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Evolution of Seabed Pockmarks in Penobscot Bay, Maine

Allen M. Gontz

EVOLUTION OF SEABED POCKMARKS IN PENOBSCOT BAY, MAINE

By

Allen M. Gontz

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Advisory Committee:

Daniel F. Belknap, Professor of Geological Sciences, Advisor

Joseph T. Kelley, Professor of Geological Sciences

Stephen M. Dickson, State Marine Geologist, Maine Geological Survey

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Thesis Advisor: Dr. Daniel F. Belknap

An Abstract of the Thesis Presented
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Seafloor depressions, called pockmarks, have been known to exist in Penobscot Bay, Maine since the mid 1980's (Knebel and Scanlon, 1985). Earlier workers (Ostericher, 1965) recognized "channels" on sonoprobe records that are in the same area as the pockmarks recognized by Knebel and Scanlon (1985). Their origins and pathways of evolution are unknown. Much speculation about the sources of pore fluids, levels of activity, and evolutionary pathways has occurred since their discovery.

Two surveys of Belfast Bay, in 1998 and 1989, have shown differences in the pockmark field population. Over the course of a decade, 36% of the field's 1998 population has either been created or destroyed by erosion and infilling. Creation of new pockmarks has outnumbered destruction of older pockmarks by 342 to 287 or by about 16%. This is definitive proof that the field is active. If the field were senescent, the destructions would outnumber the creations, creations would not be present, or the field population would be reserved from year to year.

New, high-resolution geophysical equipment was used to track the changes to a small area of the seafloor in Belfast Bay from 1998 to 2000. Over the 2-year period, significant changes to the seafloor topography occurred. The bottom was covered with

drag marks from both anchoring and fishing in 1998. The 2000 survey also showed a bottom covered with drag marks, but when the two surveys were compared, it was apparent that the drag marks on the 2000 survey were not the same as those on the 1998 survey. In fact, none of the marks from 1998 correlated with the marks from 2000. In addition to the changes in drag marks, two new types of small-scale pockmarks were identified. Tadpole pockmarks are pockmarks that are located at the terminal end of a drag mark. Beaded pockmarks are pockmarks that are arranged along a drag mark, resembling a string of pearls. The identification of these features has indicated the actions of society, specifically anchoring of large vessels and drag fishing, as possible mechanisms for pockmark initiation.

Recent detailed mapping of other locations in Penobscot Bay have revealed the presence of another significant pockmark field located close to the Black Ledges in East Penobscot Bay. Unlike the Belfast Bay field, the Black Ledges field is actually a conglomeration of six smaller, discrete pockmark fields that occur in isolated Holocene sedimentary basins

Penobscot Bay holds a wealth of information about biogenic-methane sourced pockmarks. Areas of the bay hold massive fields, small fields, isolated pockmarks, and extremely gas-rich sediments. The combination of all of these environments leads to a possible evolutionary model for pockmarks and pockmark fields. All of the locations examined in detail within the bay appear to be in infant to mature stages of evolution. The old age, death and birth stages do not appear to be represented. Addition of sites from other locations in Maine could help to further constrain the model.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1. PURPOSE

This work was designed to elucidate pockmark processes active in Penobscot Bay. Geophysical techniques and geographic information systems technology was used in combination to answer the following questions: 1) Is the pockmark field in Belfast Bay active? (Chapter 3); 2) Can the activities of society initiate pockmark activity? (Chapter 4); 4) Pockmarks are present within Penobscot Bay in locations other than Belfast Bay (Barnhardt and Kelley, 1995). Are these features similar to those in Belfast? (Chapter 5); and 5) What are the stages of evolution in a pockmark field, and what stages are evident in Penobscot Bay? (Chapter 6).

1.2. POCKMARKS: DEFINITION AND FORMATION

The release of pressurized fluids from below the seabed results in seafloor depressions, or pockmarks. Pockmarks are circular in plan view and semi-circular in cross section, with a three-dimensional section resembling one third to one fourth of a sphere. Currents and slumping can deform their basic morphology (Rogers, 1999; Hovland and Judd, 1988; King and McClean, 1970). They range from less than one meter to greater than 700 meters in diameter with depths exceeding 30 meters. Side slopes can approach the angle of repose (Hovland and Judd, 1988). All known pockmarks were reported from fine-grained sediments occurring in lakes, fjords, estuaries, inner and outer continental shelves, and deeper marine basins (Hovland and Judd, 1988)

Fluids such as water (fresh, salt, or brine) and light hydrocarbon gases create pockmarks (Hovland and Judd, 1988). Water occurs as seeps and springs on the seafloor driven by differences in head and solute concentrations. Hydrocarbon gases such as methane (CH_4), ethane (C_2H_6), propane (C_3H_{10}), butane (C_4H_8), and pentane (C_5H_{12}) can all form from thermal cracking of higher order hydrocarbon chains within the Earth's crust. Smaller molecules, such as methane, migrate more easily through overlying strata to the seafloor. Methane is also formed by decay of organic matter in anoxic environments, which occur in the shallow subsurface within unconsolidated sedimentary materials.

Reports on the composition of pore fluid in Penobscot Bay (Figure 1.1) vary. Ussler et al. (1999) reported fresh groundwater as the pore fluid for pockmark formation. More recent investigations with in situ geotechnical sampling devices identified water, CH_4, and carbon dioxide (CO_2) (H. A. Christian, unpublished report 2000). Carbon dioxide is an expected associated product, created by biological metabolism and anaerobic oxidation of CH_4. Large zones of acoustic wipeout and gas-enhanced reflectors observed on seismic reflection profiles provide additional evidence for gas in the shallow subsurface (Yuan et al., 1992) as seen in other bays worldwide (e.g., Schubel, 1974; Fader 1991; Martens, et al., 1999) (Figure 1.2). The depth to the bubble front varies, and was observed as shallow as 1.5 m below the sediment-water interface in the study area.

The mechanisms of gas release and gas transport are not yet identified in Penobscot Bay. Theories for release include: 1) catastrophic release of gas on an episodic timescale; 2) continuous release of minor amounts of methane; and 3) a

