the eastern slope of the lake, north of Mt. Independence. This northeast trend could be related to a subsurface fault that facilitates the upwelling of biogenic gas or groundwater into the lake.

From the orientations of the sediment bedforms, the direction of the bottom currents in the study area were documented. The bottom current in this southern section of Lake Champlain behaves much like a river, flowing to the north, following the local bathymetry and topography. However, both sediment waves and furrows suggest possible bi-directional currents, as well as episodic events that are characterized by an increase in current speed. The cause of these stronger, bi-directional currents is unknown, but we are speculating that it is either related to the seiche, or the dynamics of the water where it flows around a bend in the lake, or a combination of the two processes.

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Many thanks to Pat Manley for all the time you spent listening, looking through the side-scan rolls, and last-minute advising.

Dan, thank you for all the hours when you put down your own thesis work to walk me through G.I.S. (before I took the class). And thanks to Bob Churchill, for the time you spent helping me with all those little problems and programs that I did not quite understand and kept on changing.

To the rest of the geology department, Tom, Lucy, and Ray, this has been a great learning experience and a great four years, thanks. Good Luck to Dan, Steve, Brian, and Becky wherever you go, and whatever you do. I appreciate all the time and help you have given me this year.

Also thanks to my parents who not only made it possible for me to study geology, but who supported me and all my work throughout my Middlebury career. Thanks, I've enjoyed it.

Finally, special thanks to Patrick who always had a minute to come visit and helped me enjoy my senior year outside of the Science Center.

This survey was directed by the Lake Champlain Maritime Museum as part of the Maritime Cultural Resources Survey and Management Project. It was sponsored by the Lake Champlain Basin Program and executed in cooperation with Middlebury College, the Institute of Nautical Engineering at Texan A & M University, the Fort Ticonderoga Museum and the Vermont Division for Historic Preservation.

TABLE OF CONTENTS

INTRODUCTION 1

BACKGROUND 2

METHODS 8

OBSERVATIONS 12

DISCUSSION 29
Sediment Waves 32
Lineations 34
Sediment Furrows 35
Pockmarks 43

CONCLUSIONS 43

FUTURE STUDIES 47

REFERENCES 49

LIST OF FIGURES

FIGURE PAGE

1. Lake Champlain Drainage Basin 3
2. South Lake Basin of Lake Champlain 4
3. Helical Circulation and Furrow Generation 5
4. Map of Survey Area 10
5. Bathymetry of Survey Area 11
6. May 19, 1992: Ship Track 13
7. May 20, 1992: Ship Track 14
8. May 21, 1992: Ship Track 15
9. Photograph of 1872 Railroad Trestle 16

10a. Side-Scan Sonar Record of Railroad Drawboat 17

10b. Side-Scan Sonar Record of Section of Railroad Drawboat....................17

11. Side-Scan Sonar Recordof 19th Century Canal Boat 18
12. Side-Scan Sonar Recordof Revolutionary War Caissons 19
13. Side-Scan Sonar Record of Curving Sediment Waves 21
14. Side-Scan Sonar Record of Irregular Sediment Waves....................22
15. Side-Scan Sonar Record of Caissons and Sediment Waves 23
16. Side-Scan Sonar Record of Caissons and Sediment Waves 23
17. Side-Scan Sonar Record of Two Groups of Sediment Waves 25
18. Side-Scan Sonar Record of Canal Boat and Sediment Waves 26
19. Side-Scan Sonar Record of Lineations 27
20. Side-Scan Sonar Record of Furrows 28
21. Side-Scan Sonar Record of Pockmarks 30
22. Side-Scan Sonar Record of a Slump along the Shore 31

23a. Side-Scan Sonar Record of Furrows, Ferry Cable, and Buoy 37 36

23b. Side-Scan Sonar Record of Furrows and Ferry Cable around Buoy 37..37

24. Side-Scan Sonar Record of Furrows and Buoy 38 38
25. Side-Scan Sonar Record of Furrows and Sediment Waves 39
26. Side-Scan Sonar Record of Tuning Fork 39
27. Side-Scan Sonar Record of Northeast Trending Pockmarks 44
28. North- northeast trending faults in the Champlain Valley 45

LIST OF PLATES

Plate A. Location of Cultural Artifacts in the Study Area
Plate B. Location and Orientation of Sediment Waves in the Study Area
Plate C. Location and Orientation of Lineations and Furrows in the Study Area
Plate D. Location and Linear Trend of Pockmarks in the Study Area
Plate E. Direction of Boundary Current Flow mapped from the Sediment Bedforms

INTRODUCTION

Sediment bedforms are generated at the sediment water interface by the interaction of bottom water flow and bottom topography. Thus they can be found in rivers, lakes and oceans. The dynamics of these sediment bedforms have been widely researched (Allen, 1985) such that it is possible to determine the direction and to some extent the magnitude of the bottom currents that formed them.

In May of 1992, a two week survey was conducted by the Lake Champlain Maritime Museum and Middlebury College. A dual-frequency side-scan sonar was utilized to map the bottom morphology of southern Lake Champlain from Larabee's Point ferry crossing down to Chipman Point. This side-scan survey was designed to locate any cultural artifacts as well as to document the sediment bedforms present within this section of Lake Champlain. These submerged cultural artifacts are an obstruction to the bottom water flow and can generate sedimentary bedforms on the lake floor. Also the erosion and deposition process creating sediment bedforms might have an effect on the management and preservation of submerged cultural resources in Lake Champlain. In order to determine the occurrence or effects of either of these processes, we utilized side-scan sonar profiles to identify all sediment bedforms, their orientation, and location. From the analysis of these sediment bedforms, we were then able to map the average bottom water flow direction in this study region, speculate on the nature of the sediment bedforms' formation and assess the effects of erosion and deposition on the observed cultural artifacts.

BACKGROUND

Lake Champlain is ranked the sixth largest natural freshwater lake in the United States after the five Great Lakes. It drains more than 8,000 square miles in portions of Vermont, New York and Quebec (Figure 1). At its widest point Lake Champlain reaches 12 miles across and 120 miles long (Watzin,1992). The present mean surface elevation is 92.5 feet above sea level (Hunt et al., 1972). Lake Champlain is commonly divided into five geologically distinct basins to study their individual physical processes. The area studied in the 1992 survey, extending from Larabee's Point ferry crossing south to Chipman Point, is a section of the South Lake basin (Figure 2). South Lake extends from the mouth of the Poultney River north to Crown Point. This basin is generally narrow and shallow, and most places it is less than one mile across and less than fifty feet deep.

South Lake's physical processes are much like a river. The retention time of water in the South Lake is only 0.12 years (Myer and Gruendling, 1979). This rate is significantly shorter than the retention time in the Main Lake which ranges from 2.5 to 3.0 years. They also calculated a refilling rate of 40.8 cubic m/s in South Lake basin which implies a mean flow speed of 1.34 cm/s to the North if the water enters at the southern end of the basin (Myer and Gruendling, 1979).

The main flow in Lake Champlain is to the north, but the regional current patterns in Lake Champlain vary considerably from both day to day and from season to season depending on the lake stratification, wind conditions, and the internal seiche. The South Lake is too shallow to be affected by lake stratification, hence it remains well mixed throughout the

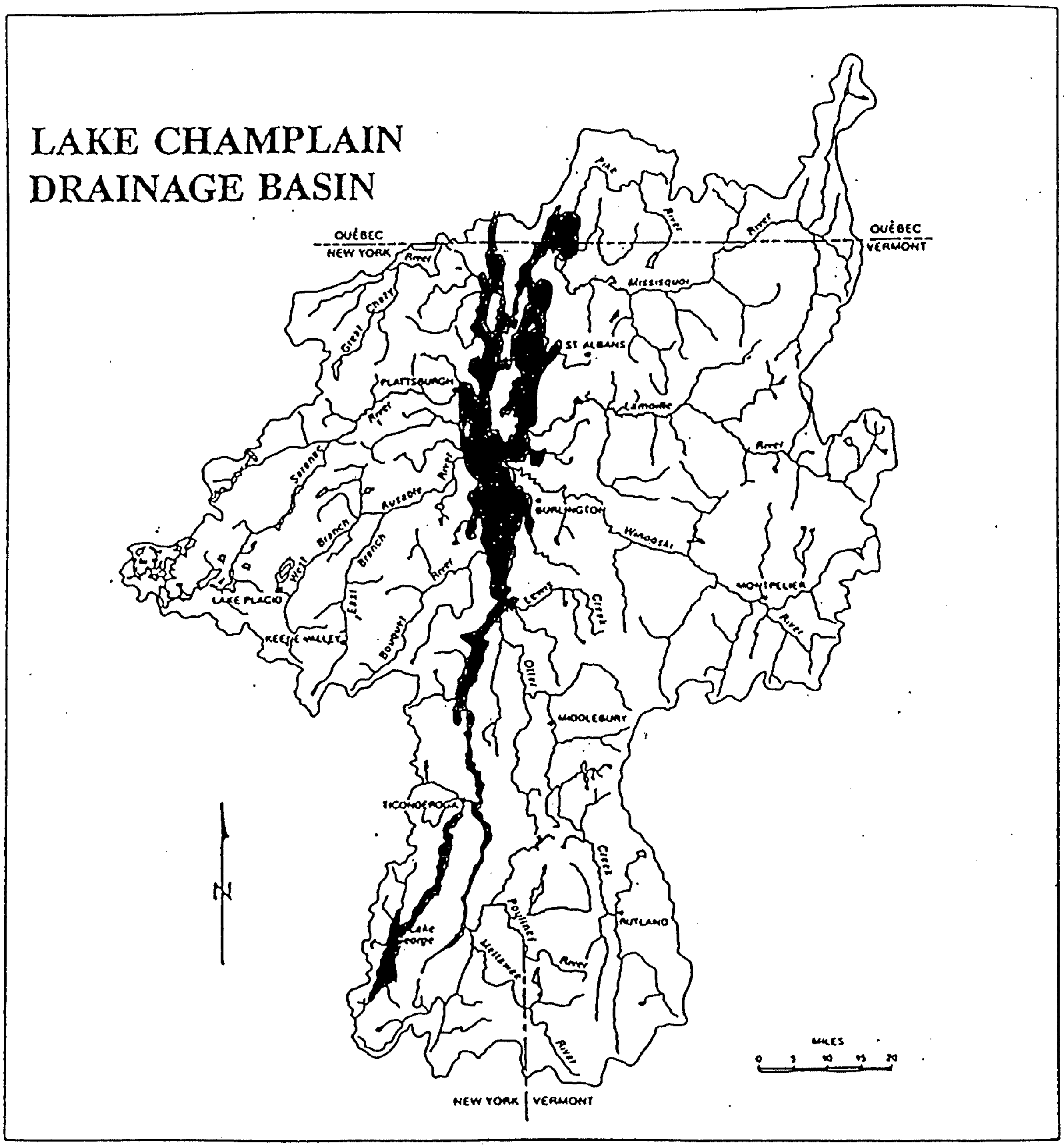

Figure 1: Lake Champlain Drainage Basin, including portions of New York, Vermont, and the Canadian Province of Quebec (after Myer and Gruendling, 1979).

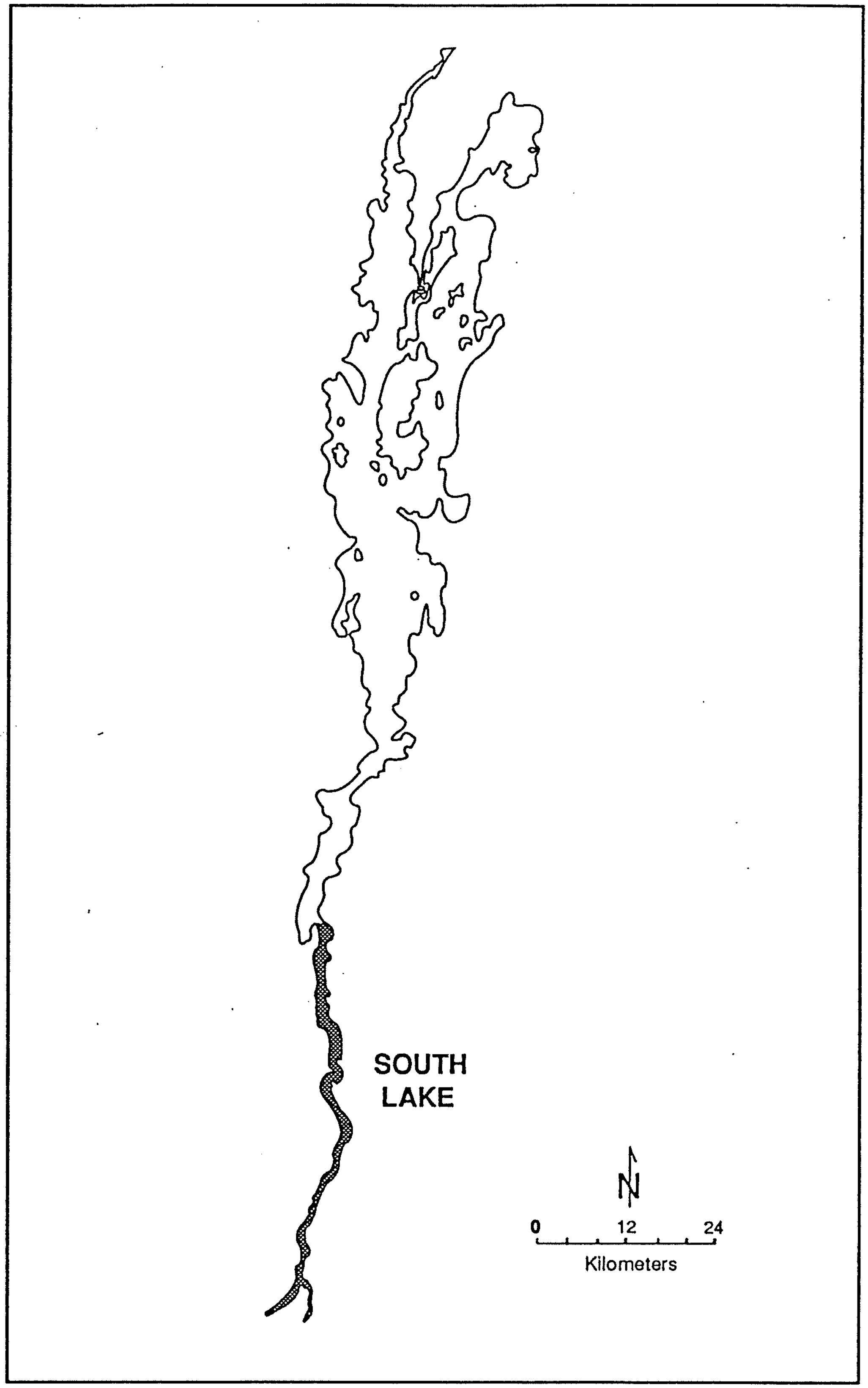

Figure 2: South Lake basin of Lake Champlain extends from the mouth of the Poultney River north to Crown Point. This basin is characteristically shallow and narrow, like a river.

year. The dominant wind direction is from the south and southwest (Watzin, 1992), but less frequent, stronger winds come from the north.

The South Lake in the study region is also oriented north-south. As winds actively move the surface waters from one end of the lake to the other, a piling up of the warm surface water occurs at one end. The pressure of this extra water tilts the thermocline down and as a result, the colder bottom water moves in the opposite direction of the surface currents. When the winds stop, the water moves back to its initial state. This back and forth movement is called a seiche. The period of the seiche is around 4 to 5 days and can create a considerable current, both to the north and to the south (T. Manley, 1993). Cold, fresh water lenses from the Main Lake have been identified as far south as the International Paper Company (5,800 meters north of our study site)(Roger Binkard, personal communication).

Little work has been done on the hydrodynamics for the South Lake. We do know that in shallow regions, currents tend to respond to the local shoreline configuration and bottom topography (Watzin, 1992). It is also possible that the currents in this section of the lake may be dominated by river processes and flow north due to a baseline gradient. Whatever the circulation, boundary currents have formed several types of sedimentary bedforms including sand waves, lineations, and furrows.

Sedimentary bedforms are created when there is a change in the transport rate of sediment carried in the bottom current (Allen, 1985). This change is normally caused by bathymetric irregularities already present on the lake floor or, as seen in this survey, submerged cultural artifacts. By varying the speed or the type of the sediment carried by the primary or secondary current, different types of sedimentary features are formed.

Sand waves are formed by erosion and deposition of sediment by currents that flow transverse to their wave crests (Allen, 1985). Sand is eroded from the upstream side of the wave by the disturbed boundary current and deposited on the downstream edge. The waves' symmetry can indicate the direction of the current that forms them. Symmetric sand waves are generally thought to be formed by bidirectional currents whereas asymmetric currents are formed by unidirectional currents flowing up the shallower slope of the wave.

Both lineations and sediment furrows are formed by currents whose flow is parallel to their axes. Currents sweeping over the lake bottom will align easily transported material into strips forming lineations. Furrows are believed to be formed by secondary circulation patterns (Flood, 1983). These helical cells, formed at a minimum current speed of 6 cm/s, create convergent and divergent boundaries between them (Figure 3). Along the convergent boundary coarser grains collect in linear piles on top of the fine-grained sediment. These sand ribbons are then swept by the boundary currents and erode the finer cohesive sediment of the lake bottom producing a trough-like structure. Once formed, the helical circulation cells and the furrows act to sustain each others existence.

Pockmarks, a fourth sediment bedform found in South Lake basin, are not formed by bottom currents but are circular depressions where it is thought that gases or groundwater may be seeping into the lake. These can be found in fields of hundreds or as just a scattered few. Also the center of the pockmarks usually has a high concentration of sand due to the winnowing away of the fines by the upwelling of gases or water (Pederson, 1992).