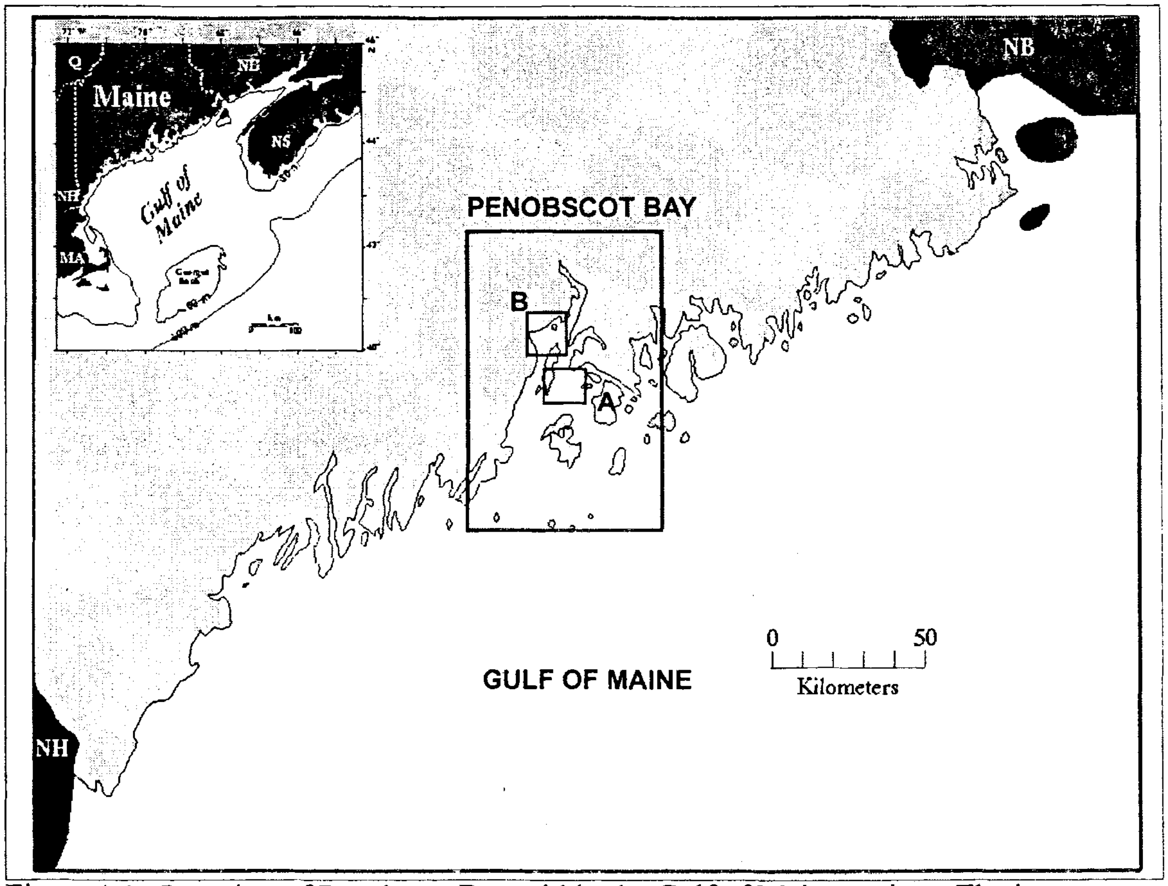

Figure 1.1. Location of Penobscot Bay within the Gulf of Maine region. The inset map shows the location of the Maine coast in the Gulf of Maine. The large box locates Penobscot Bay. The two smaller boxes locate the two study areas, Belfast Bay (A) and the Black Ledges (B). NH is New Hampshire and NB is New Brunswick, Canada. Modified from Kelley, 1987.

combination of these mechanisms with small, episodic releases on short timescales such as tidal cycles or storm frequencies, coupled with slow seepage (Kelley et al., 1994). Theories for gas transport include: 1) vertical diffusion through the sediment column; 2) lateral migration along zones of increased porosity and permeability (piping); 3) vertical migration induced by cyclical loading and unloading of the sediment column due to tides and waves; and 4) vertical migration through piping.

Grain sizes larger than silt allow CH_4, in bubble form, to pass through interconnected pore spaces and escape without developing pressurized reservoirs. Fine-grained sediments trap migrating CH_4 and allow pressurized reservoirs to develop and

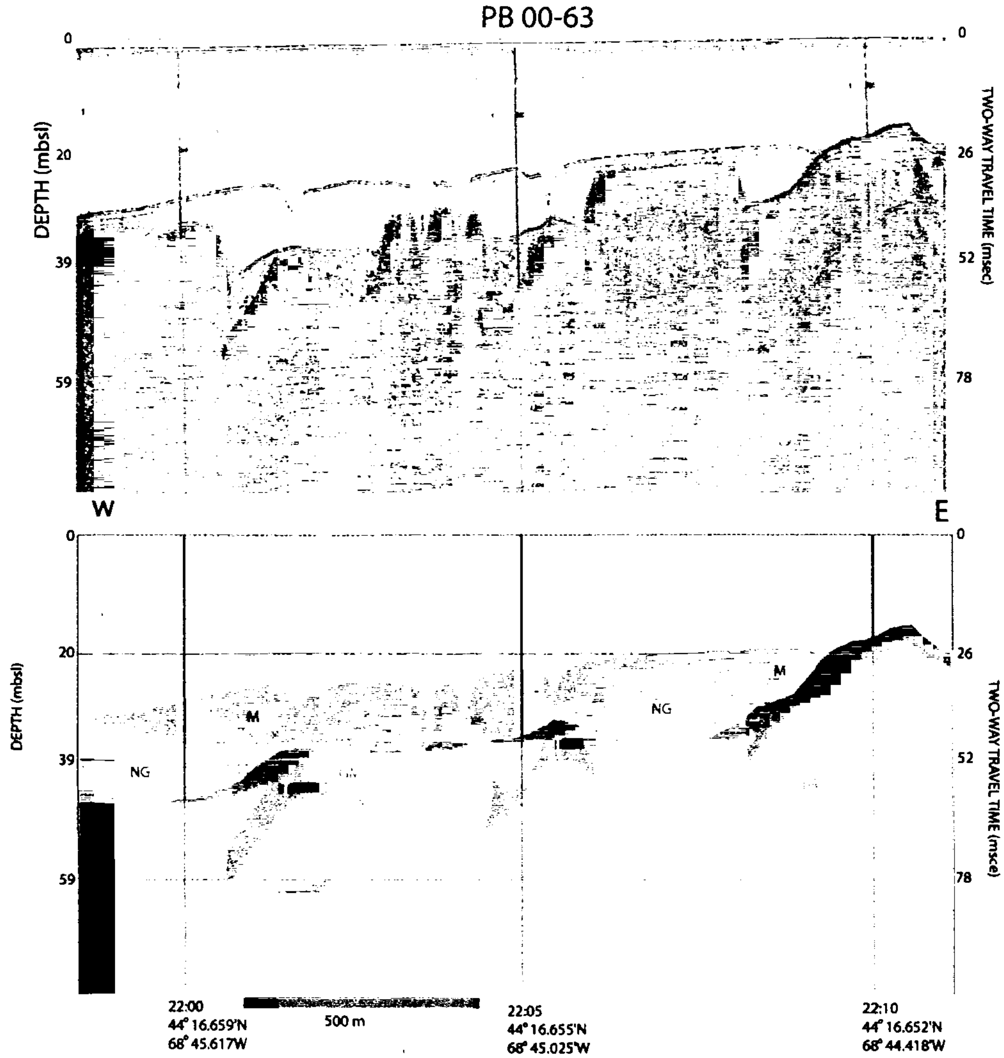

Figure 1.2. Seismic Reflection Line PB-00-63, Penobscot Bay. A sample seismic line through Penobscot Bay shows the general stratigraphy and acoustic wipeout due to gas-charged sediments and associated pockmarks. Data were collected with an ORE Geopulse boomer system at 700-2000 Hz. Units are: bedrock (BR), till (T), glaciomarine sediments (GM), Holocene mud (M), and natural gas (NG). Time marks are in EST (hr:min), DGPS navigation

possibly create pockmarks. CH_4 migrates on the molecular level and in dissolved form driven by concentration gradients. Decreased pressure or increased supply causes CH_4 concentrations in solution to become super-saturated resulting in the formation of free CH_4 gas bubbles in the sediments. Migration of bubble-form CH_4 is highly dependant on sedimentology, specifically permeability. A pockmark is formed when the buoyancy of the reservoir exceeds the pressure from the overlying water and sediment. An event, such as an earthquake, may also disturb the sediment and facilitate gas escape (Hovland and Judd, 1988).

There are three theories on how gas-escape pockmarks form in Penobscot Bay. 1) The catastrophic model indicates that pockmarks form instantaneously by major eruption events (Kelley et al., 1994). The time between major events is long for earthquakes or short if due to major storms unusual tides. The pockmark form is maintained through slow seepage of methane or current action. A large plume of sediment and pore fluid was observed on an EG&G 260 sidescan sonar image collected in 1989 (Kelley et al., 1994) suggesting this is a mechanism active in Belfast Bay. 2) In the slow-seep model, methane gas release from the subsurface occurs almost continuously (Kelley et al, 1994). The bubbling methane loosens sediment, which is transported by tidal and non-tidal currents to slowly excavate a pockmark over an extended period of time. 3) The combination model allows for both the catastrophic and slow-seep models to form a single pockmark over various time scales and methane activity levels (Gontz et al., 2001b).

Two additional theories allow pockmark formation without gas escape. 1) Paull et al., (1999) suggested ice rafting of seafloor sediments excavates forms similar to pockmarks. 2) Hovland and Judd (1988) reported the formation of pockmarks by groundwater seepage in fjords. Neither of these mechanisms is considered likely in Penobscot Bay. Temperatures at the seafloor and one meter below during December are too warm to allow freezing of freshwater (H. A. Christian, unpublished report, 2000). The glaciomarine sediments prevent the flow of groundwater in any volume.

1.3 SIGNIFICANCE OF POCKMARKS

Pockmarks affect the marine environment in several different ways including: 1) the water column is affected by increased turbidity and reduction in density; 2) biologic activity may benefit from an easily accessible source of labile carbon, if organisms able to exploit this source are present; 3) the sediment column suffers reduced strength from the presence of bubbles; and 4) there is a potentially large, but poorly understood, impact on the global climate system through the release of greenhouse gases. All of these effects are related to the release of pore fluids and sediments into the water column.

The release of pressurized pore fluids excavates a crater to a depth that is limited by the supply of the pore fluid, local sedimentology, and stratigraphy. Pockmark excavation resuspends sediment, resulting in increased levels of local turbidity, which could affect primary productivity in phytoplankton and benthic algae due to attenuation of light. Turbidity can also adversely affect filter-feeding organisms, such as clams and mussels, by inhibiting feeding processes. Fine-grained material can clog the filtering mechanisms and starve the organism (Garrison, 1996). In addition to increased turbidity, methane released into the water column alters the density of the water column. This could affect organisms and human activity that hinge on the buoyancy force of the water column.

Specialized communities have adapted to utilize CH_4 released from pockmarks and seafloor seeps. Bacterial mats formed from a methanogenic species are the basis of such communities. Other organisms, like bivalves and crabs, come to feed on the bacteria. Evidence for these communities, in the form of high concentrations of bivalve shells and white bacteria mats has been observed in pockmarks (Fader, 1991; Hovland and Judd, 1988).

Below the seafloor, CH_4 creates hazards by reducing the strength of the sediment column. CH_4 occurs in three states below the seafloor: dissolved in the pore water, as free gas bubbles, and as clathrates (methane hydrates). Although dissolved CH_4 can occur anywhere in the sediment column, only minor amounts of CH_4 can be stored in the dissolved state (0.033 ml of CH_4 per 1.0 ml of water at 20 °C, 1.0 atm) (Voltaix Incorporated, 1996). CH_4 dissolved in pore water has no effect on the sediment strength. Free gas bubbles of CH_4 occur where CH_4 production in, or transport to, an area is far greater than the amount of CH_4 that can be dissolved in the pore water or escape from the sediment column. These areas are seen as wipeout curtains or acoustic turbidity on seismic reflection profiles (Figure 1.2) (Yuan et al., 1992). Free gas bubbles have the potential to greatly reduce the strength of the sediment, creating an unstable seafloor susceptible to failure from loading or slope oversteepening (Ellis and McGuinness, 1986; Hill et al., 1992). Clathrates require high pressures and low temperatures found only on deep continental margins. The temperature and pressure regime are currently not favorable for sustaining clathrates in Penobscot Bay and they are not discussed further (see Rogers, 1999 for details).

Once CH_4 is released from sediments, it can travel through the water column to the atmosphere. Within the water column, chemical oxidation and biological metabolism alters CH_4 to CO_2 and water. CH_4 that enters the atmosphere has potentially profound effects on the global climate system. CH_4, like CO_2, is a greenhouse gas and can induce global warming. One molecule of CH_4 is as potent as 21 molecules of CO_2 in trapping infrared radiation, thus enhancing the "greenhouse effect." The amount of CH_4 that enters the atmosphere from sub-seabed sources is unknown (Lammers et al., 1995). Large volumes of CH_4 are thought to have contributed to events such as the extinction of the dinosaurs at the Cretaceous-Tertiary boundary and Tertiary climate warming (Max et al., 1999).

Research has yet to observe definitive signs of enhanced biologic activity in Penobscot Bay, but studies indicate that the potential exists (R. Arnold, unpublished report, 2001). The volume of CH_4 released to the water column and atmospheric system are unquantified. Research is needed to fully understand the dynamic environments and climate system present in Penobscot Bay.

1.4 Site Characterization: Penobscot Bay

My work focused on two major areas of Penobscot Bay, Maine: Belfast Bay and the Black Ledges (Figure1.1). Belfast Bay, the site of a well-mapped pockmark field (Kelley et al., 1994; Rogers, 1999), is a small northwest extension of Penobscot Bay at the head of West Penobscot Bay. The Black Ledges is a series of bedrock ledges and small islands in East Penobscot Bay.

Penobscot Bay is the largest embayment on Maine's coast, encompassing nearly 1720 km^2. The bay is located midway between the New Hampshire and Canadian borders, aligned nearly due north-south and centered on 68° 55' W. The river drains 19,464 km^2 north of Eddington (120 km from the mouth) within the state of Maine, and has a mean peak flow of about 1530 m^3/sec during the spring freshet in March. The Bay drains an additional 428 km^2 within the state of Maine, but not encompassed in the Penobscot River drainage basin.

Penobscot Bay experiences diurnal tides. The head of tides is located at Veazie, approximately 93 km north of the outer edge of the bay, where a hydroelectric dam exists. Spring tidal ranges are about 5.1 m at Bangor near the head of tides, 4.4 m at Belfast, and 3.6 m at Owl's Head on the outer bay (International Marine, 2000). The tidal ranges experienced in Penobscot Bay fall near the boundary between mesotidal and macrotidal environments.

Various rock types and formations dominate the Penobscot Bay area. Precambrian to Devonian bedrock is mantled with a blanket of unconsolidated Quaternary deposits. The Quaternary section is discussed below. Rocks comprising the bedrock are metamorphic and intrusive complexes; sedimentary rocks are absent (Figure 1.3) (Osberg et al., 1985). Metamorphism heated the original sedimentary and volcanic rocks well beyond the temperature-pressure regime for petroleum production (the oil window); thus any hydrocarbons that might have been present have been volatized or converted to bitumen (Figure 1.4) (Floodgate and Judd, 1992).