Historically, the Lake Champlain region has been occupied for nearly 12,000 years which has resulted in rich cultural resources both on the

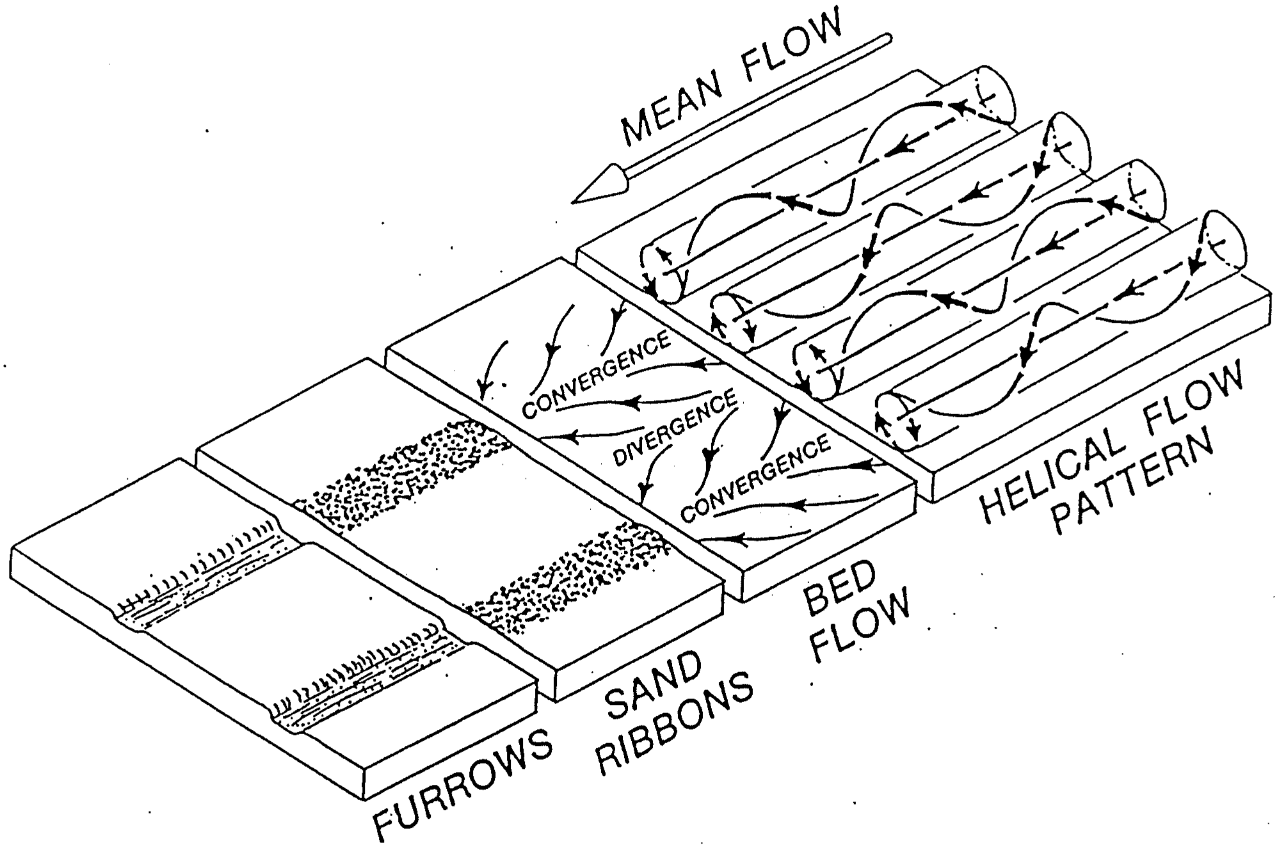

Figure 3: Furrows are formed parallel to the mean flow direction. Helical, secondary-flow cells create convergent bed flow patterns that align the easily transported, coarse sediment into sand ribbons. The furrow trough is then scoured out of the cohesive mud by the coarse sediments pushed by the current. (Flood, 1983).

shore and submerged in the lake's waters (Watzin, 1992). The basin holds artifacts from early Iroquois and Mohawk Indian settlements, European exploration and settlement in the early 1600's, the French and Indian War, the American Revolutionary War, the War of 1812, and from its role in the 19th century as a major transportation corridor under French colonial rule (Hill, 1976 and Watzin, 1992). In the South Lake section cultural artifacts including vessels from the British/French fleets of 1758 and 1759, parts of the Revolutionary War "Great Bridge," and 19th century canal boats, railroad drawboats, and remains of an 1872 railroad trestle were all located in the survey area.

Despite its large size, limited studies have been completed on Lake Champlain. Renewed interest in the well-being of the whole lake as a result of population growth and industrialization sparked this survey, sponsored by the Lake Champlain Basin Program. The hopes of this survey were to locate and determine the state of being of the cultural artifacts within Lake Champlain's waters. The side-scan sonar survey identifying the location of cultural artifacts as well as areas with high erosion or deposition will aid in the development of a preservation and management program for the cultural artifacts. These results will also be of use to document the immediate and long-term changes occurring in the boundary currents and sediment bedforms of South Lake basin.

METHODS

All field data were collected during a ten day period in May 1992, between Larabee's Point and Chipman Point in the South Lake of Lake Champlain (Figure 4). Two research vessels, Middlebury College's R/V *Baldwin* and the R/V *Neptune*, were used during this survey. Navigation on the R/V *Baldwin* was Loran C and Global Positioning System (GPS) which recorded latitude and longitude of the ship's location approximately every four seconds. Loran C was used on board the R/V *Neptune* and recorded the geographic position every 8 seconds. This information was recorded and transferred to ARC/INFO Geographical Information Systems at Middlebury College where the ships' navigation tracks were plotted.

A dual frequency (100 and 500 kHz) Klein Digital Sonar System 590 (side-scan sonar) was used to cover 6 km^2. The fish was towed approximately 5 to 10 meters behind the research vessel. The ship's speed was kept within 2 to 3.5 knots to maintain the fish's constant depth, 4 meters, above the lake floor. The depth of the lake was recorded every 2 seconds by a 200 kHz precision depth sounder; the average depth of the lake in the study area is 6.1 meters. The PDR data gathered on the R/V *Baldwin* was used to generate a three-dimensional model of the bathymetry of the entire survey area from Larabee's Point down to Chipman Point using Silicon Graphics' Interactive Surface and Volume Modelling program(Figure 5). In addition to the side-scan sonar and PDR, a proton precession magnetometer was towed behind the research vessel to locate any iron cultural artifacts or iron-rich sediments by identifying local magnetic anomalies.

One hundred transect lines, oriented predominantly north-south, imaged the study area. Some transect lines were repeated and some regions

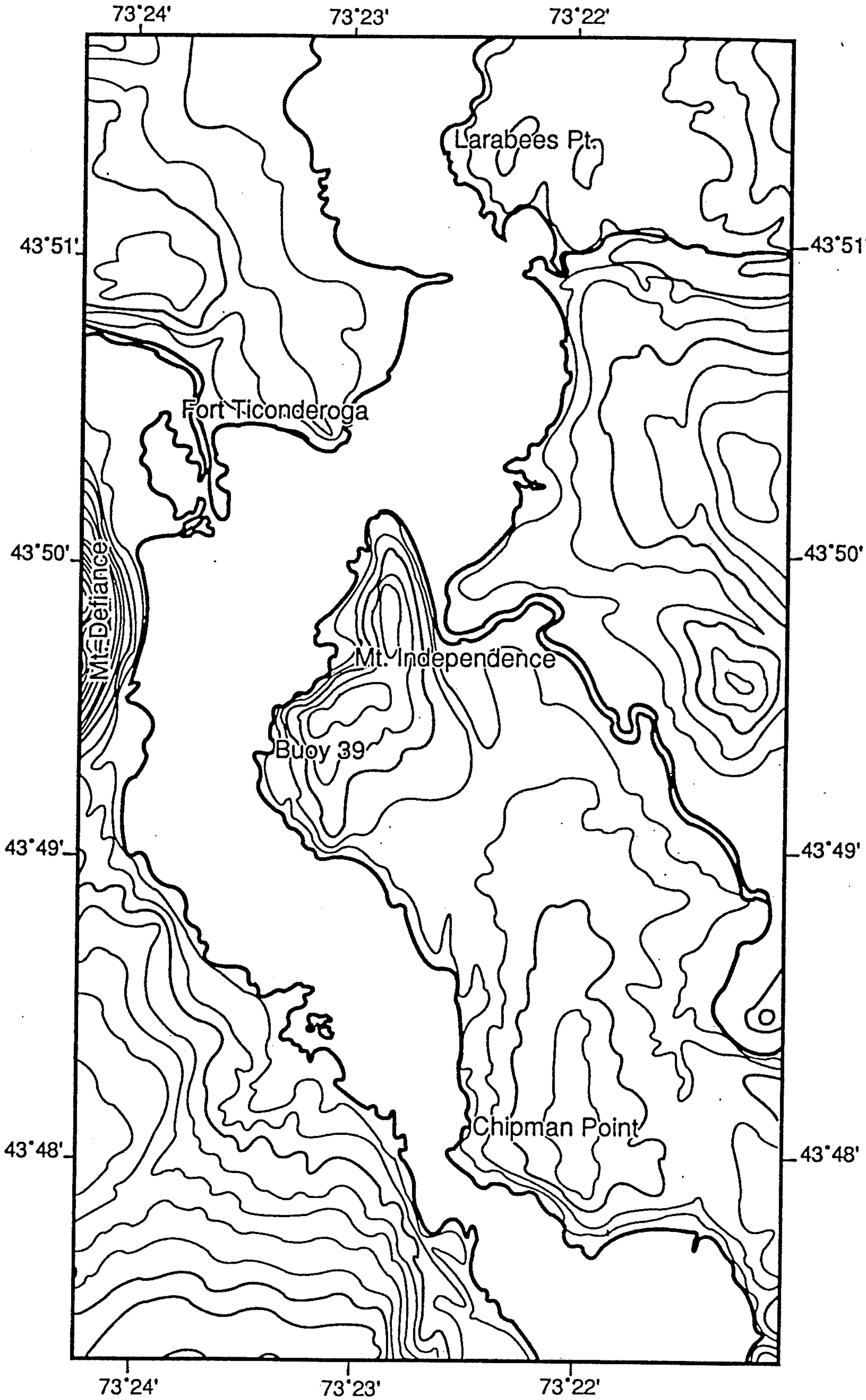

Figure 4: Survey area extended from Chipman Point to Larabee's Point. One hundred ship track lines, generally oriented north-south, covered this area from shore to shore in order to image as much of the region as possible.

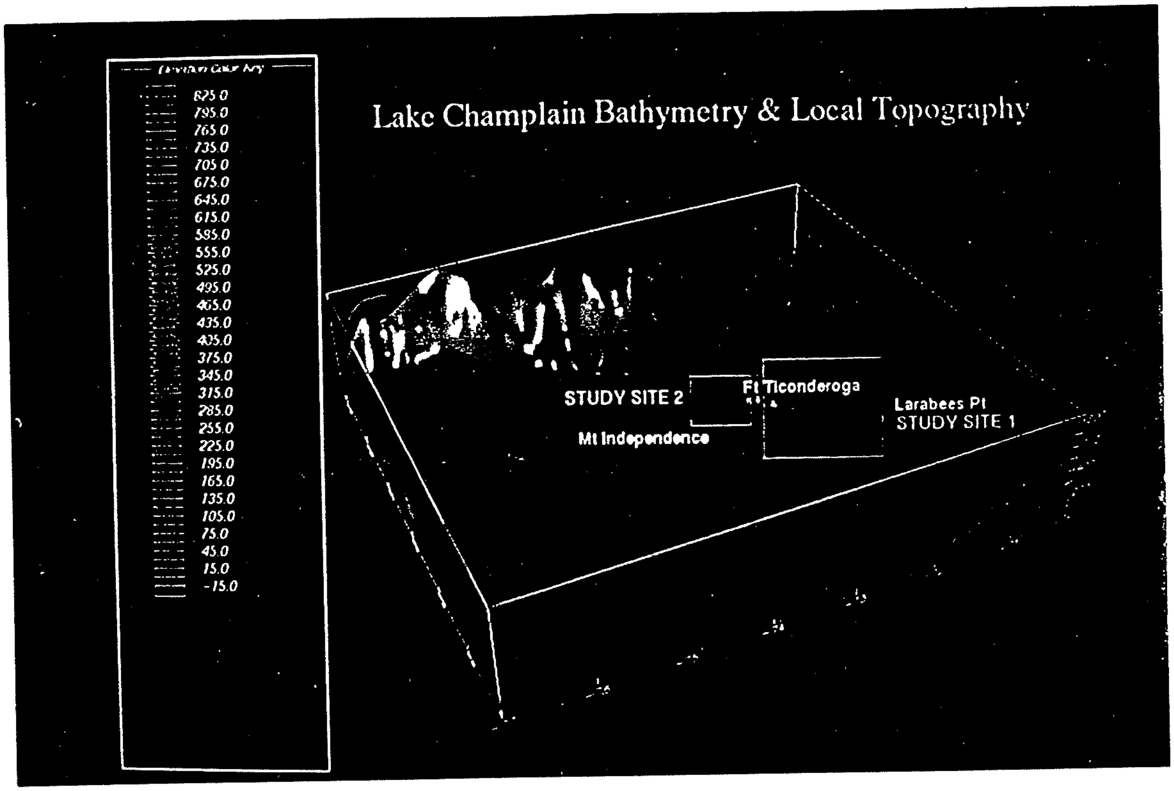

Figure 5: In the box diagram above north follows the closest long axis off to the right. The darkest blue represents depths greater than 15 feet which is the location of all of the sedimentary bedforms present in the study area.

were imaged several times by overlapping track lines. This allowed cultural artifacts and sediment bedforms to be imaged at different angles permitting better interpretation of the bottom morphology as well as navigation correction.

All of the cultural artifacts and sediment bedforms imaged by the side-scan sonar were plotted onto navigation maps. Control points such as Larabee's Point ferry cable and buoys were used to verify the location of these features. Slant range correction was not applied in this study due to the shallow water depth at which the fish was towed. This resulted in a negligible correction of 0.2 meters, well within the error limits of navigation. However, bottom features were corrected for layback which ranged between 5.2 and 8.5 meters.

The side-scan sonar profiles taken from Chipman Point north to Larabee's Point revealed that the sediment bed forms in this region of the lake are found primarily north of Buoy 39. The rest of the observations and interpretation will be limited to the section of the survey that extends from Buoy 39 north to Larabee's Point. This portion of the survey area was covered during the first three days of the survey, May 19, 20, 21. The track lines for these days are shown in Figures 6, 7, and 8.

OBSERVATIONS

Several nineteenth century cultural artifacts were found submerged in this section of the survey area. Debris from the 1872 floating railroad trestle that connected Ticonderoga Lighthouse peninsula across to the other side of the lake was found on the lake floor extending across that distance (Plate A, Figure 9). Midway between those two points a broken railroad drawboat

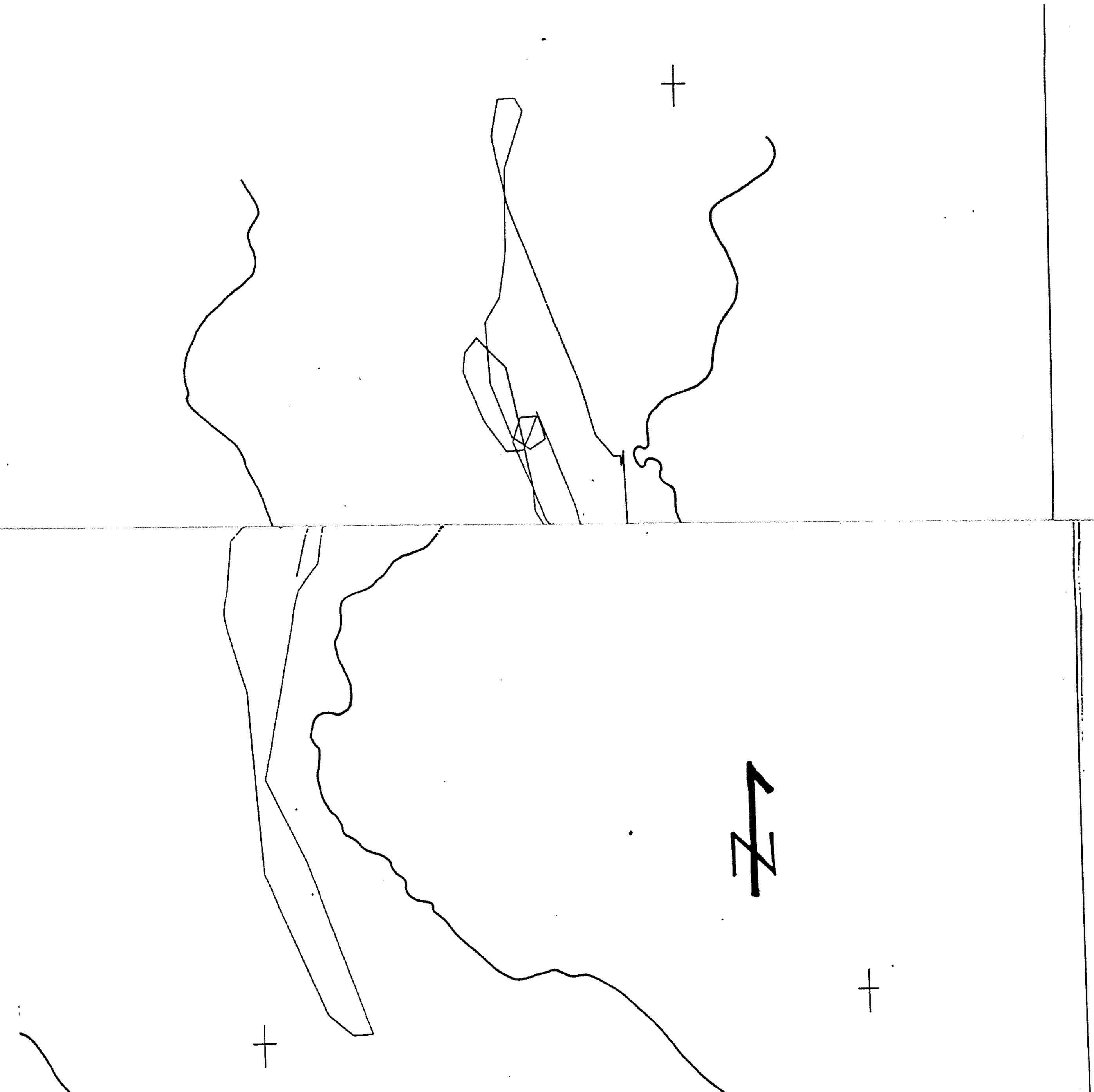

Figure 6: Ship track lines for May 19, 1992. Scale 1:40,000

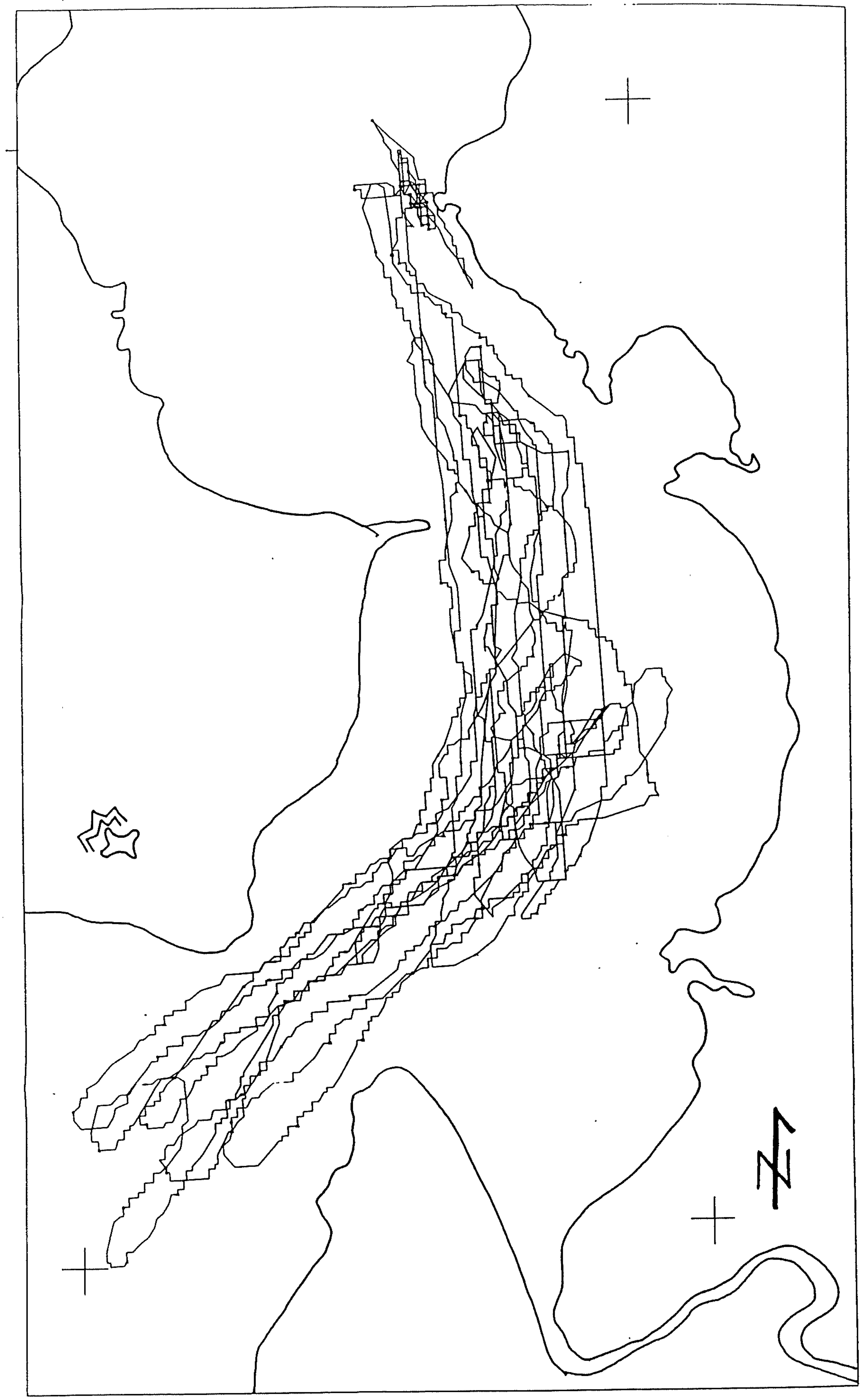

Figure 7: Ship track lines for May 20, 1992. Scale 1:40,000

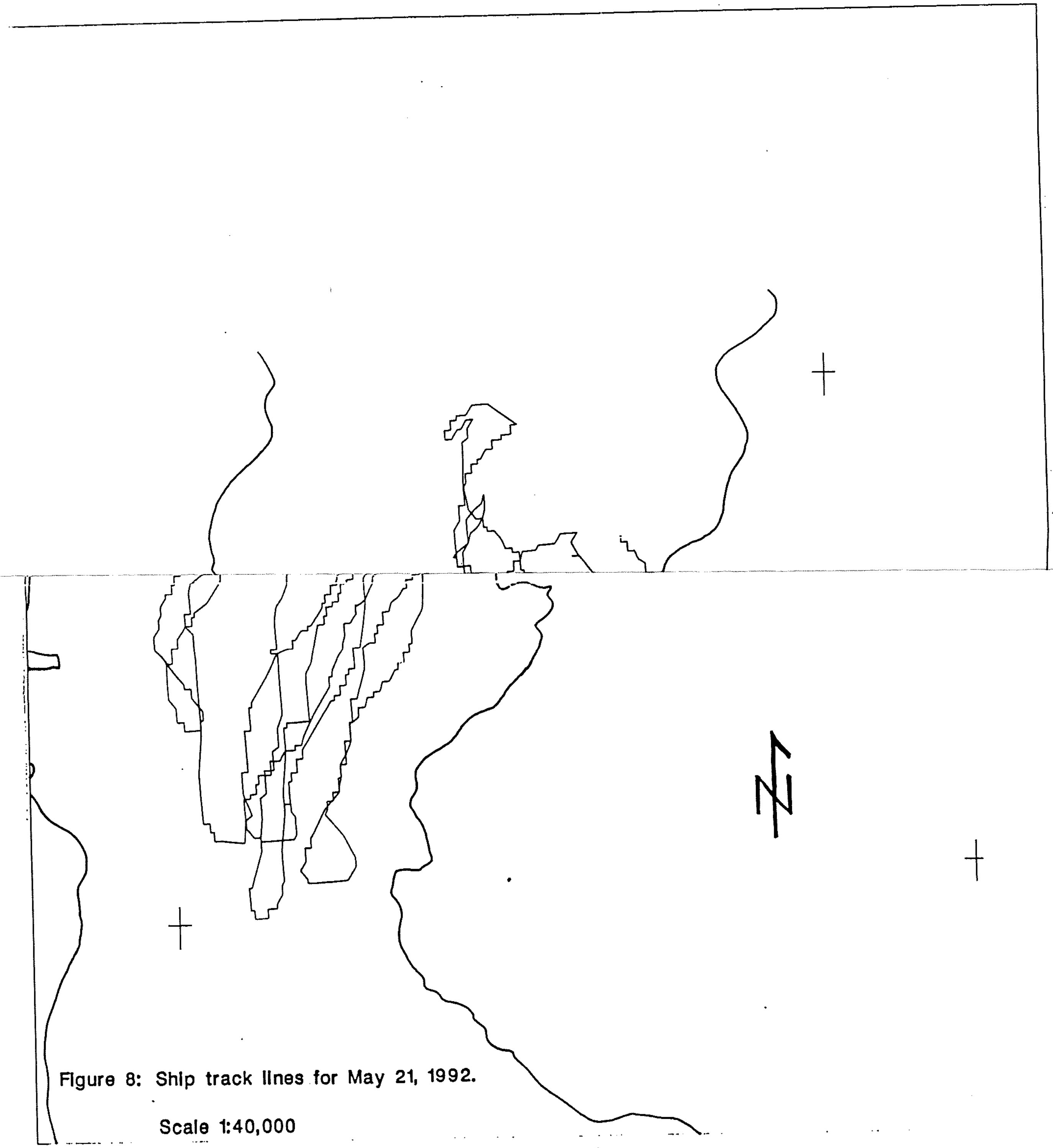

Figure 8: Ship track lines for May 21, 1992.

Scale 1:40,000

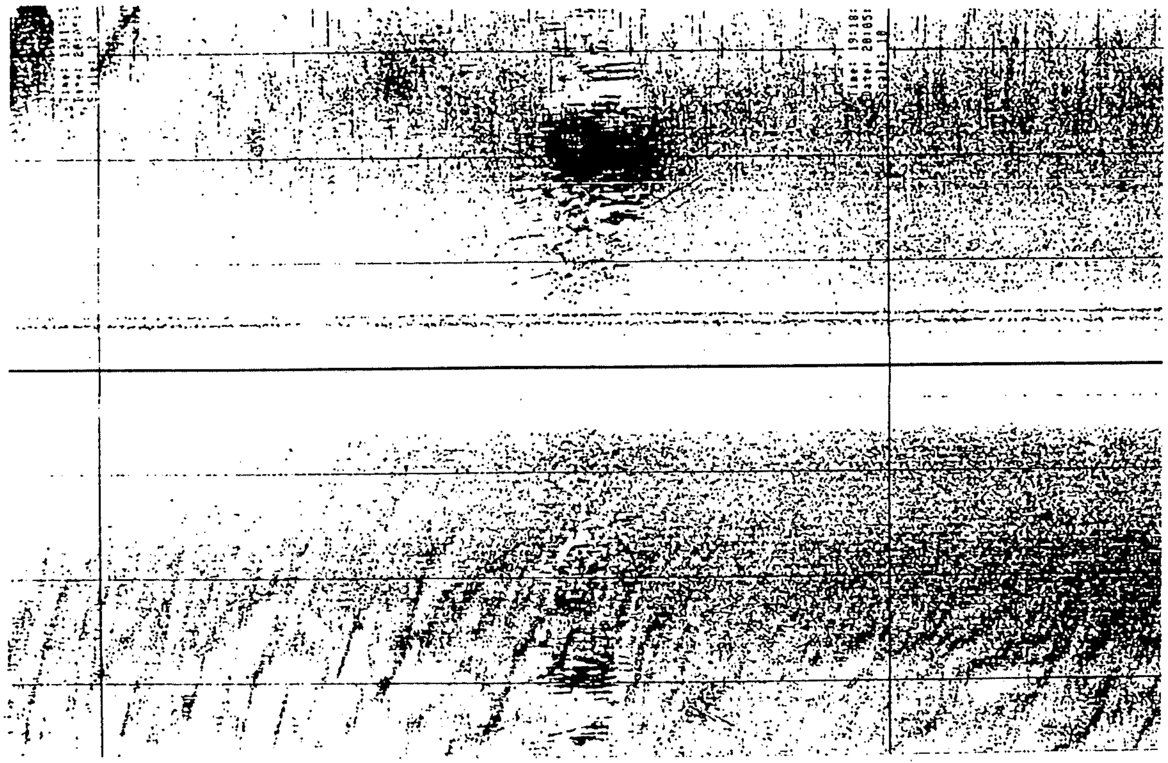

Figure 9: Side-scan sonar profile (500 kHz) of debris from 1872 floating railroad trestle. These artifacts are present from Ticonderoga Lt. across to the eastern shore of Lake Champlain. Fish is headed north (direction indicated is always to the left). (Horizontal scale: 1cm = 9.27 m).

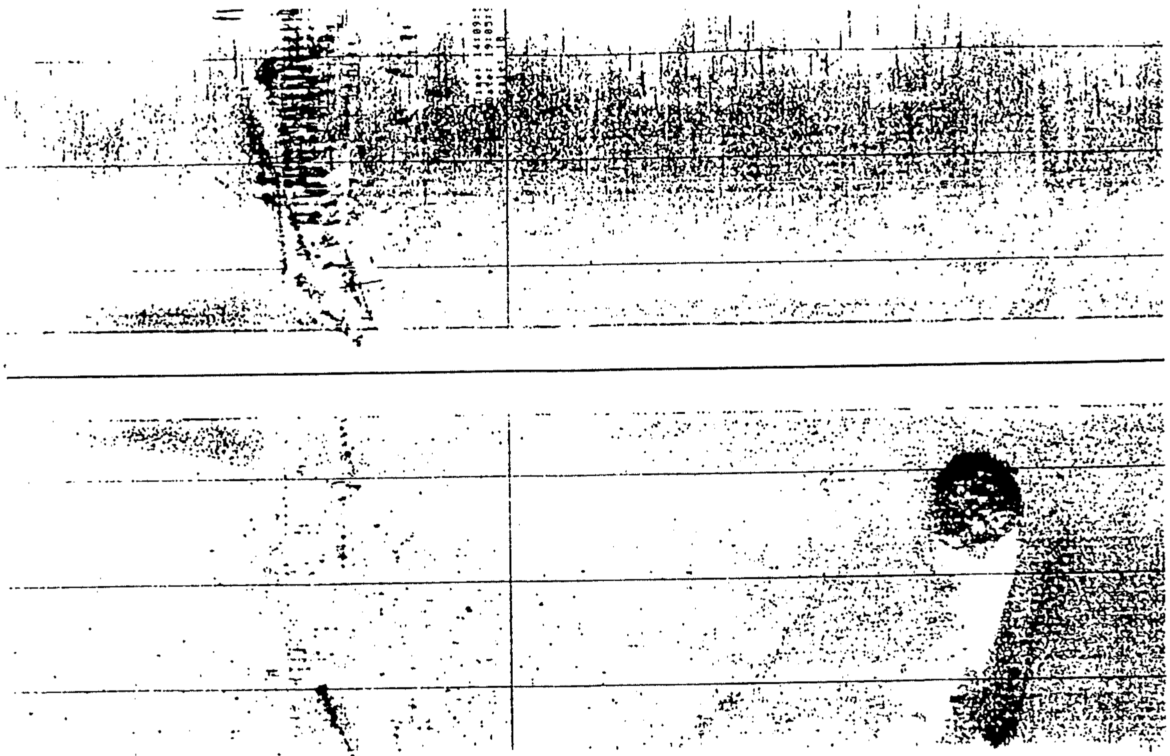

Figure 10a: Side-scan sonar profile (500 kHz) of submerged, broken railroad drawboat. Circular feature is an unknown mound of sediment. Fish is headed north. (Horizontal Scale: 1cm = 8.0 m).

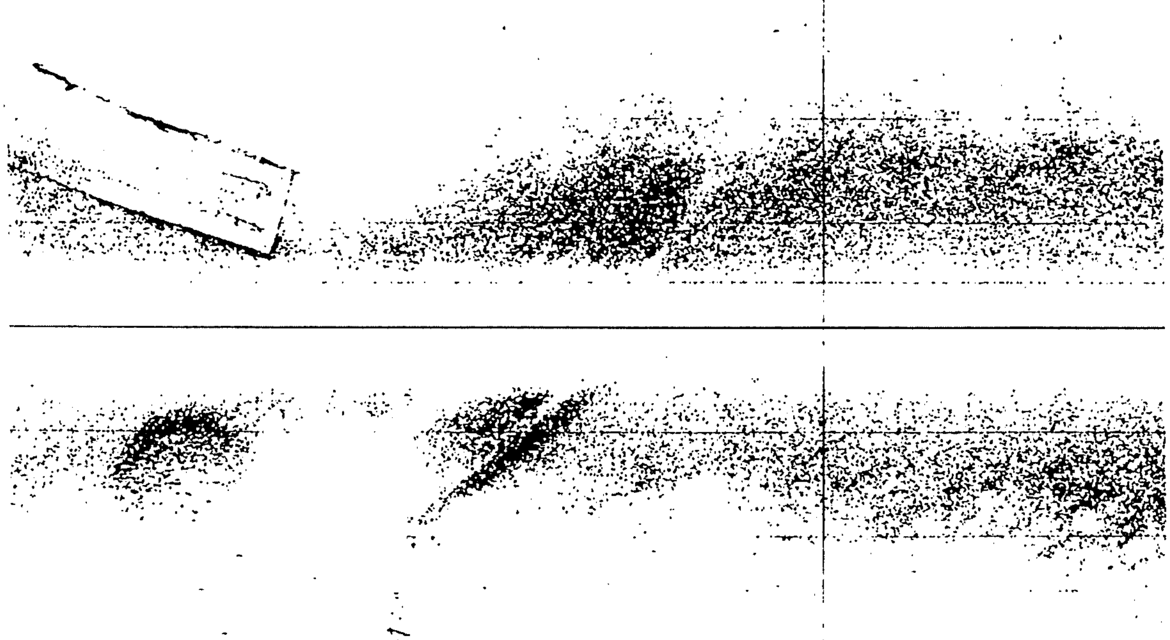

Figure 10b: Broken piece of the drawboat oriented southwest-northeast shown on side-scan sonar record (100 kHz). Fish is headed to the south. (Horizontal scale: 1cm = 9.27 m).

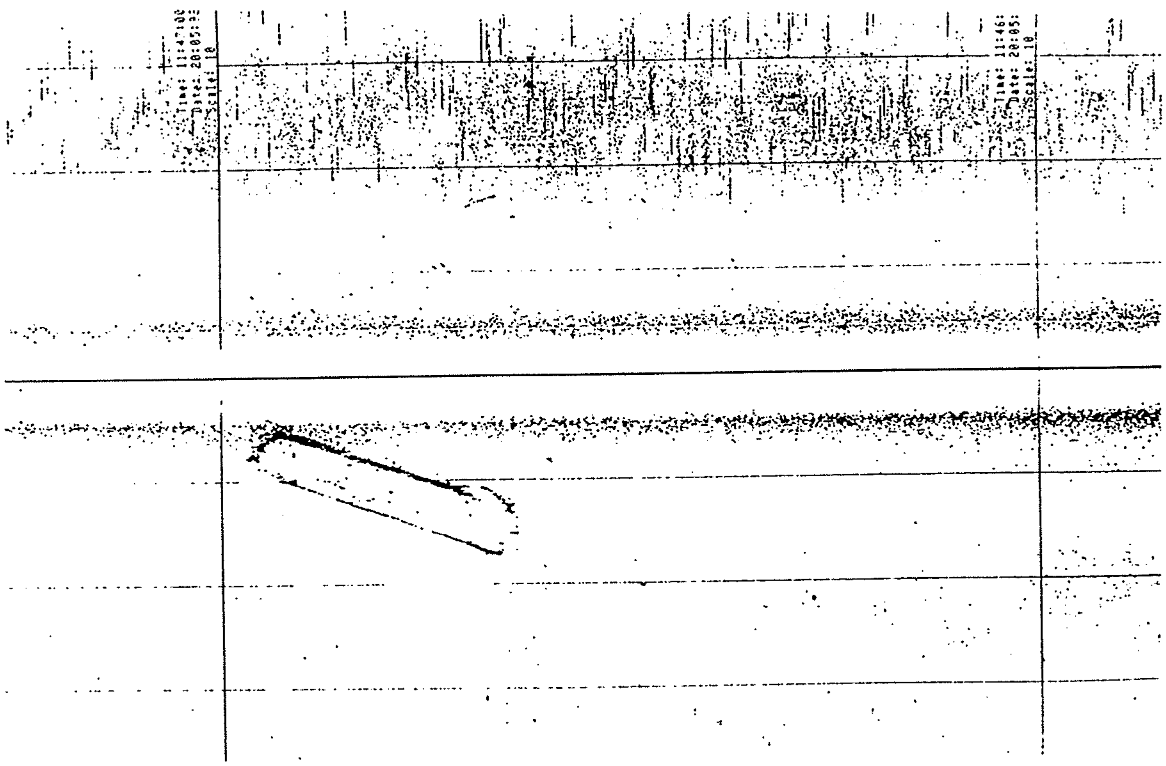

Figure 11: Side-scan sonar image (500 kHz) of a canal boat submerged north of Mt. Independence. Fish is headed to the south. (Horizontal scale: 1cm = 9.27).