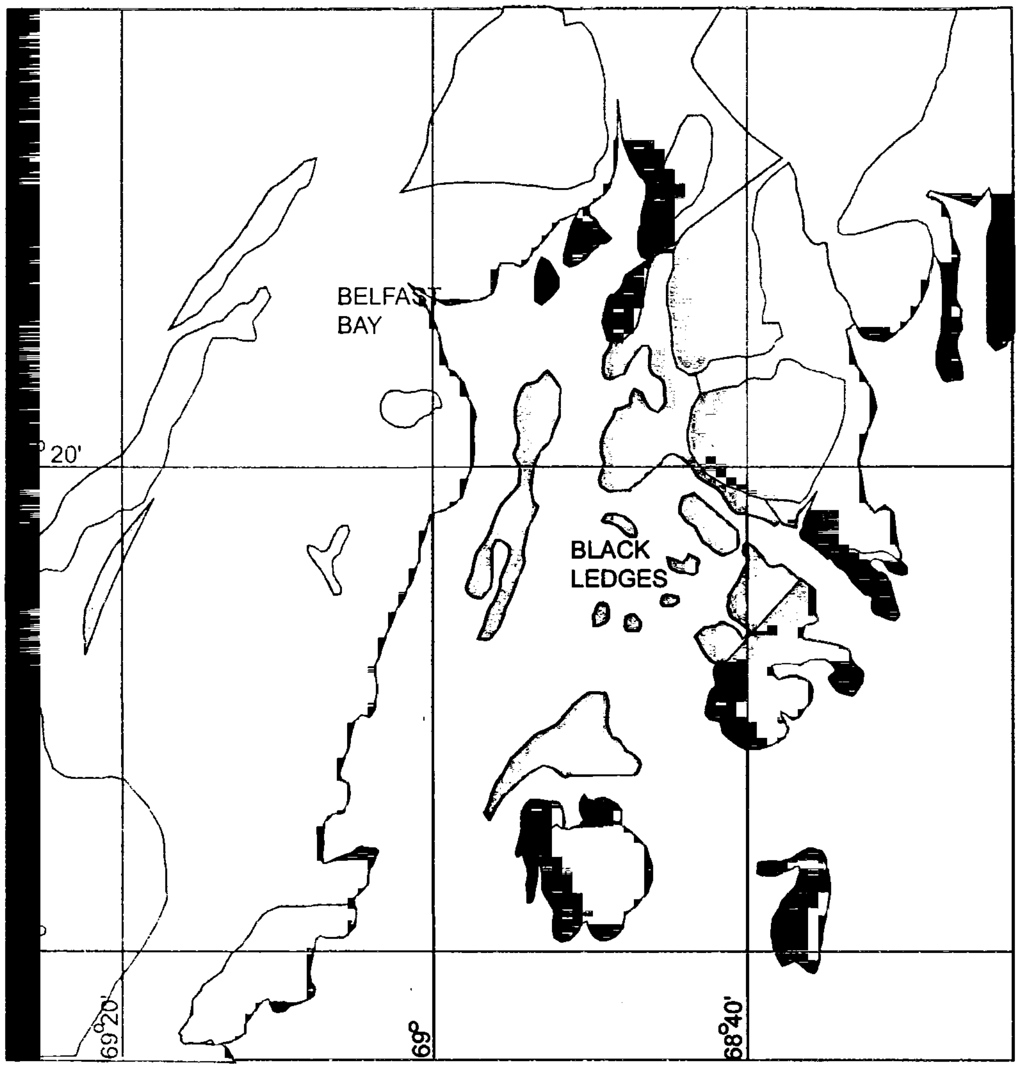

Figure 1.3. Simplified Bedrock Map of Penobscot Bay Region. Rock units found within the Penobscot Bay region include metasedimentary rocks (pink), metavolcanic rocks (yellow), and intrusive complexes (blue). Bedrock ages are older than Silurian. Features have been omitted from the Blue Hill Bay region for simplicity. Modified from Osberg et al., 1985.

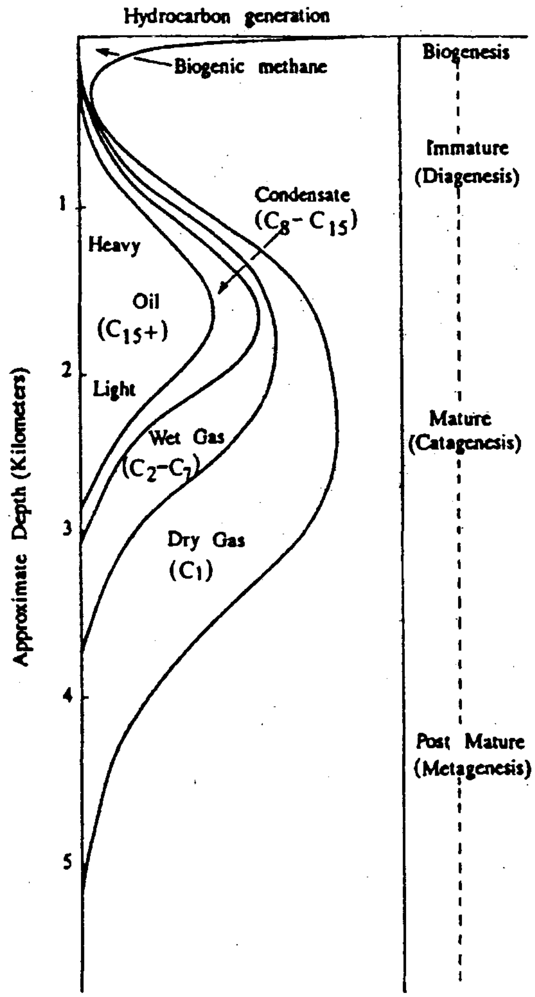

Figure 1.4. The Oil Window. The form of hydrocarbon found in the subsurface is a function of the pressure the hydrocarbon-bearing unit has experienced. Lithologies in the Penobscot Bay region traveled through the window to the metagenesis stage prior to present exposure near the surface (Floodgate and Judd, 1992).

The position of islands and channels are governed by the bedrock composition and structure. The channels of both East Penobscot Bay and West Penobscot Bay in the vicinity of Isleboro Island are fault controlled (Osberg et al., 1985).

Glaciogenic sediment represents the Quaternary Period. Retreat of the latest Wisconsinan ice sheet left its mark through glacially scoured bedrock outcrops mantled by unconsolidated sediments (Thompson and Borns, 1985). Generally, bedrock is overlain by a thin drape of till, with thickening on the southeast sides of slopes. Till is occasionally absent from this section. The Presumpscot Formation (Bloom, 1963), a glaciomarine mud with occasional sandy beds, overlies till and/or bedrock. Two distinct seismic facies are present in the Presumpscot Formation (Belknap et al., 1989; Belknap and Shipp, 1991). A lower, regionally extensive unit is found directly over bedrock or till and is draped concentrically over the underlying topography. An upper unit occurs filling in topographic lows within the draped unit occurs in limited areas. The Holocene-Pleistocene unconformity truncates acoustic reflectors of the Presumpscot Formation between the shoreline and lowstand of sea level. Holocene sediments, sourced from eroding Pleistocene deposits and riverine contribution, cap the section. Natural gas, biologically generated CH_4, occurs within the unconsolidated section, most often within the Holocene sediments and within several meters of the seafloor (Belknap and Shipp, 1991; Barnhardt and Kelley, 1995; Rogers, 1999) (Figure 1.5).

Sea level in the Penobscot Bay region varied 130 m since deglaciation. The relative sea-level curve for Maine (Figure 1.6) details the changes (Barnhardt et al., 1995). Paleodeltas were created seaward of current river mouths along Maine's coast during lowstand (Barnhardt, et al., 1997) and transgression (Belknap et al.,

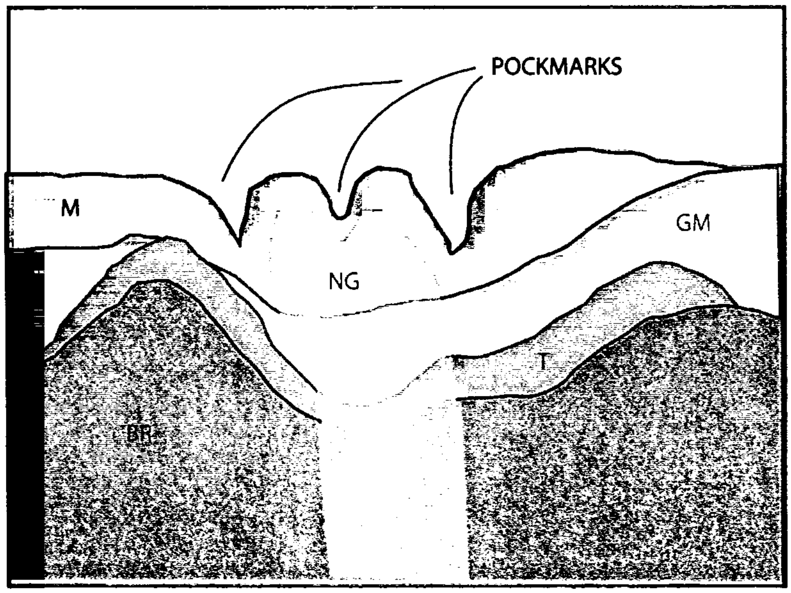

Figure 1.5. Simplified Quaternary section representative of Penobscot Bay. The units in the surficial geology of Penobscot Bay are Bedrock (red) Paleozoic and older; Till (purple), Pleistocene; Glacial marine clay, the Presumpscot Formation (blue) with two seismic facies, lower draped and upper ponded facies, Pleistocene; Modern muds (gray), Holocene; and Natural Gas (green), Holocene

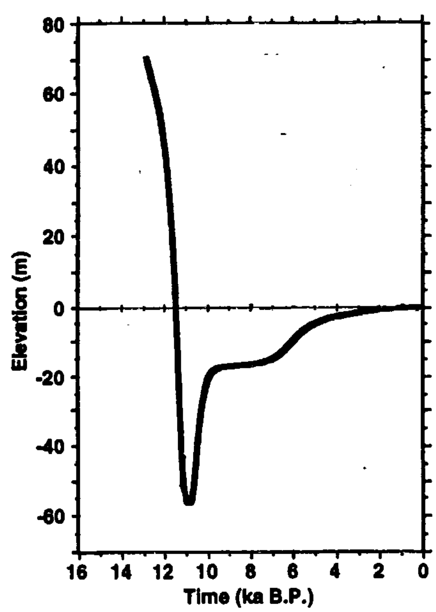

Figure 1.6. Relative sea-level history for coastal Maine. Sea level has varied greatly due to glaciation. Highstands at 140m inland and ~70m in Penobscot Bay are recognized from paleodeltas and lowstands at -60 m from submerged shoreline features from offshore (modified from Barnhardt, et al., 1997).

2001). During lowstand and transgression (about 10 ka to present), lakes and various types of wetlands were probably created on the emergent surface. As sea level rose, these features were drowned and potentially buried by sediments. It is these features that are hypothesized as the source of organic material for CH_4 genesis (Kelley et al., 2000).

Current research has revealed a paleodelta within Penobscot Bay (Belknap et al., 2001). The delta is located in the upper region of East Penobscot Bay at about 30 m below present sea level. Radiocarbon dates on life-position *Mya arenaria* place the feature at about 8730 uncorrected radiocarbon years before present (Barnhardt et al., 1997). This delta's construction apparently coincides with a slow-down of sea-level rise. Preservation of the feature could be due to channel avulsion or a rapidly increased rate of sea-level rise around 6-7 ka (Belknap et al., 2001).

1.4.1 Belfast Bay

Belfast Bay is a northwest extension of Penobscot Bay at the head of West Penobscot Bay. The Passagassawaukeag River flows into Penobscot Bay at the town of Belfast, creating a harbor. The major, present-day channel of the Penobscot River flows into Belfast Bay from the east and runs through West Penobscot Bay, along the northwestern and western shore of Isleboro Island (Figure 1.7). The area is also home to a marine-based economy with a major port facility, which provides an opportunity to investigate anthropomorphic effects.

Belfast Bay was well mapped twice within a ten-year time frame (1989 and 1998). Minor outcrops of till and bedrock occur in the bay at several locations, but muddy sediments dominate Belfast Bay (Figure 1.8) (Kelley and Belknap, 1989;