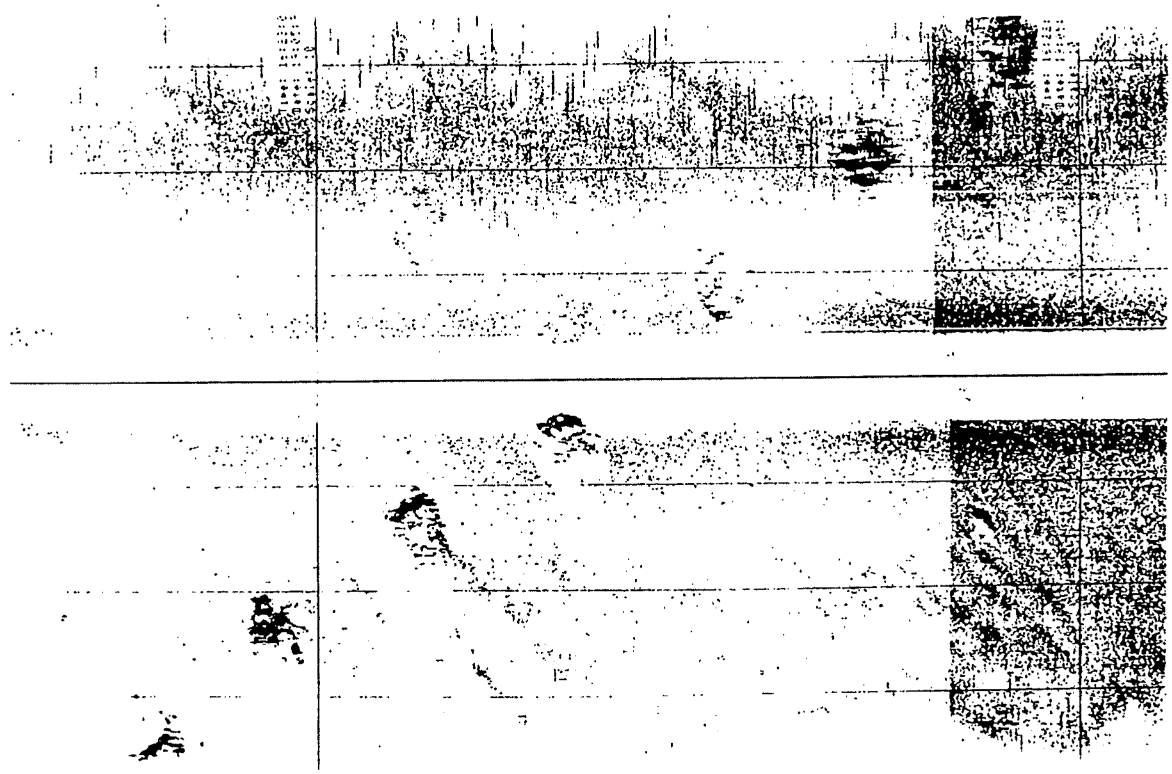

Figure 12: Revolutionary War "Great Bridge" caissons submerged in between Mt. Independence and Ft. Ticonderoga shown on the side-scan sonar profile (500 kHz). Fish was towed to the north. Note the sediment waves surrounding the caissons. (Horizontal scale: 1cm = 8.0m).

(Figures 10a and 10b) was located as well as another drawboat and two 19th century canal boats (Figure 11). Extending from Mt. Independence across to Fort Ticonderoga are the remnants of the Revolutionary War "Great Bridge" caissons (Figure 12). Caissons are wooden cribs filled with rocks that were used to anchor this floating bridge. Approximately 18 caissons were found reaching from the eastern slope of the lake to the west. Since cultural artifacts may cause flow perturbation we are interested in plotting their location with respect to the sediment bedforms.

Four different types of sediment bedforms were found within this study region: sediment waves; lineations, furrows, and pockmarks. Sediment waves are limited almost entirely to the region in between Buoys 38 and 39 (Plate B). They are also bounded to the east and west by the slopes of the shoreline, so that they are located within the deeper section of the lake. These features can be distinguished on the side-scan sonar profile by a repetition of a dark band followed by a light grey or white band. The heaviest concentration of sand waves is found surrounding the caissons around Mt. Independence and Fort Ticonderoga. These artifacts appear to act as a divider between two groups of sediment waves.

South of the caissons as well as in between them, sediment waves are oriented north-northwest to south-southeast, or perpendicular to the shoreline, and are asymmetric with the steep side facing north. All of the wave crests are straight with one obvious exception in the long field of waves just west of Mt. Independence (Figure 13). The southernmost of this first group of sediment waves are larger and more irregular (Figure 14), but as they get nearer the caissons, they are more regularly spaced and smaller scale (Figures 15 and 16). The sand waves in the south have a height that varies from 0.27 to 0.50 m, and a spacing of 6.5 to 12 meters. On the other hand those

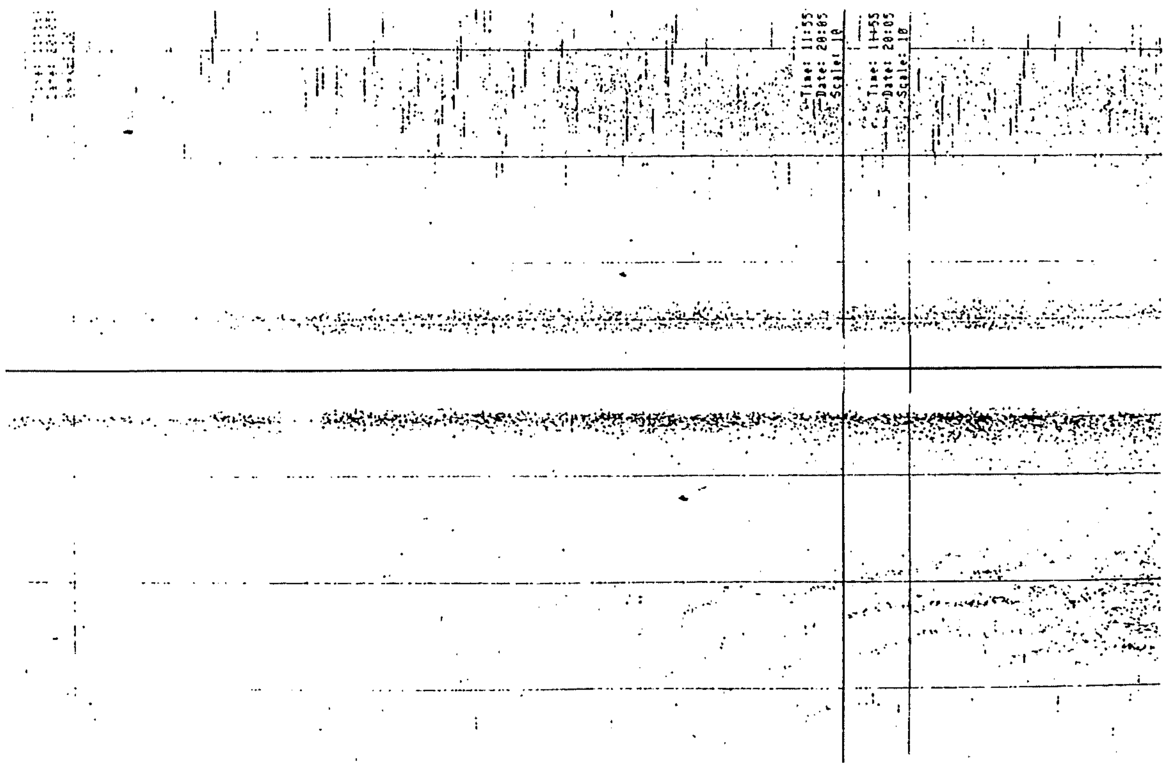

Figure 13: Just west of Mt. Independence, the crests of the sediment waves curve, but they are still perpendicular to the shoreline. In this side-scan sonar profile (500 kHz), the fish is headed to the south. (Horizontal scale: 1cm = 9.27 m).

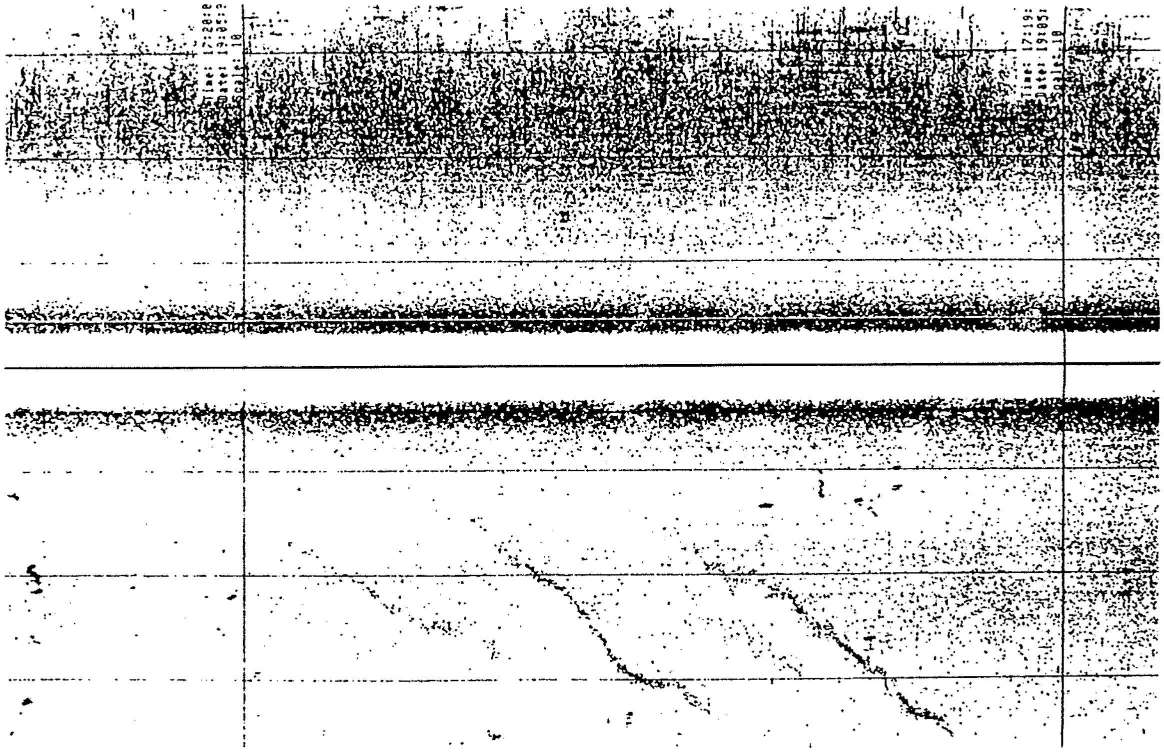

Figure 14: To the south, these sediment waves become more irregular and further spaced out as seen on the side-scan sonar image (500 kHz). Fish is headed to the north. (Horizontal scale: 1cm = 8.0m).

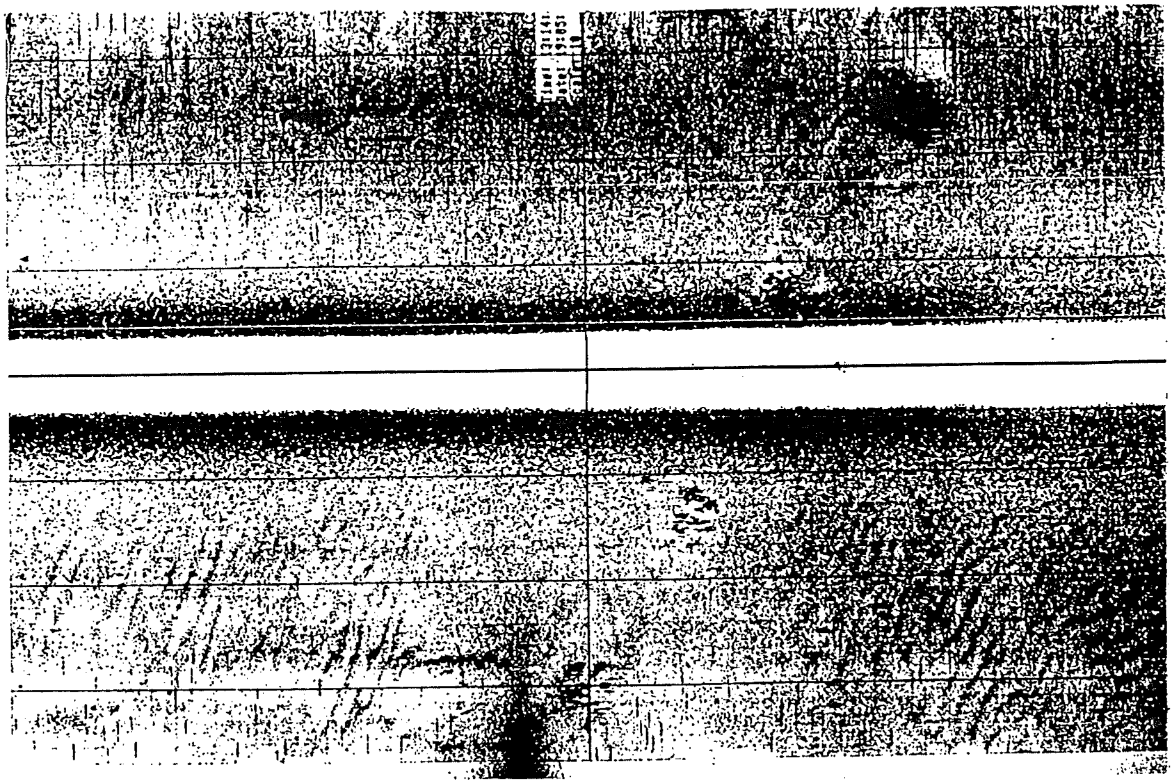

Figure 15: A side-scan sonar image (500 kHz) of small-scale, asymmetrical sediment waves surrounding the caissons with a northwest-southeast orientation. These waves are evenly spaced and parallel to the linear trend of the caissons. Fish headed north. (Horizontal scale: 1cm = 8.0 m).

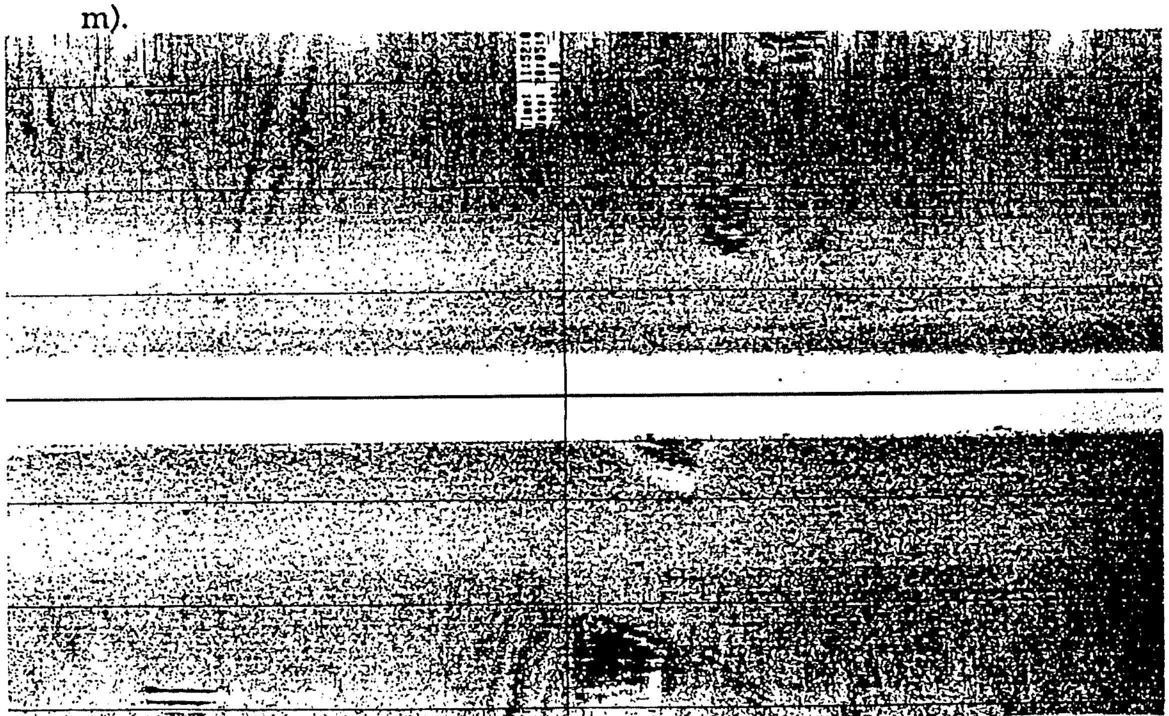

Figure 16: More sediment waves (500 kHz side-scan sonar profile) that are evenly spaced and parallel to the linear trend of the caissons with a longer wavelength than those above. Fish is headed to the south. (Horizontal scale: 1cm = 9.27 m).

waves that directly surround the caissons have an average height of around 0.1 m and spacing of 1.5 meters but the same orientation. North of the caissons these smaller scale bedforms are superimposed onto larger scale sand waves having an east-northeast to west-southwest trend with the steep side caissons is around 0.31 m, and the average wavelength is 10.7 meters. Sediment waves with a northeast orientation and dimensions similar to the larger waves south of the caissons are positioned around a canal boat northeast of the caissons (Plate A, Plate B, Figure 18). The scale of the sediment waves, the orientation, and asymmetry clearly separate these two groups of waves.

Lineations are the most abundant morphologic feature within the area of study. They are found on the side-scan sonar profiles between Buoy 39 up to Larabee's Point (Plate C). The side-scan record of a lineation appears as a faint linear feature with alternating dark and light trends (Figure 19). The lineations in this study section are oriented parallel to the shoreline configuration and confined to the deepest sections of the lake. Their lengths range from several tens of meters up to roughly 200 meters.

Two significant sediment furrow fields exist within the focus area; these are found around Buoy 37 and Buoy 38 (Plate C). Furrows return a side-scan image that has a distinct band of white followed by a dark band (Figure 20). Both fields are located in close proximity to the slope of the shoreline. The groups of furrows turn around the bend in the lake following the local bathymetry. The depth of the furrows in these two fields ranges from 0.14 m to 0.46 m. The width and spacing are 2 to 3.5 m and 10 to 20 meters respectively. This creates a width to spacing ratio of 1:5 to 1:10. The furrow length varies from 50 to around 600 meters, although the average length is around 450 meters. These parameters define the currents that formed this

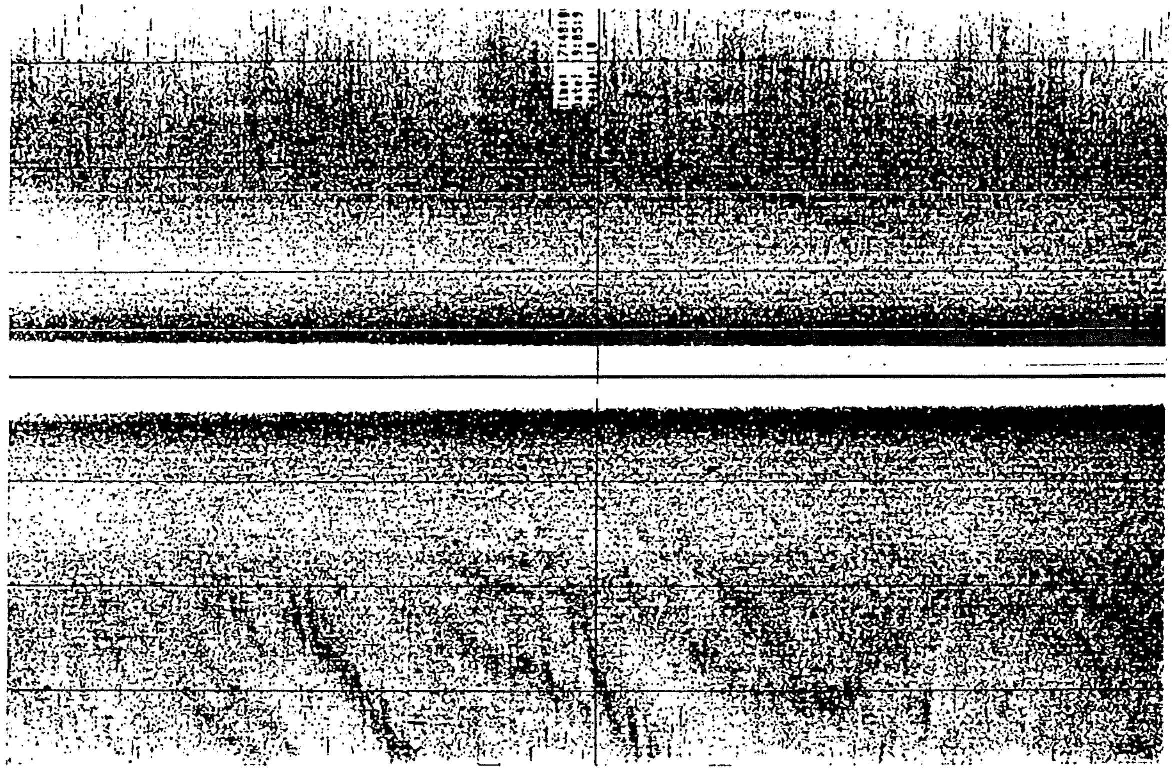

Figure 17: There are clearly two separate groups of sediment waves north of the caissons distinguished by their size, orientation and asymmetry as shown on this side-scan image (500 kHz). The smaller scale waves are shown at bottom right while the larger scale features are visible to lower left. The fish is headed to the north. (Horizontal scale: 1cm = 8.0 m).

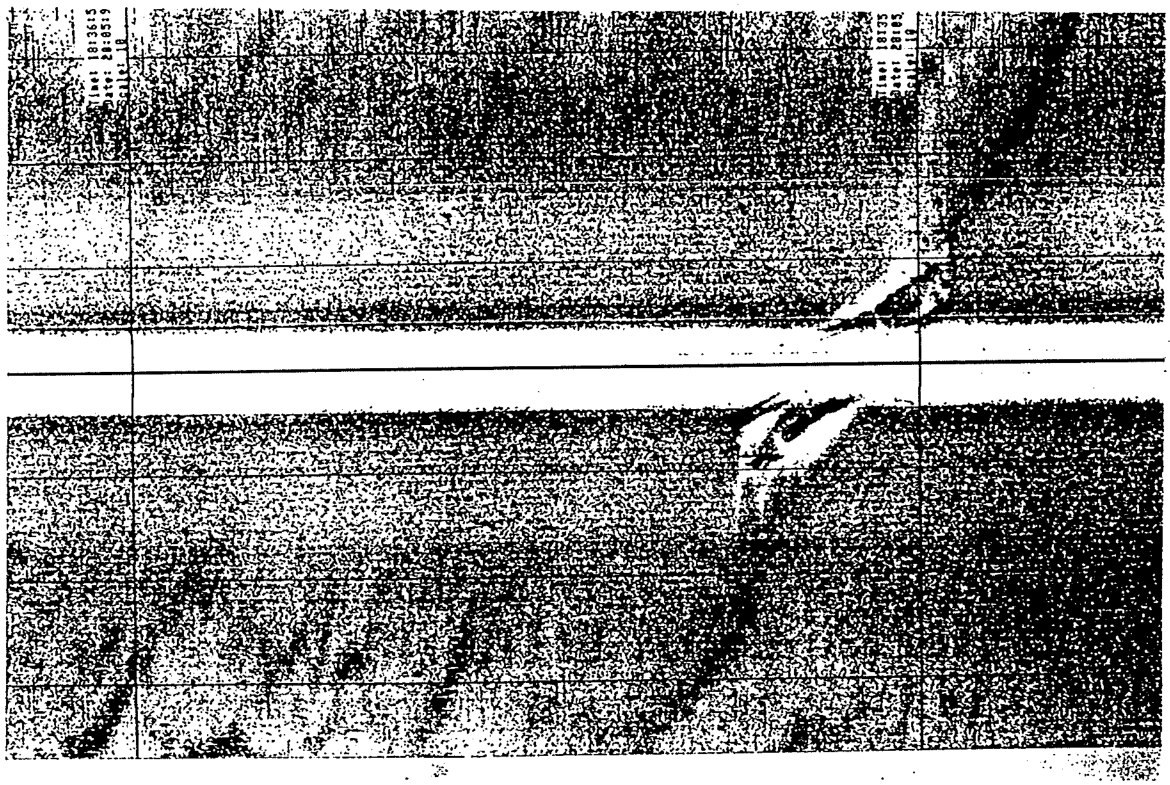

Figure 18: Side-scan sonar profile (500 kHz) of the canal boat northeast of the caissons surrounded by sediment waves to the north. The fish is headed north. (Horizontal scale: 1cm = 9.27 m).

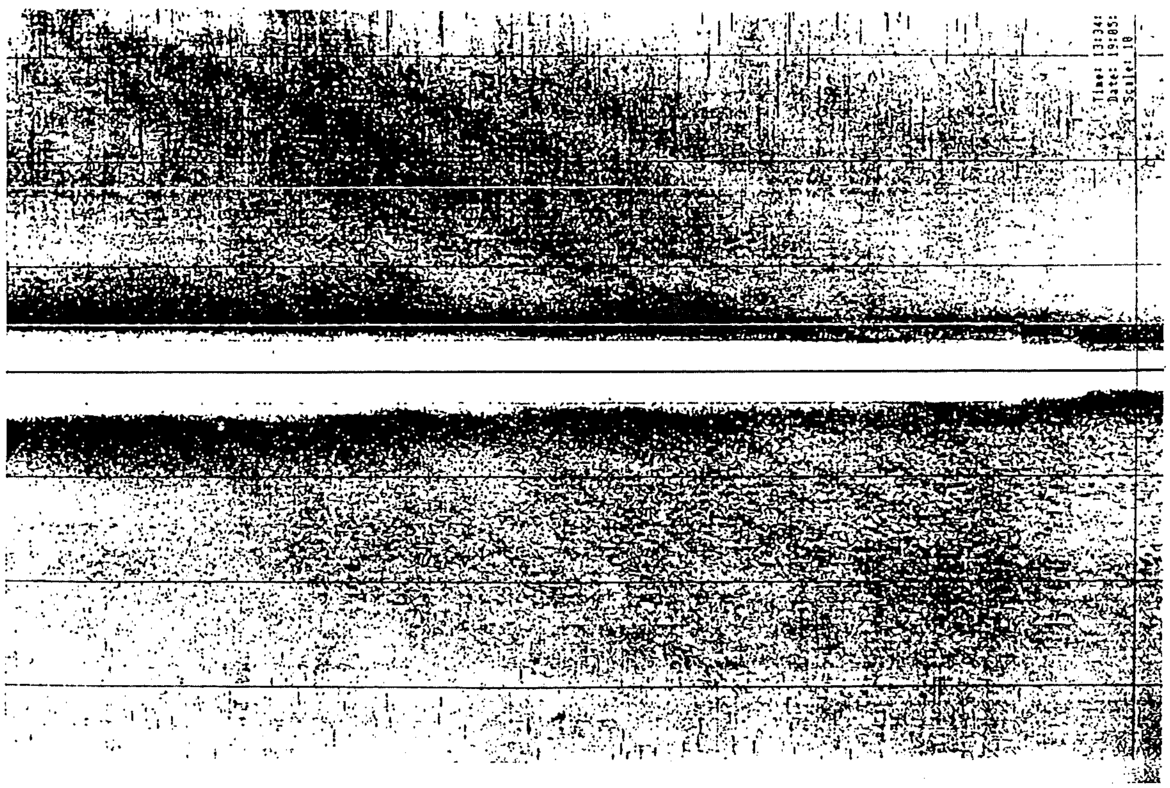

Figure 19: Imaged by a side-scan sonar system(500 kHz channel), the trend of a group of lineations is from the upper left corner to the middle right side, southwest-northeast. The fish is headed north. (Horizontal scale: 1cm = 8.0 m).

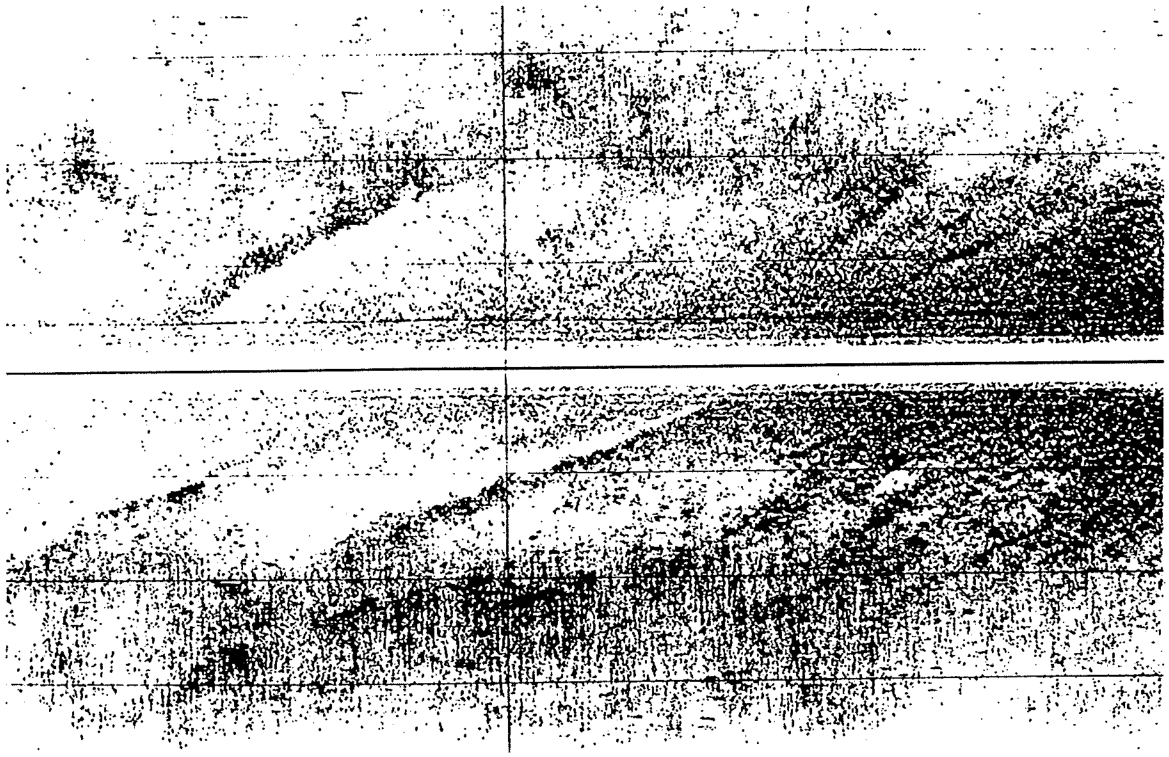

Figure 20: Side-scan sonar image (100 kHz) of a portion of a field of furrows. The white band in the image is the trough followed by a dark band which is a return from the opposite wall of the furrow facing the fish. The fish was heading north. (Horizontal scale: 1 cm = 8.0m).

type of furrow. According to R.D. Flood's furrow classification (1983), they are type 1A; furrows that have steep, symmetrical walls and relatively flat floors.

Pockmarks are the last sediment bedform identified during the 1992 survey. These can be identified on the side-scan sonar profiles as circular depressions with a semicircular band of white closest to the fish and the far semicircle sending a dark return back to the fish (Figure 21). The most prominent pockmarks in this area were found in a linear trend parallel to the shoreline north of Mt. Independence (Plate 4). There are between 60 to 80 pockmarks with depths of 0.3 m to 0.5 m and 5 to 10 meter diameters located along this northeastern trend. Another small linear trend of depressions is directly parallel to the 12 foot contour to the North. These features appear to be slump features because of their location on a steep slope and their shape and position on the fringes of a mass wasting deposit (Figure 22).

DISCUSSION

The bottom features mapped from the side-scan sonar (Fish and Carr, 1990; Johnson and Helferty, 1990; Klein Associates, Inc., 1985, Vogt and Tucholke, 1986; Laine et al., 1986) profiles reveal the average bottom water flow direction in this study region. Since sediment bedform formation is controlled by bottom currents, the orientations of the sediment waves, lineations, and furrows are clues to the direction of the bottom current that formed them. From this information we can hypothesize about the general bottom current directions in the study area (Plate E), and the forces controlling these currents. No bottom current data has been collected from this area, so the actual directions and controls on the boundary currents in the South Lake basin of Lake Champlain are unknown. Speculations can be

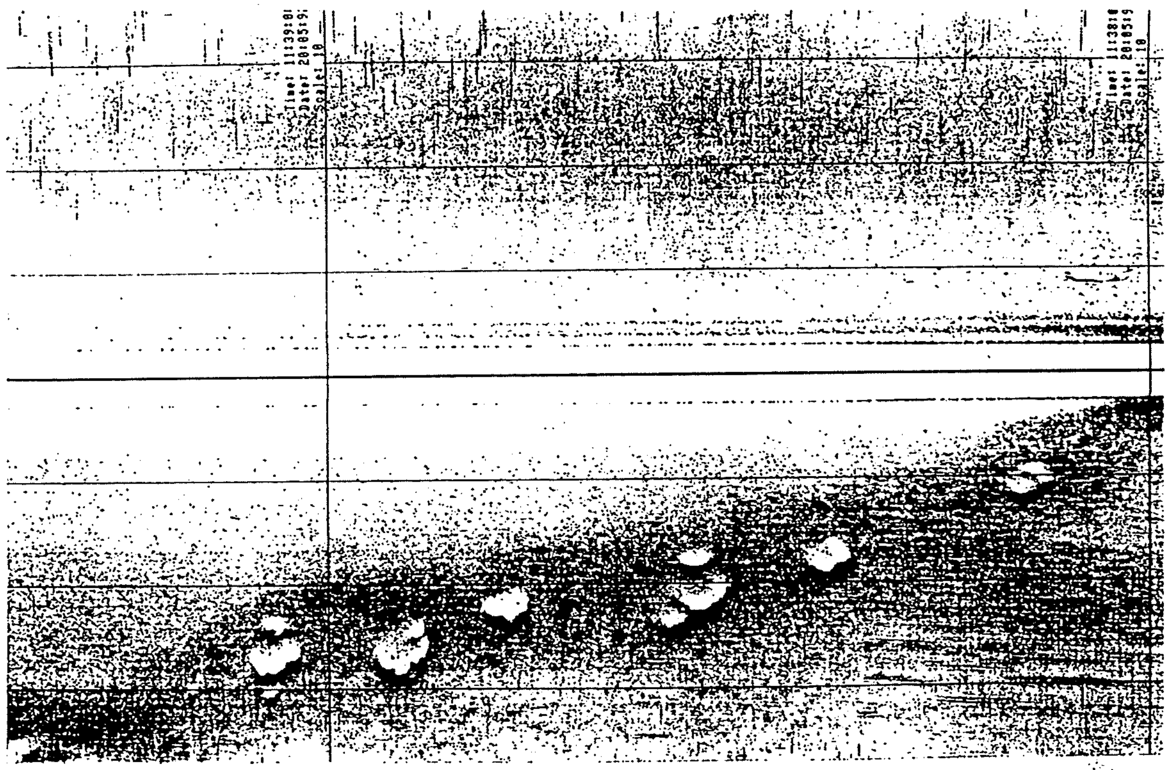

Figure 21: Side-scan sonar image (500 kHz) of pockmarks. The fish is heading to the southwest which indicates that the pockmarks are aligned in a trend toward the northeast. The darker reflection shown around the pockmarks is probably a result of the amount of sand in the sediment. (Horizontal scale: 1cm = 9.27 m).

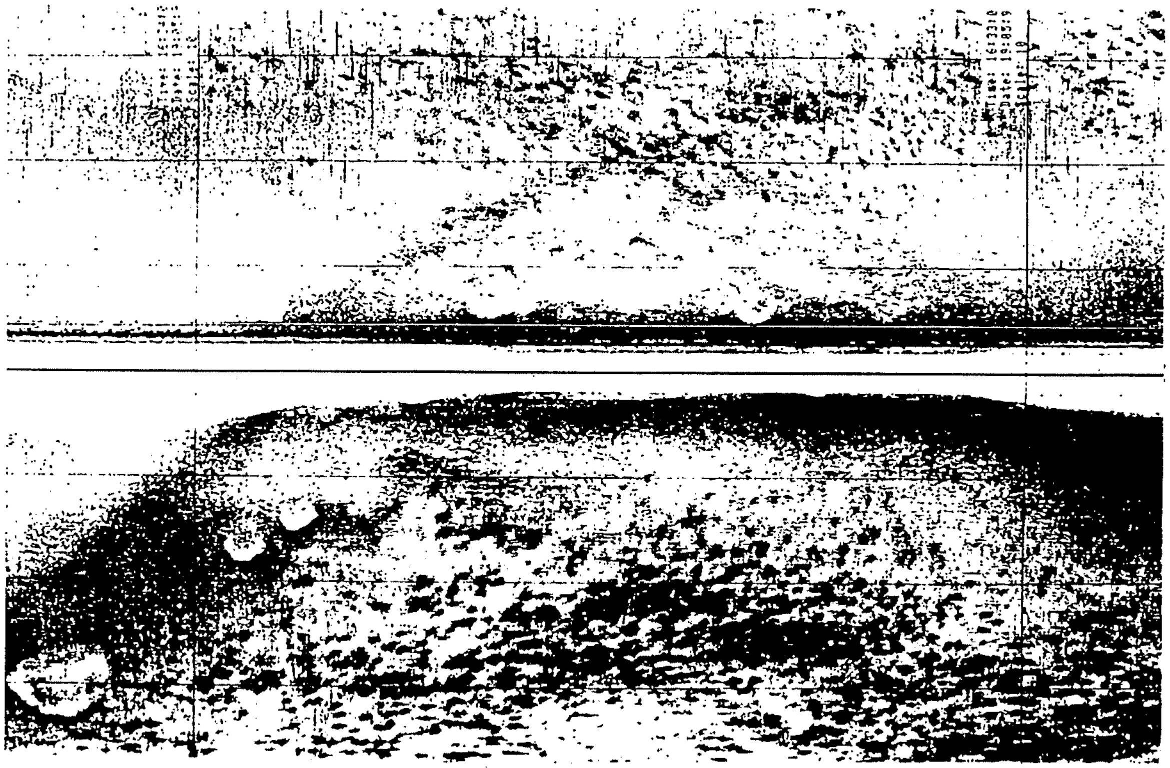

Figure 22: The depressions seen on the edges of this mass wasting deposit are not pockmarks, but features related to the slump. The fish is heading south in this side-scan sonar image (500 kHz). (Horizontal scale: 1cm = 8.0m).

made by examining the type of furrow. According to R.D. Flood's furrow classification (1983), they are type 1A; furrows that have steep, symmetrical walls and relatively flat floors.