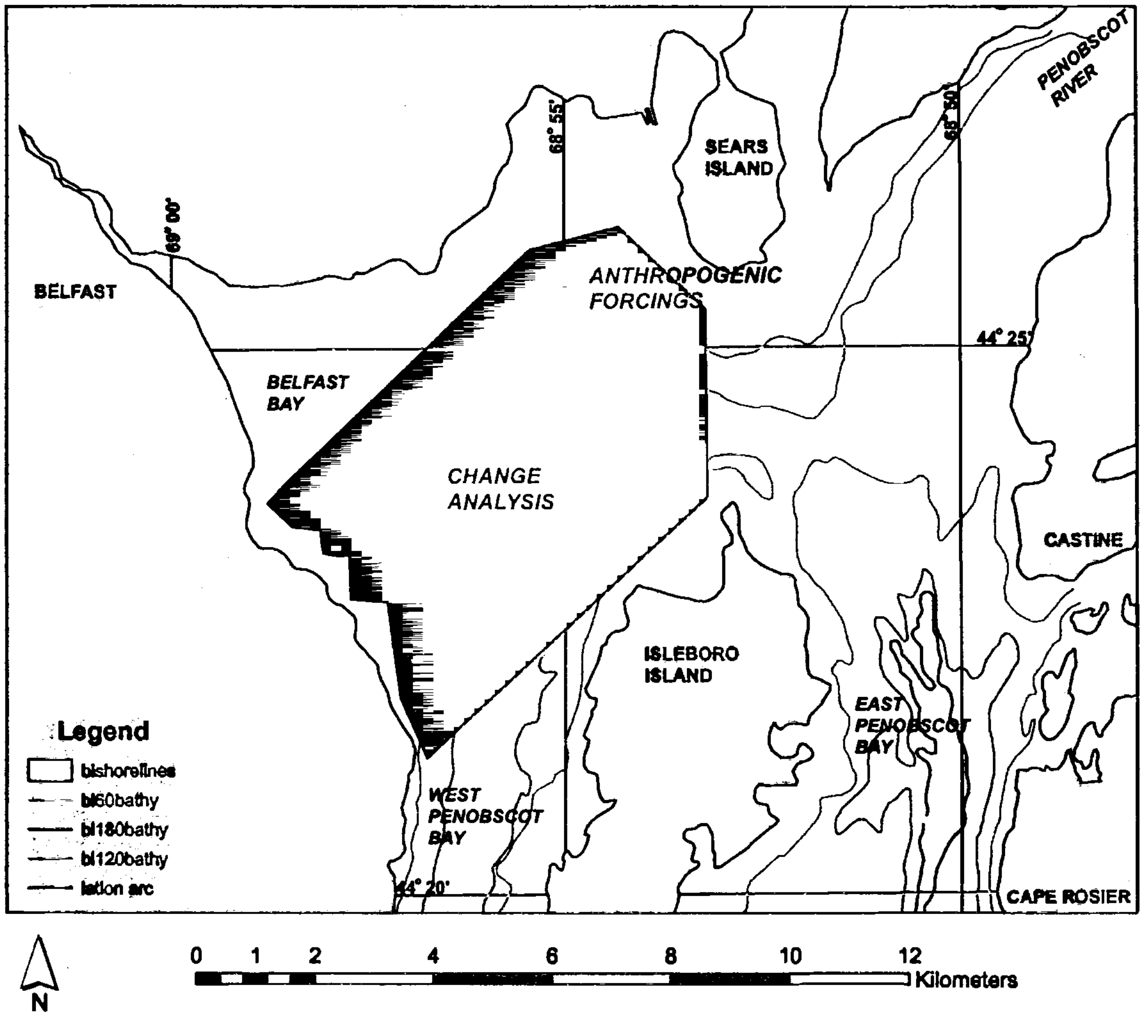

Figure 1.7. Location of the Belfast Bay study areas. Belfast Bay is located in the northwestern portion of Penobscot Bay (Figure 1.1). The heavily outlined large box shows (A) the area of study for Chapter 3 and the small box (B) shows the study area for Chapter 4. Coastline and bathymetry were simplified from NOS chart 13302.

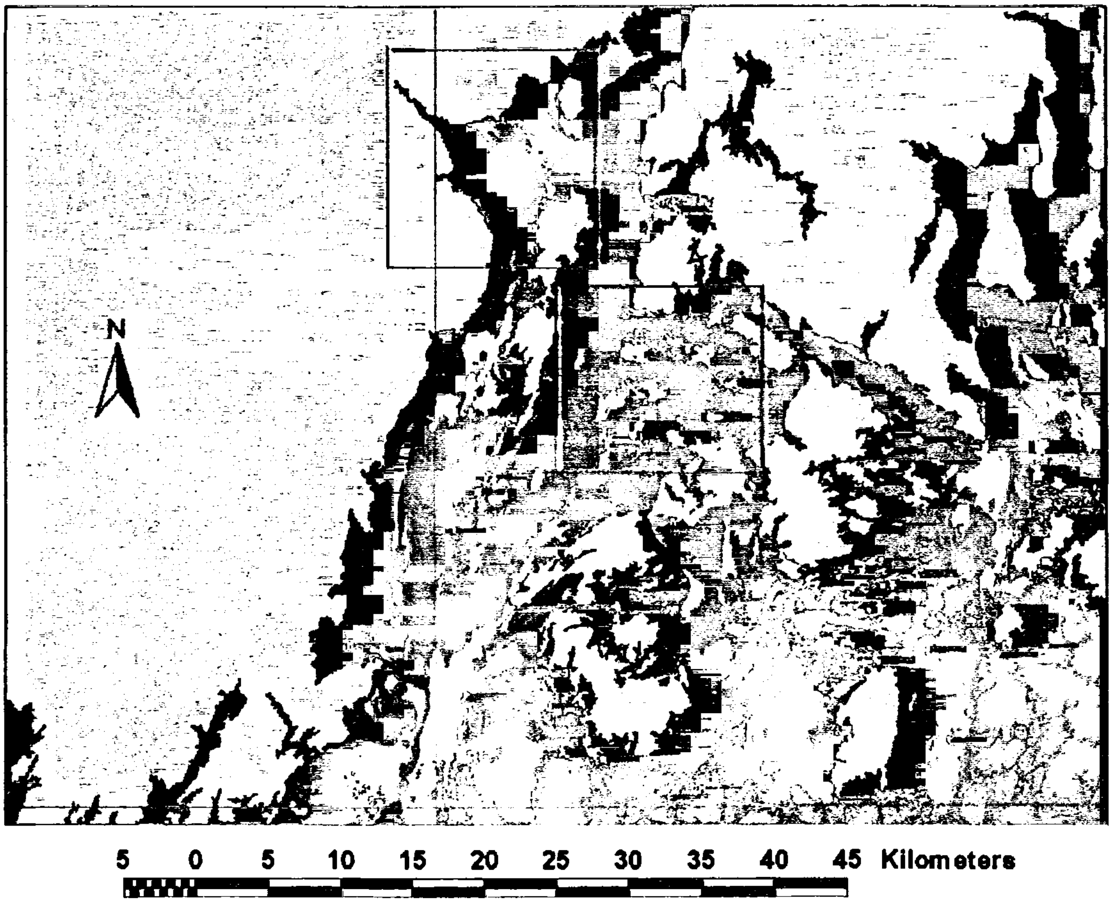

Figure 1.8. Surficial geology of Penobscot Bay. Belfast Bay is located within the upper left box and Black Ledges within the lower right box. Gray areas are land, blue is muddy, green is gravelly, red is rocky, and yellow is sandy. Modified from Barnhardt et al., 1996 a,b.

Barnhardt et al., 1996b). Based on Roger's (1999) measured seismic data, the muddy Holocene sediments can reach thicknesses of well over 30 m and are gas-charged in many places.

Water depths throughout Belfast Bay vary greatly. Generally, the water is about 20 m to 25 m deep in the central bay, with depths approaching 70 m in the southern portion. Variation in depth is controlled by three factors: 1) flat, scoured, sloping seafloor; 2) pockmarks; and 3) till and bedrock outcrops.

1.4.2 Black Ledges

The Black Ledges area is located in central East Penobscot Bay (Figure 1.9). The area is a collection of islands, ledges and shoals with narrow channels and large areas of open water between. This study is centered at 44^{o} 16' N by 68^{o} 49' W and encompasses 38 km^2. Black Ledges and several small rocky shoals and islands form the northern limits of the study area. To the south lies Beach Island and numerous other small islands and rocky shoals. To the east lies Little Deer Isle. The western boundary comprises the main channel of East Penobscot Bay. This area south of the Black Ledges has not been mapped in detail prior to this work, although several reconnaissance lines were collected in the area during multiple cruises by University of Maine (UM) and Maine Geological Survey (MGS) researchers after 1983.