Sediment Waves

Sediment waves are produced by changing the transport rates of the currents. These disturbed currents create wavy beds by alternating erosion and deposition along the direction of flow (Allen, 1985). Sediment transport is frequently disrupted where there are bathymetric irregularities or the where the lake floor is "obstructed by a shipwreck or other obstacles" (Flood, 1983). In southern Lake Champlain we can speculate that sand waves have formed as a result of the boundary current interrupted by the submerged cultural artifacts (boats, caissons, etc.).

In between Mt. Independence and Ft. Ticonderoga, sediment waves have formed surrounding the Revolutionary War caissons (Plate 2, Figures 12, 15, and 16). The northwest-southeast trending sediment waves found several hundred meters south of the caissons are larger and more irregular than the fine-scale sand waves located in close vicinity to the caissons. This observation suggests that the currents that formed these two different sized bedforms varied in speed. However, the boundary current did not vary in direction. The prevailing sediment wave orientation is perpendicular to the slope of the shoreline. Around the obstruction, sand waves of varying sizes, heights, and direction indicate large fluctuations in the current velocity and direction (Fish and Carr, 1990). These sediment waves have a distinctly asymmetrical shape that allows us to determine their main flow direction. The waves have a gentle slope that faces to the south and a steeper slope facing the north section of the lake. This morphology was created by a current flowing to the north.

Few deviations from this boundary flow direction occur south of the caissons, but another trend develops directly to the north of the caissons. Here, there are still waves trending northwest-southeast, but there are also groups of sediment waves which are oriented approximately east-west (Figure 17). On average, the sediment waves trending east-west have a wider spacing and a slightly larger height indicating a faster current speed than the one forming the smaller sediment waves to the south. The currents that formed them, according to the asymmetry, comes from the north. We speculate that these bedforms were formed by a southern flowing current of high magnitude. Observations of the smaller scale sand waves superimposed onto these large, east-west trending waves supports the interpretation that the southward current is also episodic. The northern current is more constant and regular and, therefore, generates the smaller scale northeast trending sediment waves over the east-west trending waves. It is possible that the seiche could create the high speed current flowing episodically to the south. This high speed current would only be episodic because only a large-scale seiche, perhaps where the wind piled up an excessive amount of water in the north, could create sediment waves in this section of the lake.

To the northeast of the caissons, a submerged canal boat is surrounded by sediment waves (Figure 18). The bedforms are found primarily to the north of the vessel, although a few are present to the south. Their orientation is northwest-southeast and their asymmetry imply that the predominant north-flowing current formed them flowing parallel to the shoreline (Plate E). Two sediment waves are each positioned at an angle to the rest of the sediment waves and in contact with the canal boat (Figure 18).

These bedforms might show the effects of the current as it is bending or diffracting around the cultural artifact due to the northward flow.

Lineations

According to Flood and Johnson (1984) lineations form parallel to both the current direction and to the shoreline. They are formed when fine-grained material or easily transported and lighter, coarse-grained material is aligned into strips by the current (Figure 19). Because lineations are found throughout the study region, they are helpful in determining the bottom current flow path. Unfortunately, it is impossible to determine whether the flow, in this case, is to the north or to the south (lines with no directional arrows on Plate C). In many instances these lineations are found in conjunction with sediment waves south of Mt. Independence. The lineations are positioned transverse to the sediment waves and reconfirm the local current direction while the symmetry of the sediment waves verifies the absolute direction of the current. The lineations and sand waves in between Buoy 39 and Mt. Independence indicate that the current in the deepest sections of the lake flows to the north following the local configuration of the shoreline.

In the northern section of the area of study, the lineations have several different orientations. However these are located at two significant bends in the lake. Their orientations remain parallel to the local bathymetry and topography suggesting that the main current of the deepest section of the lake stays on this path.

Furrows

Furrows are narrow, longitudinal depressions which form parallel to the mean current direction in fine-grained, cohesive sediments (McCave and Tucholke, 1986). Their development and form is controlled by the sediment type, the depositional environment, bottom water flow patterns, and helical secondary circulation (Flood, 1983; Viekman, Wimbush, and VanLeer, 1986; Viekman, et al., 1992). The best furrow development occurs where currents have a steady flow direction, although episodic, as well as where bidirectional (tidal) currents exist, will also develop furrows. The furrows found in this region of Lake Champlain are located in two main fields, one around Buoy 37 and one surrounding Buoy 38. Flood (1983) noted that most documented furrows are aligned parallel to a dominant physiographic features such as the regional contour of the sea bed, long axis of an estuary or the shoreline. The southern field of furrows is aligned parallel to the western slope of the shoreline (Figures 23a and 23b). The northern field around Buoy 37 is spread out laterally more than the southern field, but its orientation closely follows the bends in the local shoreline as well (Figures 24, 25, 26).

The sediments required to form furrows are coarse-grained material overlying a cohesive sediment. The coarse grained sediment must be light enough to be easily transported and aligned into sand ribbons, but also coarse enough to abrade the finer cohesive sediment below. Cohesive mud covers a large percentage of the surveyed area, as observed by the backscatter on the side-scan profiles, and there must be enough sand present to create the furrows.

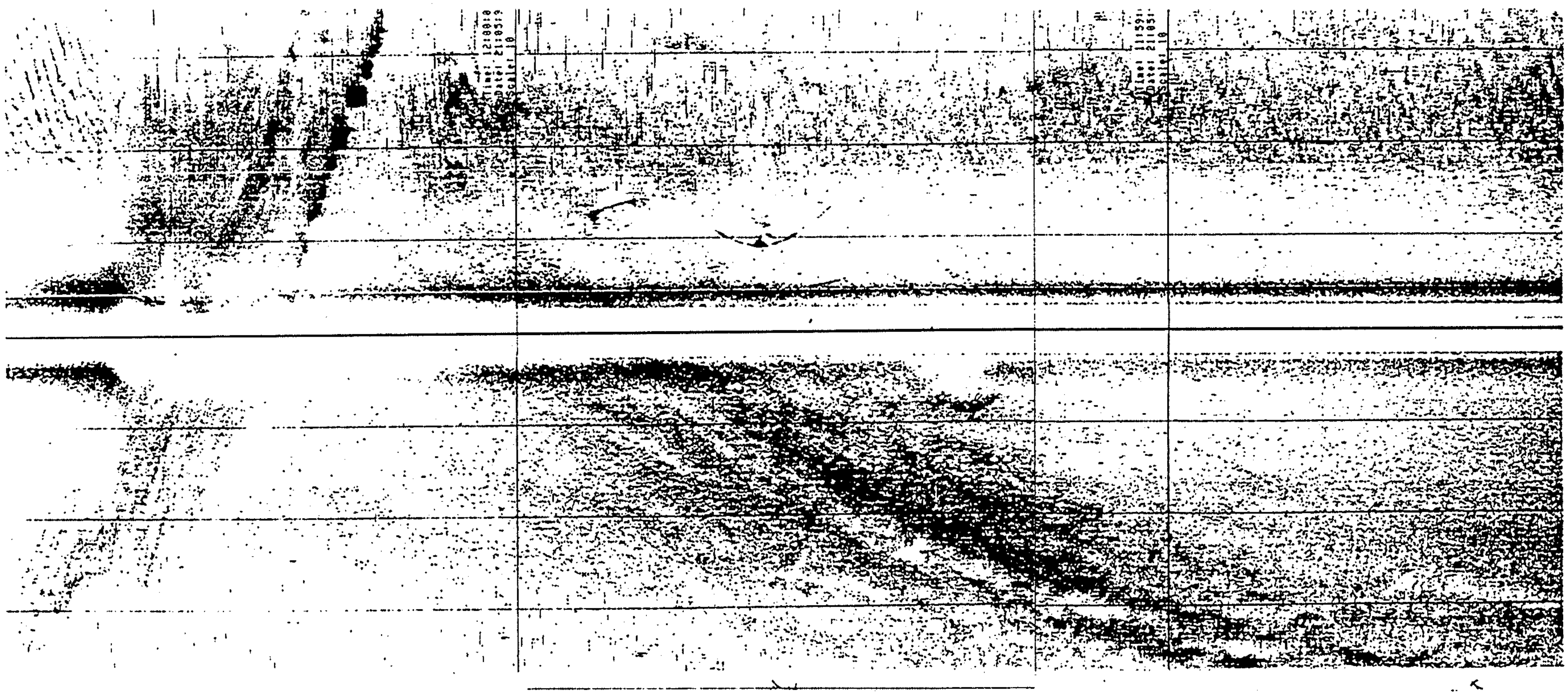

Figure 23a: Side-scan sonar image (500 kHz) of furrows and ferry cable around buoy 37. Fish is headed to the north. A portion of the field of furrows in this area is visible on the port side of the fish track. Crossing the fish track to the north is the disturbance of sediment created by the ferry cable. (Horizontal scale: 1cm = 9.27 m).

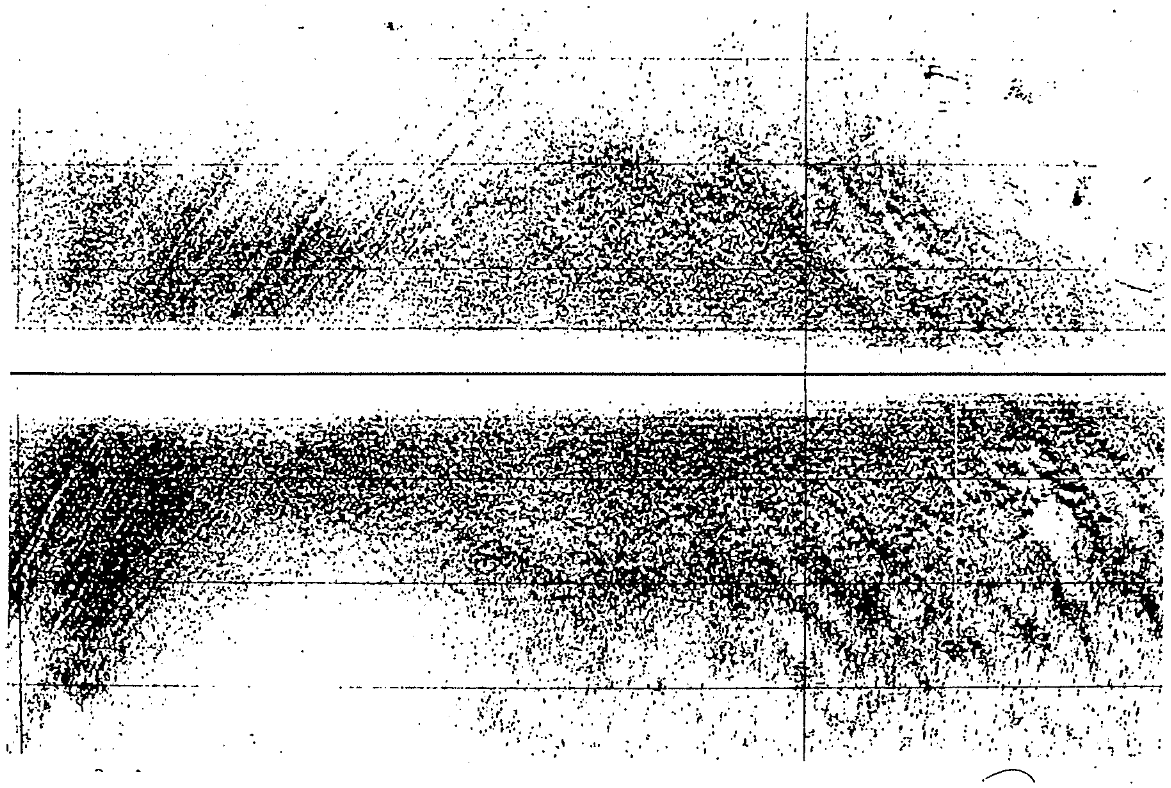

Figure 23b: This is another side-scan sonar profile (100 kHz) of the same set of furrows. Here the fish was headed to the south at a slightly different angle, and as a result more furrows are visible. (Horizontal scale: 1cm = 9.27 m).

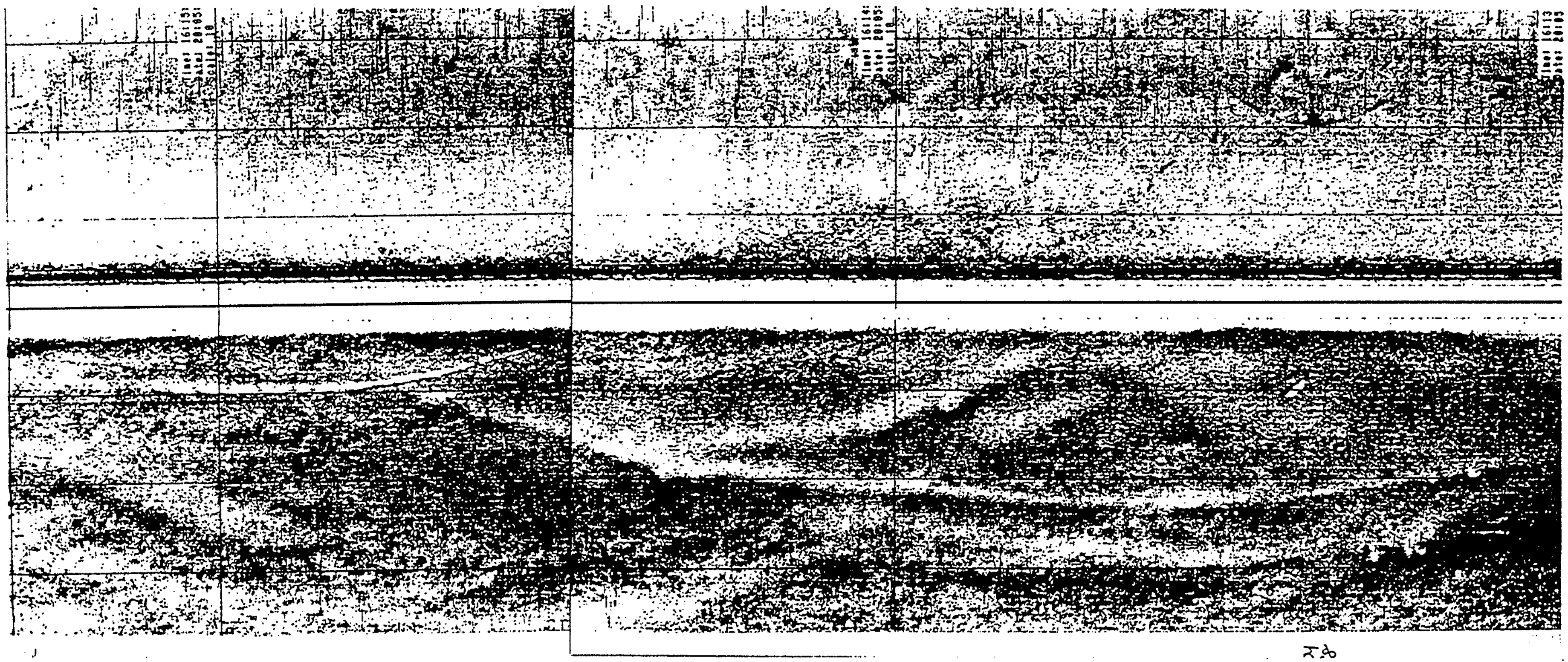

Figure 24: Side-scan sonar image (500 kHz) of furrows and buoy 38. Fish is headed to the north. The fish track is running parallel to the field of furrows present in this section north of Fort Ticonderoga. Note the converging furrows, in both directions, on the port side the fish track. (Horizontal scale: 1cm = 9.27 m).

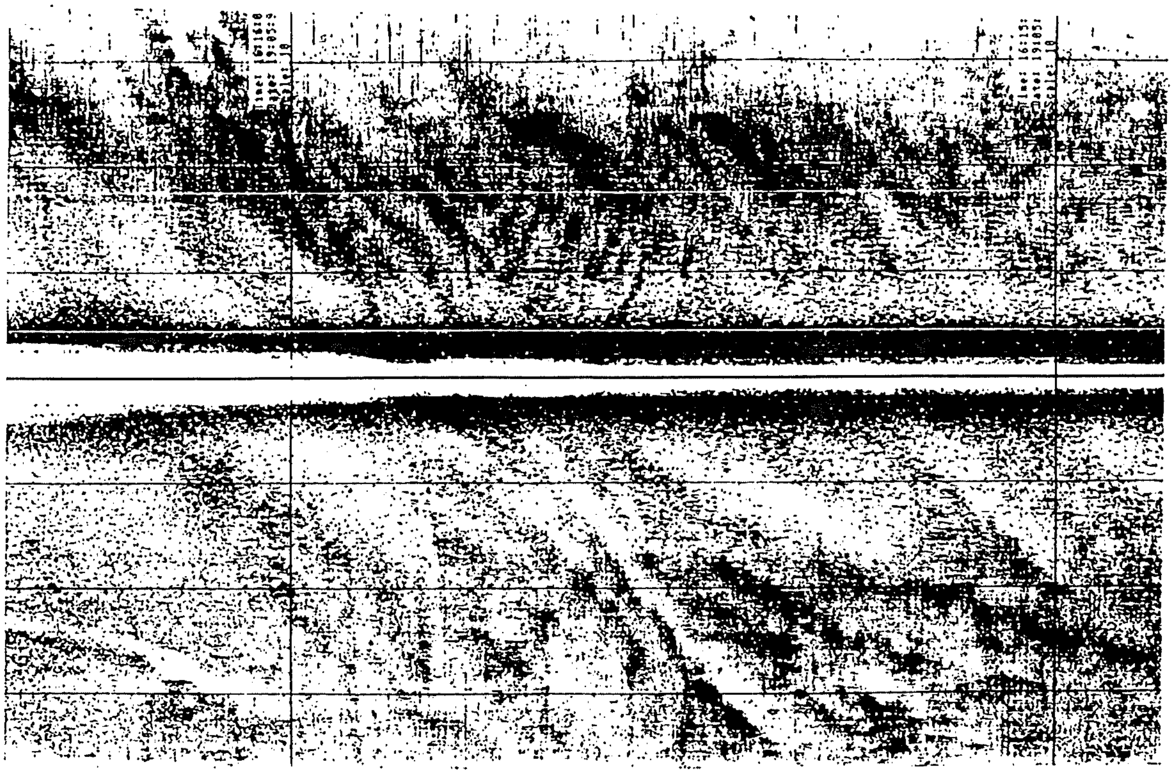

Figure 25: An additional track line headed to the south (500 kHz) that passes over the furrows near Buoy 38. Note the sediment waves present in between the furrows on the starboard side of the fish track. (Horizontal scale: 1cm = 8.0 m).

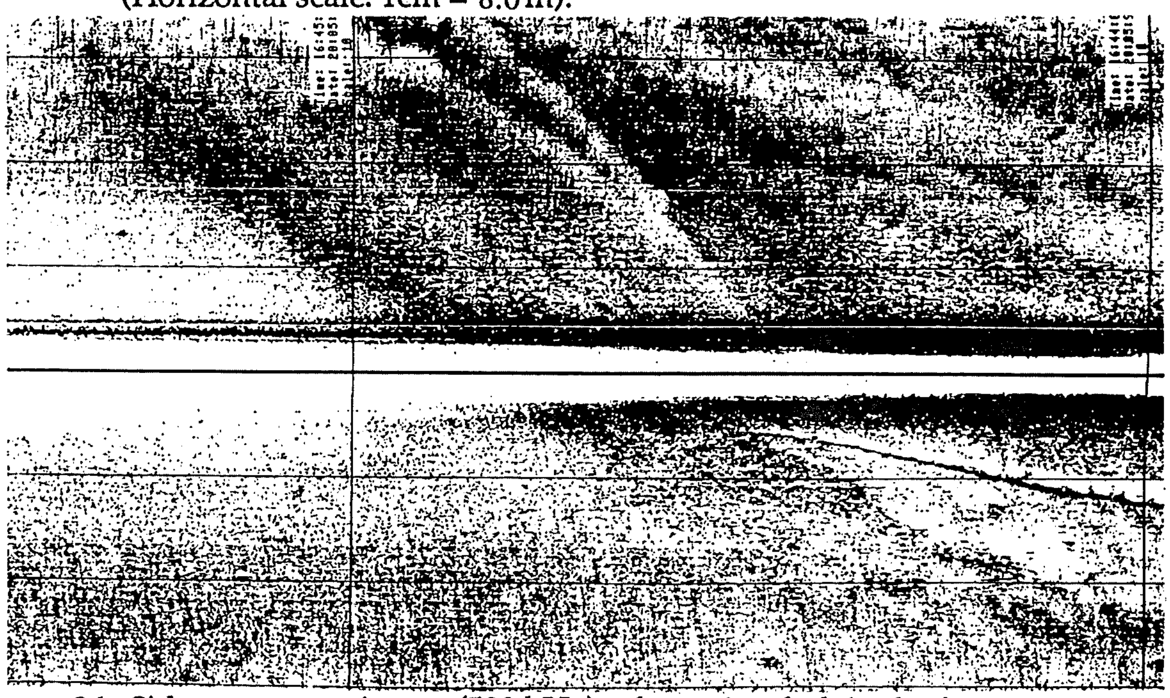

Figure 26: Side scan sonar image (500 kHz) of a tuning fork in the furrows around Buoy 38. The fish is headed to the south, so the furrows are converging to the north indicating a northward flow. (Horizontal scale : 1cm = 9.27 m).

These furrows are classified as a type 1A as described by Flood (1985). This classification suggests that the furrows are formed by a steady current flowing in between 5 and 20 cm/sec. Once established, the development of these furrows is now controlled by the balance between deposition and erosion (Flood 1983). It is understood that type 1A furrows indicate that rate of deposition has exceeded erosion rate. Tuning fork junctions, where two furrows converge and form one, indicates the direction of the generating flow with furrows being joined in the direction of flow (Flood and Bokuniewicz, 1986). Furrows are found to join both to the north and to the south (Figure 24). This indicates the presence of a bidirectional flow. The majority of tuning forks join to the north, verifying that the dominant current direction for the southern lake is to the north. The presence of tuning forks converging to the south confirms the interpretation that some of the sediment waves are formed by a south-flowing current in southern Lake Champlain. Flood's analysis of the growth state of 1A furrows, indicating that deposition is exceeding erosion, supports the theory that the current to the south, forced by the seiche, is episodic. In between large erosional events, sediment deposition will start to fill the furrow, making them narrower until the next event.

The location of these furrow fields, on the inside bends of Lake Champlain, raises more questions regarding the factors controlling the boundary currents that generated and perpetuate these furrows. Turbulent waters are needed to maintain the helical secondary flow. The minimum current speed needed to generate the helical circulation to produce a furrow in Lake Superior is 6 cm/sec (Viekman et al., 1989). If this is truly the case, then the mean current speed documented by Henson (1972) and Henson and Gruendling (1977) as 1.34 cm/sec to the north must somehow be increased periodically to achieve speeds for furrow formation. Flood (1983) noted that brief events of increased current strength interrupting constant deposition could generate and maintain the sediment bedform.

The furrow fields are located along the slopes of the shoreline where the depth of the lake ranges from 3 to around 8 meters. This shallow depth allows the waters to be kept turbid by the wind (Myer and Gruendling, 1979). The main wind direction is to the northeast and northwest (Fitzgerald, 1973) although there is a noticeable wind pattern to the south. Fitzgerald (1973) studied the surface currents around Fort Ticonderoga, specifically the plume of water emitted from Ticonderoga Creek. Fitzgerald (1973) noticed that the stronger the wind blows from the southeast or southwest direction, the closer the water plume emitted from Ticonderoga Creek fits the shoreline contour surrounding Ft. Ticonderoga. This is in direct line for the furrow field around buoy 38. Although Fitzgerald(1973) only documented the surface currents, it is possible because of the shallow depth and lack of stratification in the South basin that the wind direction creates the current speed necessary to generate furrows.

Langmuir circulation could also contribute to the helical vertical motion within the subsurface waters. Fitzgerald (1973) documented the presence of Langmuir cells created by the wind. "The effect of wind is thus to produce a series of alternating right and left helical vortices in the water having horizontal axes parallel to the wind." The winrows were located parallel to the north wind, but showed local changes where they met the shorelines at high angles (Fitzgerald, 1973). The Langmuir cells were observed to have a constant 9 meter horizontal spacing even though the water depth changed from 3 to 8 meters, the depth to bottom found in the survey area. These cells were believed to be flattened to fit the bathymetry with a shorter vertical distance while the horizontal remained the same. The spacing between the furrows measured from the side-scan sonar profiles was approximately 10 to 20 meters. The Langmuir cells' horizontal spacing corresponds to the spacing of the furrows found around the two buoys and may aid in their development.

The general northward flow with the additional current speed created by the wind and turbulence maintained by the Langmuir cells may be enough to explain the presence of the furrows. It is still unknown why they formed along the inside bends of the lake. The furrow fields are both located where buoys are anchored to the ground. Flood (1983) suggested that the initiation of furrow development can be influenced by the presence of an obstacle. This obstacle may create a sand tailing behind the object (with respect to the current direction) which is similar to the "sand ribbon" stage in furrow development. Once the coarse sediment is lined up and the turbid conditions are correct, helical circulation could develop to form the depressions.

Another possible explanation for the location of the sediment furrows on the inside of the bends of the lake is similar to the fluid dynamics along a meander or a bend in a river. When the water flows into a turn, it does not smoothly flow around the bend, but flows into the outer bank, piling up a noticeable amount of water. The weight of this pile of water on the outside of the meander creates a large helical flow down from the outside bend, along the bottom to the inside of the lake meander. It is possible that this large scale helical flow is enough to disrupt the helical flow that creates furrows only on the outside of the bend. This occurs because the large scale helical flow differentially increases one side of the converging secondary helical flow prohibiting the proper, even development of furrows. This large-scale helical circulation could preferentially destroy the secondary helical circulation on the outside of the bend in the lake. If friction was great enough to stop or slow down the large scale circulation before it affected the inside helical cells, then those inside, helical, secondary-flow patterns could create furrows.

Pockmarks

The last feature found on the lake floor in this region is pockmarks (Plate D, Figure 27). Pockmarks have been found in other regions of Lake Champlain (Pederson, 1992; Manley, 1991). It is accepted that they are the result of ground water or gases being pushed through the lake floor sediments. The interesting observation made about these pockmarks is that there is a large number of them located in a linear trend approximately 700 meters long. This obvious trend is oriented southwest-northeast. One explanation for this orientation relies on the regional structural geology. Welby (1961) documented a

> series of longitudinal faults, some well-authenticated, others shown by physiographic evidence on the lake bottom [that] provide a horst and graben sequence between the Adirondacks and the western half of the Central Champlain Valley.

Welby (1961) notes that the Champlain Valley is cut into blocks by a series of north-northeast striking faults (Figure 28). Some of these north-northeast trending faults have been found underneath Lake Champlain sediments to the north around Crown Point (Hatton, 1983). The trend of pockmarks found in this survey area could be outlining a subsurface fault which is facilitating the movement of gases or groundwater into the lake.

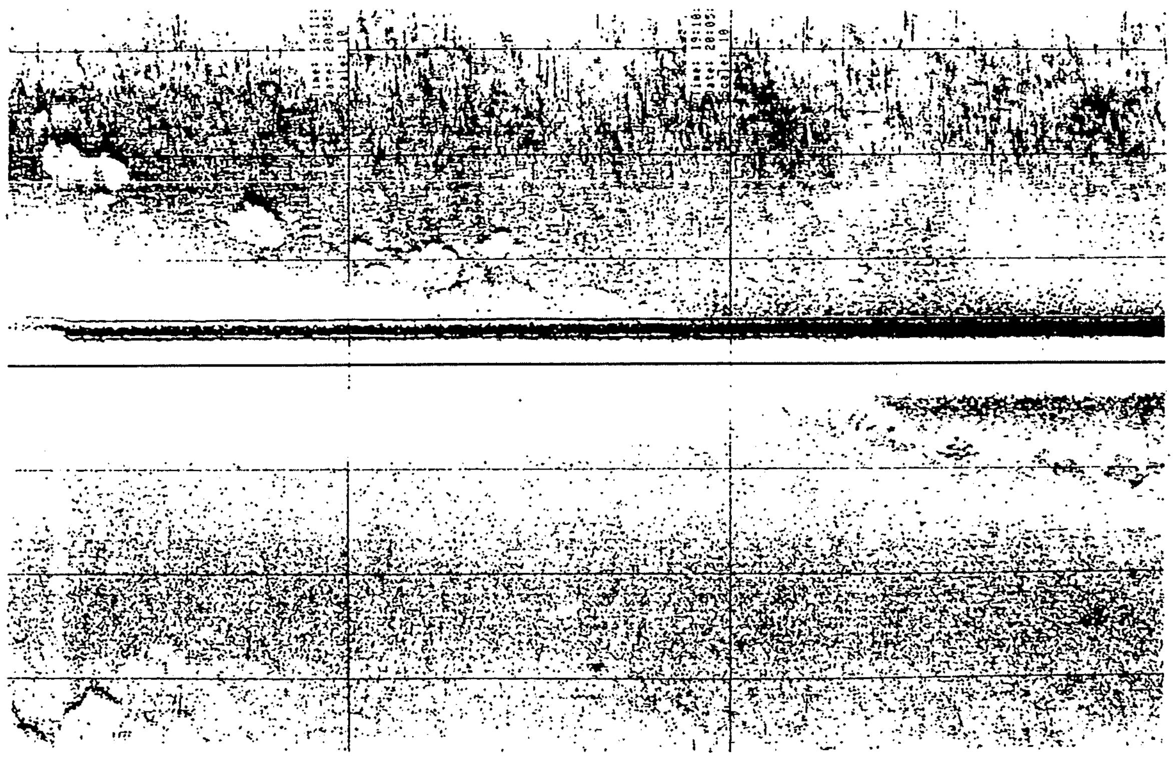

Figure 27: Side-scan sonar profile (500 kHz) of pockmarks trending to the northeast. The fish is headed to the north. (Horizontal scale: 1cm = 9.27 m).

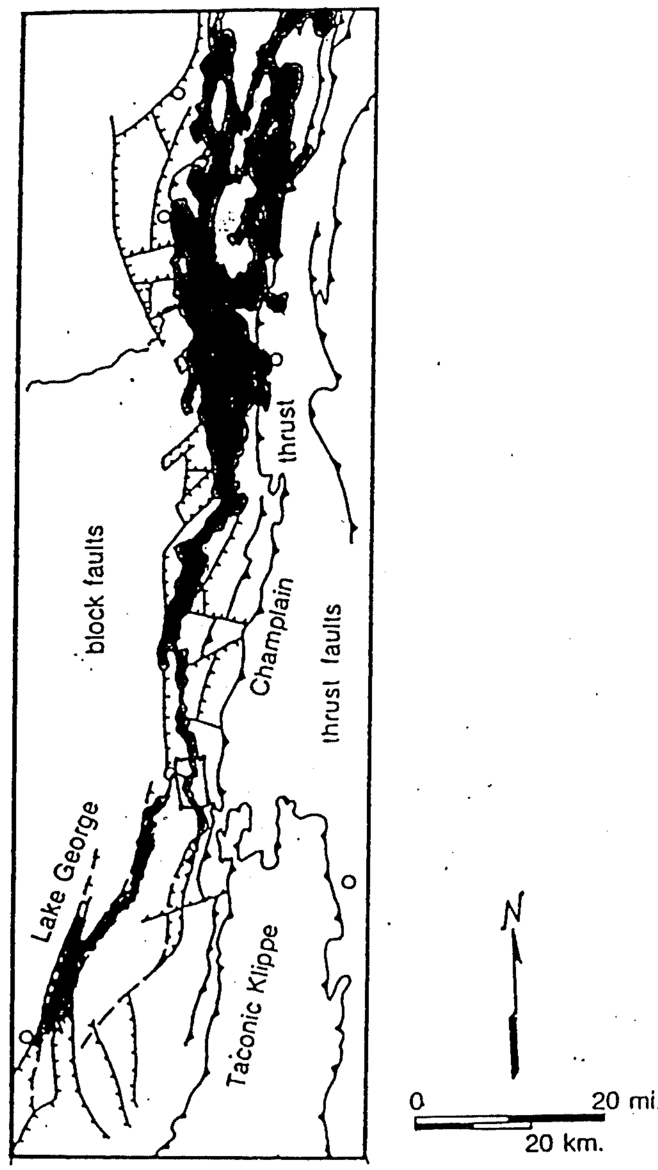

Figure 27: The Champlain Valley is cut into blocks by north-northeast striking block and thrust faults. The Champlain Thrust, located to the east of Lake Champlain, is the main fault in this region. The study area is highlighted by the red box. (Van Diver, 1987).

CONCLUSIONS

From the observations of the cultural artifacts and sediment bedforms taken in the study area, we are able to speculate on the formation of the bedforms and the direction of the currents that produced them. There is an obvious correlation between the presence of cultural artifacts and the formation of sediment waves. In the study area, the caissons and a canal boat acted as obstructions to the current creating sediment waves. Two groups of sediment waves, present in the Mount Independence-Fort Ticonderoga area, suggest that there are two distinct currents flowing in this region. The first is a current with a constant speed in the northward direction. We are hypothesizing that this current formed the sediment waves in the southern survey region up to the caissons as well as around the canal boat. A second current was suggested by the presence of larger asymmetric sediment waves that we are interpreting to have been generated by a flow to the south. Because of their shape and orientation, it is possible that these sediment waves were formed by a strong, episodic current that was driven by the winds or the seiche. In between these larger scale events, the smaller sediment waves grow over the large-scale waves. In both cases the currents follow the local topography and bathymetry.

The sediment furrows in this study area are only present on the inside bends of the lake. Without any current meter information, it is only possible to speculate on the generation of the furrows in this location. Hence, we are hypothesizing that a large, helical flow is created when water travels around the bend in the lake. This flow disrupts the secondary, helical flow circulating in the boundary layer on the outside of this bend. On the inside, however, the helical, secondary-flow is not affected by this additive force, so furrows are able to form. The observed furrows have been formed by a bidirectional current, so we are assuming that the seiche, actively initiated by the wind, is able to produce the extra force in the current needed to form the helical flow and furrows. The roles of lake stratification, the wind, Langmuir circulation, and the seiche must all be determined before furrow development in this study area can be fully understood.

The linear trend of pockmarks observed in the survey area may be influenced by the local and regional structural geology; perhaps this trend corresponds to a local north north-east trending fault.

FUTURE STUDIES

There are many possibilities for future studies in this survey region. This side-scan survey can be considered a preliminary study of the Fort. Ticonderoga- Mount Independence region. The observations of sediment waves and furrows were only a surface picture. Installing a current meter in this section of the lake could answer many questions regarding the formation of furrows and sediment waves as well as the roles that the seiche, the wind, and lake stratification play in their formation. Another side-scan survey in this area would document the changes that have occurred in this area over a one year period. This would be a start in monitoring the movement of the sediment bedforms over time. Core samples could also be taken to determine whether the sediment waves are migrating by looking at the structures beneath the present waves. Gathering meteorologic information, specifically wind data, could help in interpreting the generation of the bidirectional currents in the area. Deposition or erosion rates need to be calculated for this region of the lake to develop an appropriate management program for the cultural artifacts located beneath the lake's waters. In addition to monitoring the currents, it may be useful to do a seismic survey over the linear trend of pockmarks to determine if there is a fault in the area. If these are pockmarks, then it would be of interest to do a geochemical analysis of the water seeping into the lake because of the possibility of contamination to the lake from the groundwater source.