Bottom sediments in the Black Ledges area are highly variable (Figure 1.8). Surficial geology is composed of muddy or gravelly sediments along with rocky areas, representing the lithologic and acoustic units of the described section (Figure 1.5) (Kelley and Belknap, 1989; Barnhardt et al. 1996 a,b). Gas-enhanced reflectors are common,

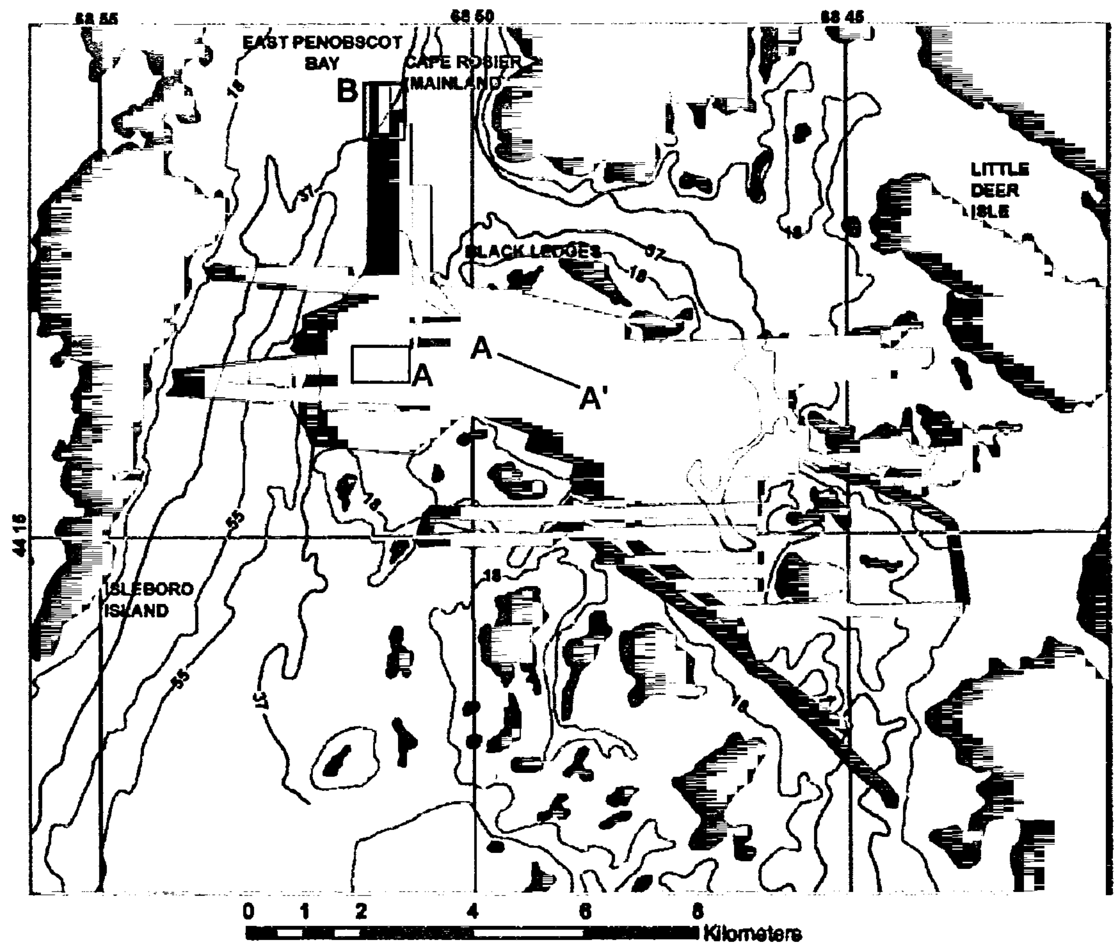

Figure 1.9. Location of the Black Ledges study area. The Black Ledges area is a series of islands and shoals in East Penobscot Bay (Figure 1.1). The heavily outlined box details the area of study for Chapter 5. Coastline and bathymetry were simplified from NOS chart 13302.

but large areas of gas-charged sediments are absent. This indicates that methane is present in the subsurface, but in concentrations less than those occurring in Belfast Bay.

Water depths within the Black Ledges area are generally shallower than 25 m. The deepest areas occur on the western edge along the main channel of East Penobscot Bay, and approach 50 m. Ledges and rocky shoals form shallow areas, several of which are aerially exposed during astronomically low tides.

1.5 Previous Work

King and McLean (1970) first identified pockmarks on the outer continental shelf. Since then they have been recognized in various environments worldwide, such as lakes, fjords, estuaries (Hovland and Judd, 1988; Fader, 1991; Kelley et al., 1994), outer continental shelf (King and McClean, 1970; Hovland and Judd, 1988), and deep marine basins (Hovland and Judd, 1988). The proposed mechanisms for formation are as varied as the environments of occurrence and include escape of freshwater (Harrington, 1985; Hovland and Judd, 1988), marine mammal feeding traces (Nelson et al., 1987; Hovland and Judd, 1988), ice rafting (Paull et al., 1999; Ussler et al., 1999), and earthquakes (Field and Jennings, 1987; Hovland and Judd, 1988; Hasiotis et al., 1996). CH_4 can form from biogenic sources (Hovland and Judd, 1988; Kelley et al., 1994; Rogers, 1999; Kelley et al., 2000) or deep-seated hydrocarbon deposits (Hovland and Judd, 1988;). Gas and fluid migrate based on diffusion and advection, lateral migration along zones of increased porosity, pressure differences, and cyclic loading (Wheeler, 1992).

1.5.1 Pockmark Occurrences

King and McClean (1970) used sidescan sonar to recognize circular depressions on the Scotian Shelf. They coined the term "pockmark" for circular to subcircular depressions on the seafloor. After their initial discovery, other workers recognized pockmarks in many locations and environments. Pockmarks are found in freshwater environments as well, including Lake Champlain and Lake Superior (Hovland and Judd, 1988). The majority of pockmark research has focused on continental shelves and deeper marine basins where petroleum development is concentrated.

The Scotian Shelf, North Sea, and Arabian Gulf are all known for their petroleum reserves. Pockmarks are found in great abundance in these areas in water depths of about 200 m to 350 m. The large pockmark fields are in close association with known subsurface petroleum reserves and upward migration of light hydrocarbon gases from these reservoirs are the likely source of fluids for pockmark formation (King and MacLean, 1970; Josenhans et al., 1978; Ellis and McGuinness, 1986; Hovland and Judd, 1988).

Ostericher (1965), lacking sidescan sonar, incorrectly identified pockmarks in Penobscot Bay as tidal channels with a subbottom profiler. Knebel and Scanlon (1985) and Scanlon and Knebel (1989) used sidescan sonar in the same area and reinterpreted Ostericher's tidal channels as pockmarks. Other mid to high-latitude glaciated estuaries on the North American east coast, such as Blue Hill Bay, Maine (Kelley et al., 1994), Passamquoddy Bay, Maine, USA and New Brunswick, Canada (Fader, 1991) and Halifax Harbor, Nova Scotia, Canada (Fader, 1991) hold large pockmark fields.

Wherever pockmarks are recognized, fine-grained sediments dominate the surficial sediments. Sediments with grain sizes larger than clay and silt have increased permeability, and allow the pore fluids to escape, without building up the required pressures for pockmark formation. In these environments, sand and mud volcanoes develop in place of pockmarks (Hovland and Judd, 1988).

1.5.2 Mechanisms for Formation

Two major theories of formation, both involving expulsion of pore fluids, have been proposed for the pockmarks of Penobscot Bay including: 1) freshwater seepages and ice rafting and 2) expulsion of gases from subsurface pressurized reservoirs. These two theories are supplemented with an additional mechanism, feeding traces.