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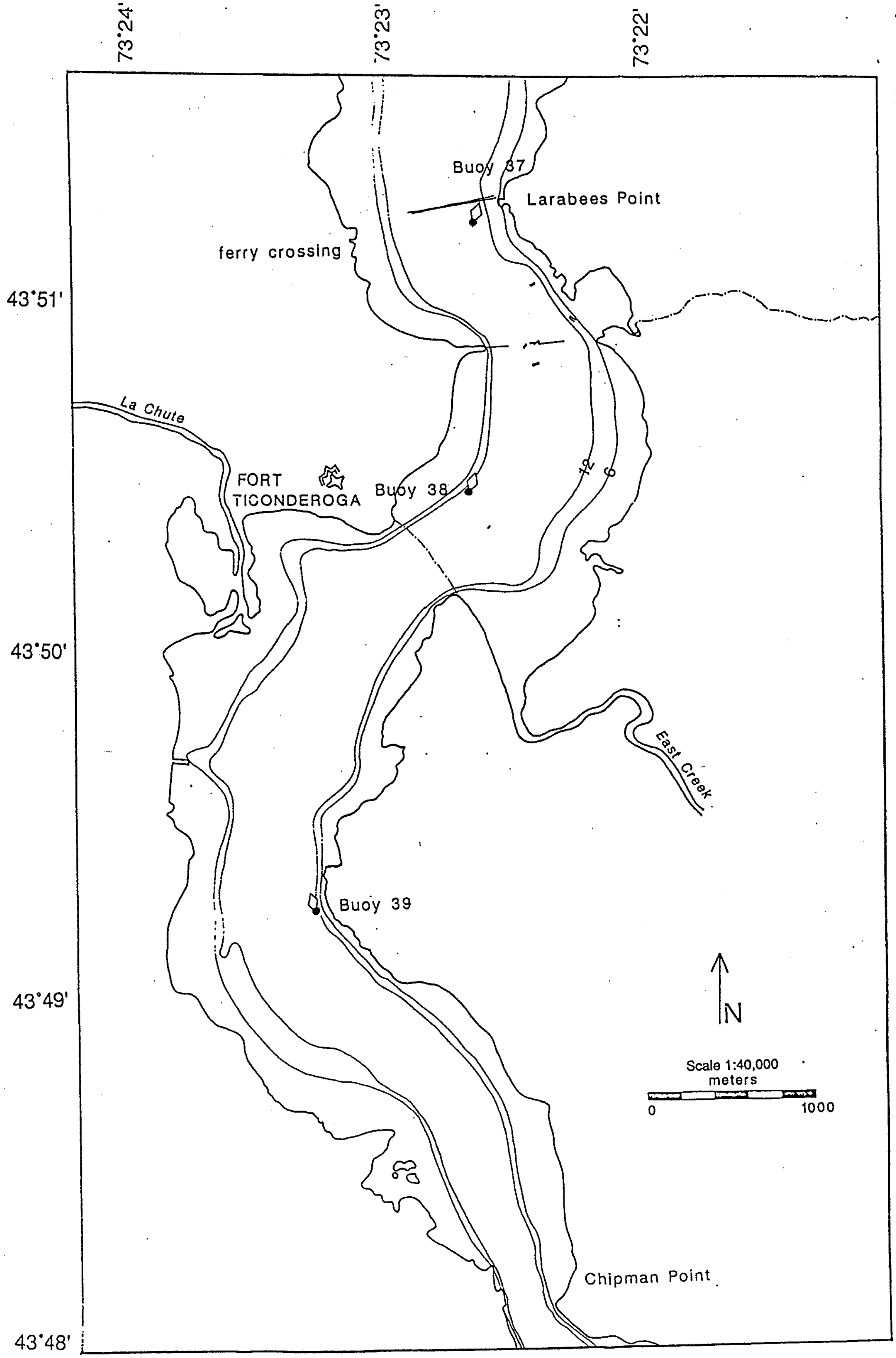

PLATE A: General location of submerged cultural artifacts in Lake Champlain.

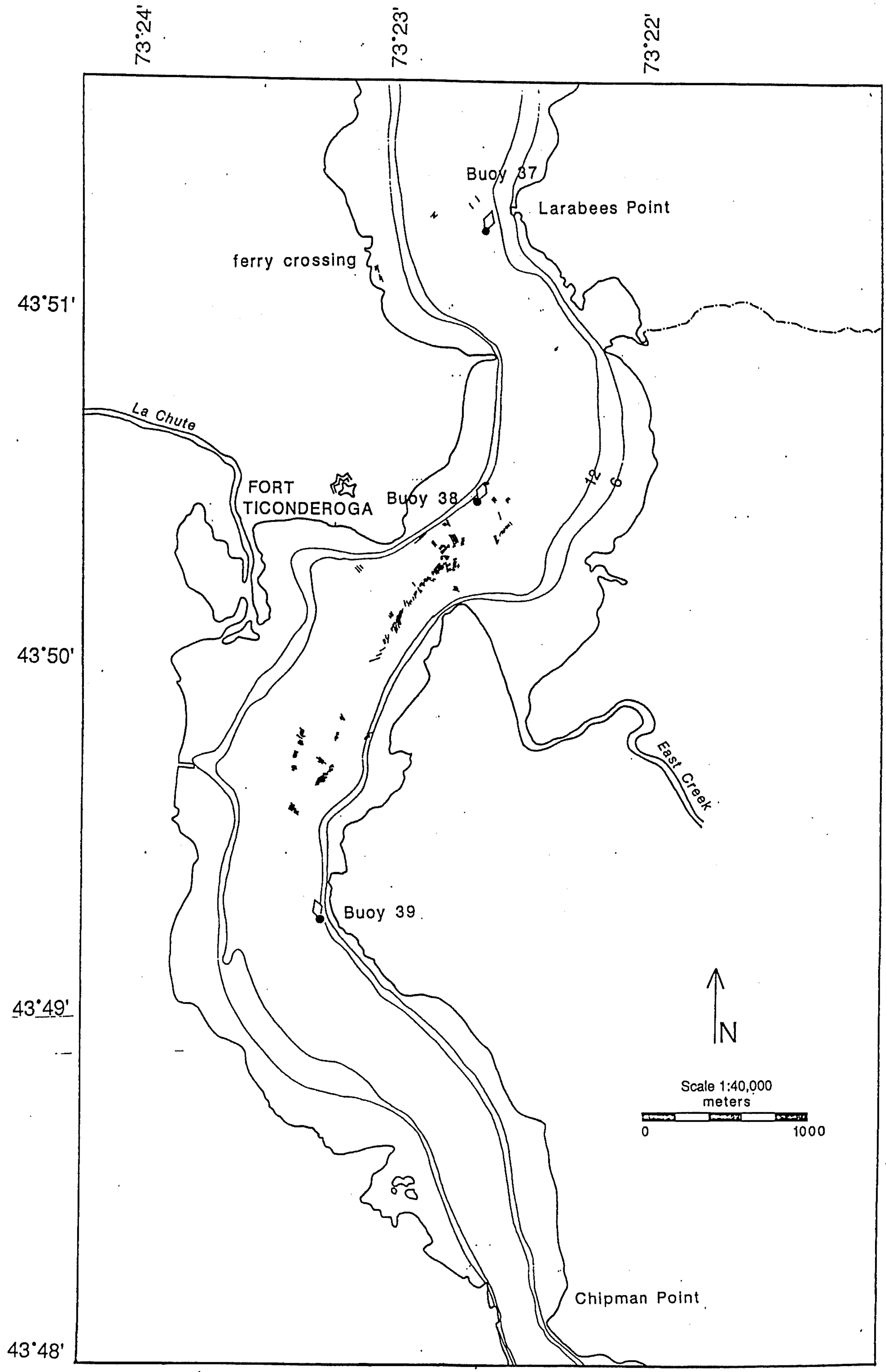

PLATE B: Orientation and location of sediment waves in study area.

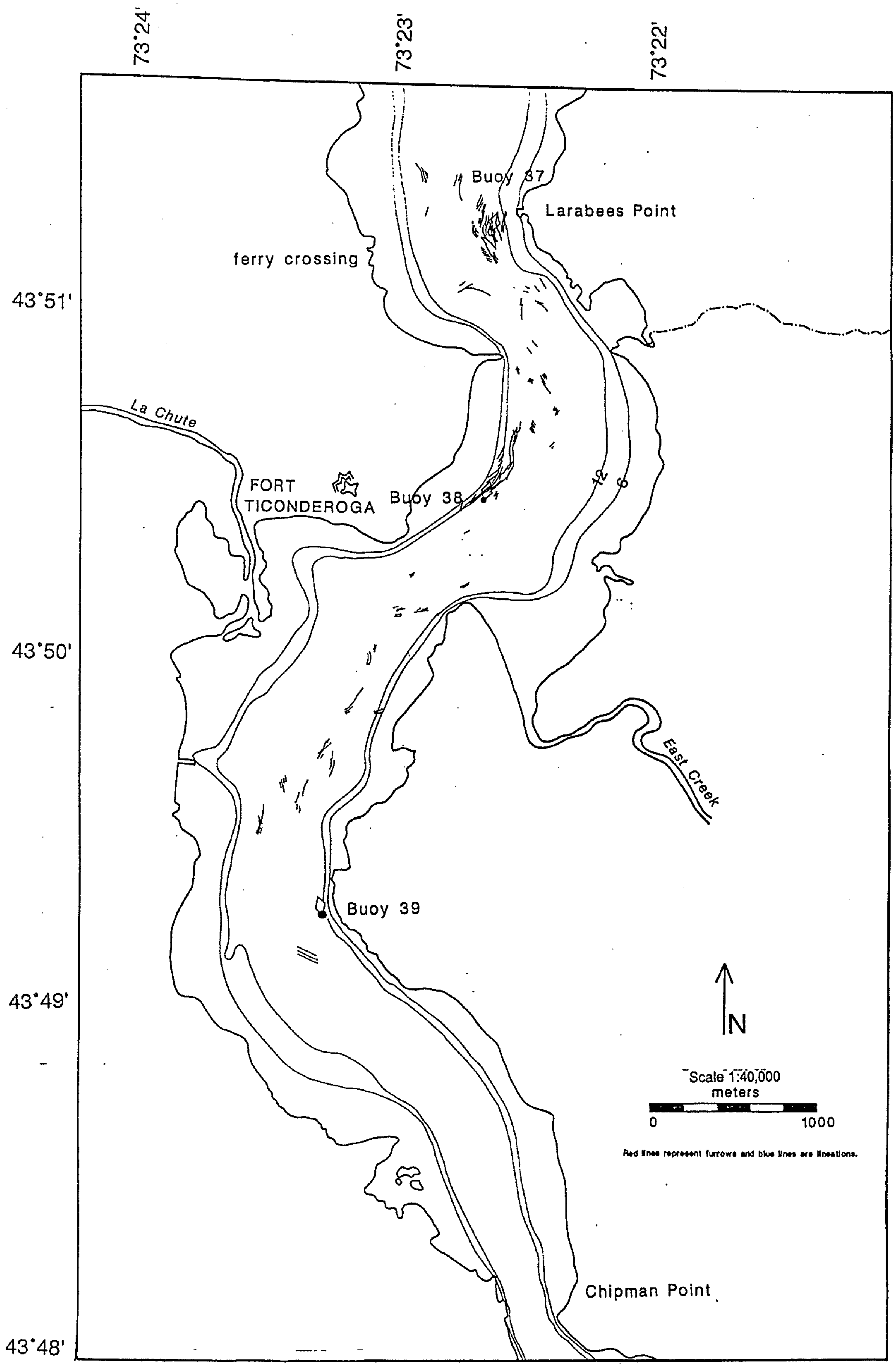

PLATE C: Orientation and location of lineations and furrows in study area.

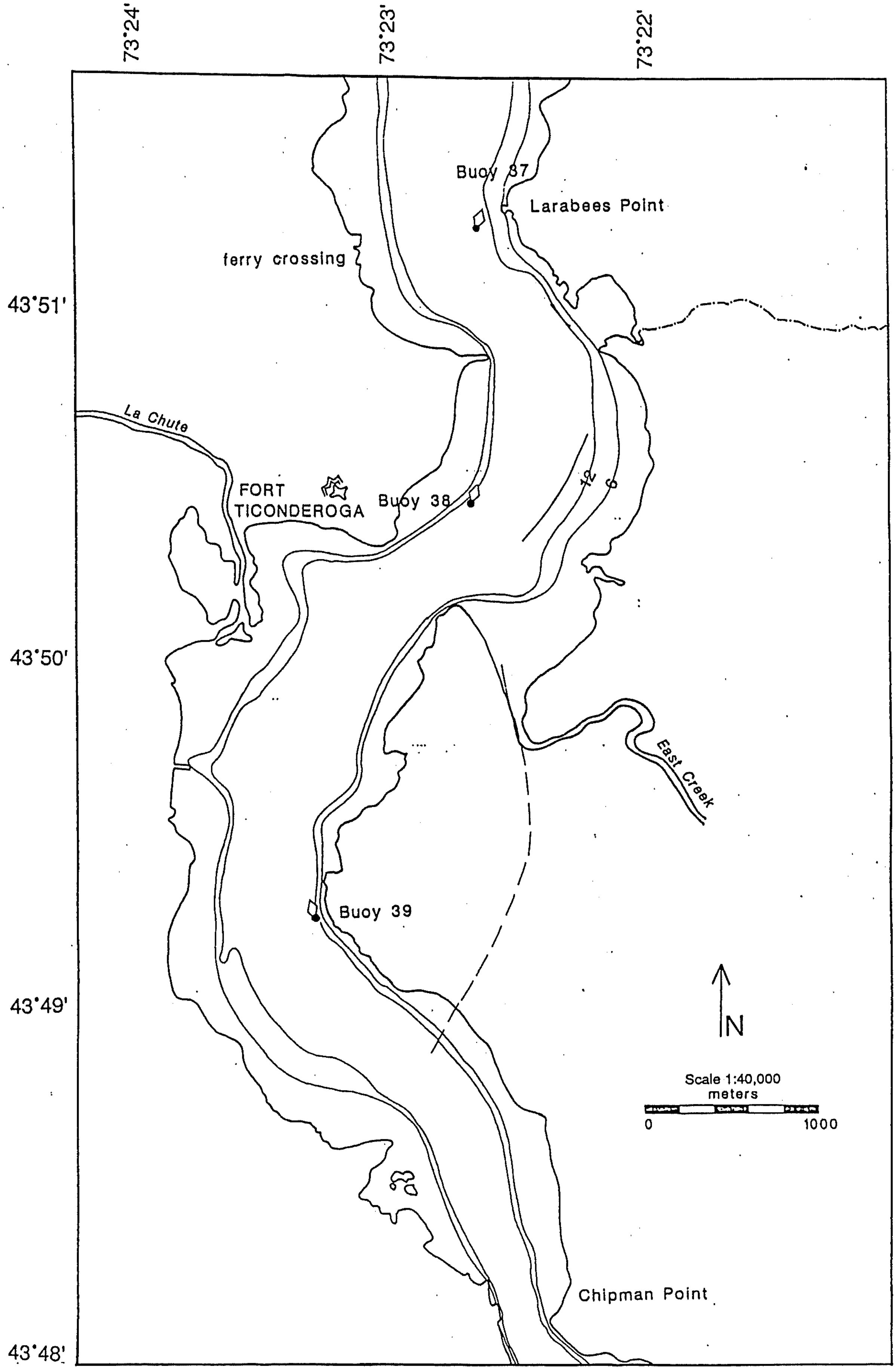

PLATE D: Location of linear trend of pockmarks in study area.

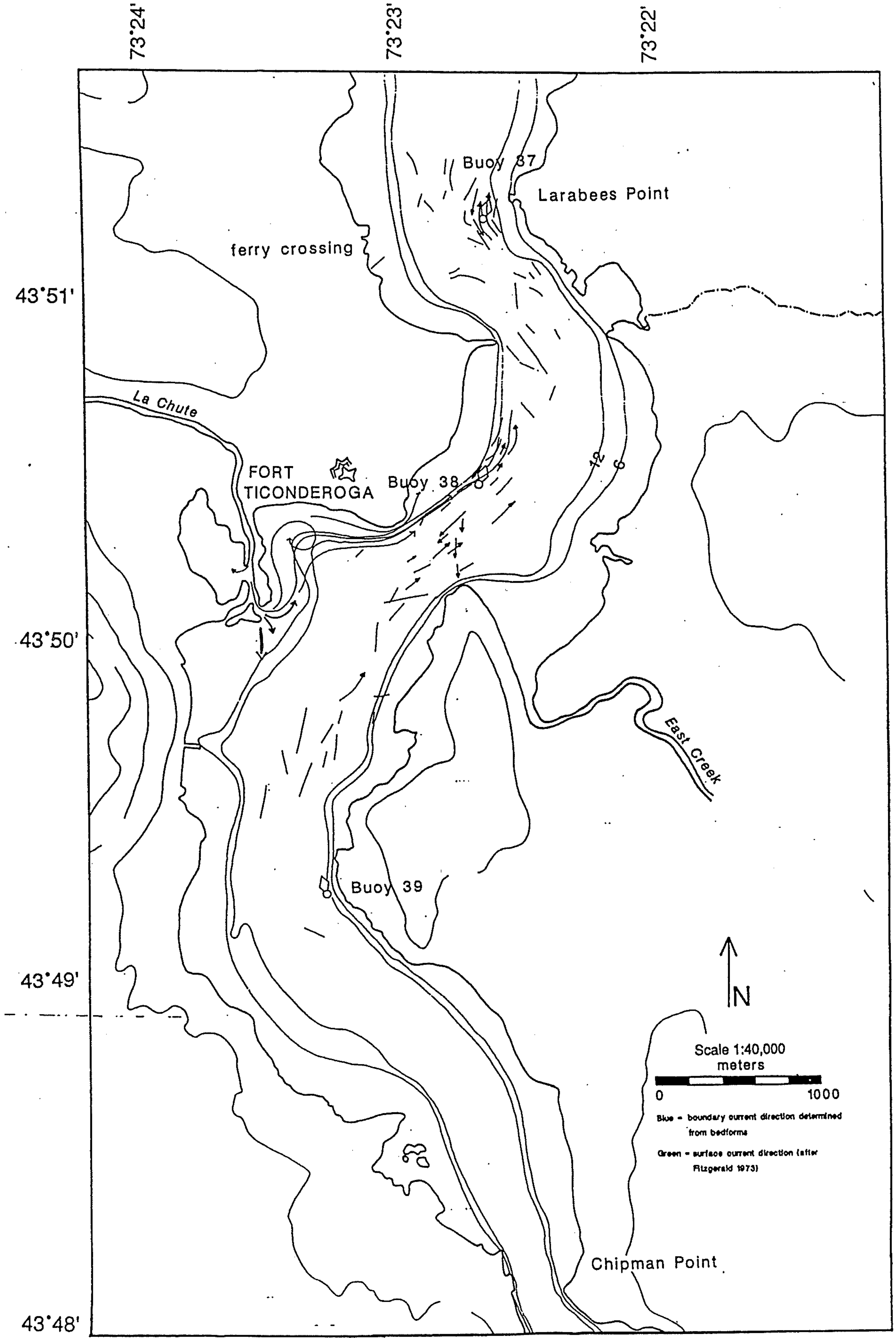

PLATE E: Orientation of boundary current direction as interpreted from sediment bedforms. The length of the line does not correspond to the magnitude of the current. Lines without arrows indicate where there was no further evidence from the bedforms to determine an absolute current direction.