Nelson et al. (1987) proposed that large depressions on the floor of the Bearing Sea are the result of feeding behavior of gray whales. The waters where pockmarks are found within Penobscot Bay are shallower than 50 m and in close proximity to land. The waters also experience heavy ship traffic. Gray whales are not found in the Gulf of Maine and none of the species of whales inhabiting the Gulf of Maine are bottom feeders.

Paull et al. (1999) suggested ice rafting as a mechanism for pockmark formation (Figure 1.10). Their suggested mechanism is that fresh groundwater would upwell from the sediment into the overlying seawater. The seawater would be cold, below the freezing point of freshwater. The freshwater would freeze upon mixing with the overlying seawater. The ice would break free from the seafloor and carry small amounts of sediments away. Over an extended period of time a depression would form over the seep. This mechanism has not been directly observed, and is definitely discounted in Penobscot Bay for several reasons: 1) seafloor temperatures during winter months are not sufficiently cold enough to freeze freshwater, 2) the glaciomarine sediments act as an aquaclude and transmit minimal amounts of groundwater, and 3) a total of over 5,500 pockmarks have been observed in Penobscot Bay, suggesting at least that number of freshwater seeps within a limited area.

Hovland and Judd (1988) present a model for pockmark formation via the expulsion of pressurized pore fluids (Figure 1.11). Natural gas forms reservoirs in the subsurface and become pressurized from addition of natural gas or changes in the confining pressure. The pressure of the reservoir exceeds the confining pressure or the reservoir is disturbed allowing the reservoir to vent and expel pore fluids. The expulsion

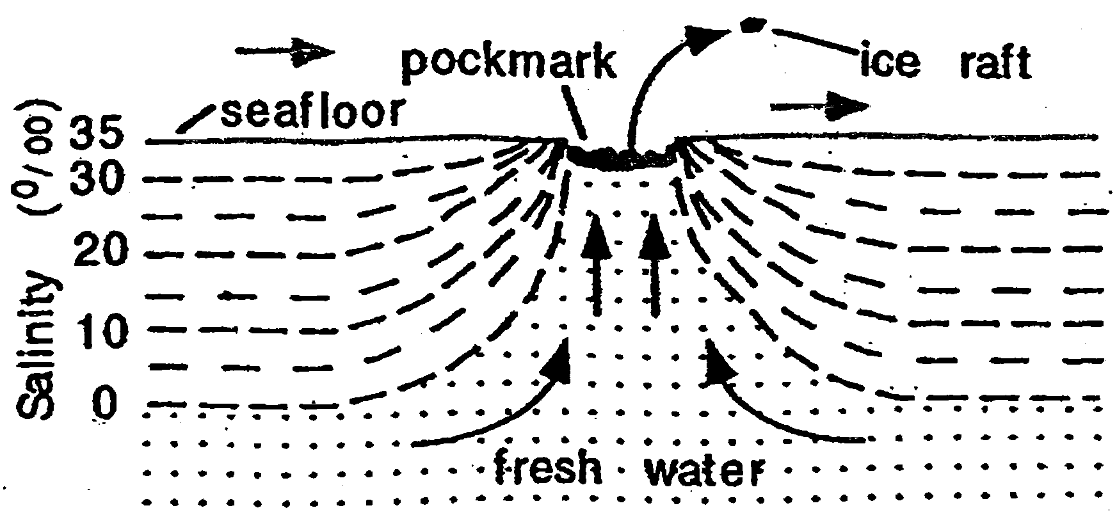

Figure 1.10. The Paull et al. (1999) model for pockmark formation. Paull et al. (1999) presented a model for pockmark formation involving upwelling of freshwater into sub-freezing seawater. Ice would form at the seep and carry sediment away as the ice lifted from the seafloor. This action would create a depression at the source of the freshwater seep.

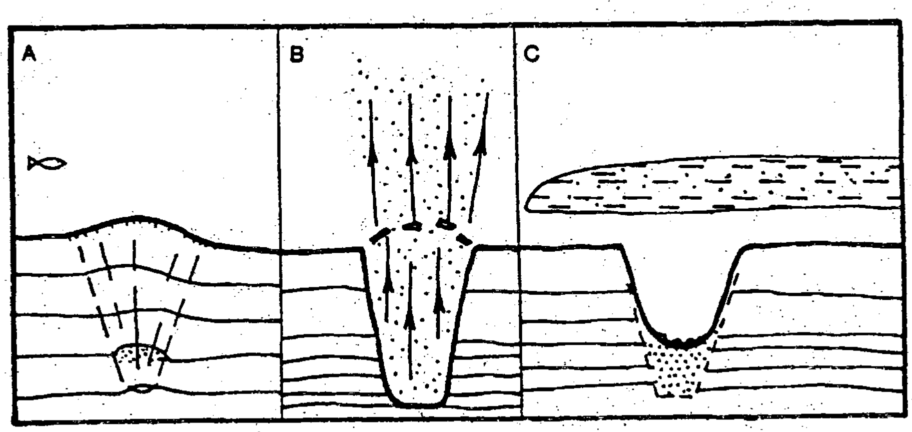

Figure 1.11. The Hovland and Judd (1988) model for pockmark formation. Hovland and Judd (1988) presented a model for pockmark formation
n driven by expulsion of pressurized pore fluids. A pressurized reservoir develops in the subsurface over time. The reservoir either becomes unstable due to disturbances in the pressures by changes in the water column elevation, alteration of the thickness sediment, or static loading of the sediments overlying the reservoir. Once unstable, the reservoir erupts, expelling pore fluid and sediments into the overlying water column. This results in the excavation of a pockmark.

of pore fluids excavates the pockmark form. This is the mechanism hypothesized for Penobscot Bay for several reasons including: 1) large concentrations of methane in subsurface in close association with pockmarks (Figure 1.2), 2) direct observation of a plume emanating from a pockmark on sidescan sonar for Belfast Bay (Kelley et al. 1994), 3) collection of CH_4 from the subsurface (H. A. Christian, unpublished report, 2000), and 4) observed overpressurization of gas-charged sediments from in situ sampling in Belfast Bay and slightly north of the Black Ledges (H. A. Christian, unpublished report, 2000).

1.5.3 Methane Genesis

Methane can form along two pathways. Themogenic methane involves breakdown of longer chained hydrocarbons while biogenic methane is produced through biologic activity.

Long-chained organic molecules, hydrocarbons and kerogens, are broken down, or "cracked", into smaller chained hydrocarbons within the Earth's crust. This breakdown results from heat and pressure associated with relatively deep burial or plate tectonic movements. The types of hydrocarbons present are governed by temperature and pressure (Figure 1.4). Increases in heat and pressure crack larger molecules into increasingly smaller molecules. The light, volatile component is driven off. The increase can remove all smaller chained molecules, leaving only a tarry substance. The rocks underlying Penobscot Bay have progressed through the zone allowing natural gas production, volatizing the hydrocarbons and driving off any gas or oil that could have been present. The structure of the Penobscot Bay area, though highly faulted, shows no evidence of older rocks emplaced as a thrust over younger, gas-rich rocks. In fact, none of the lithologies present in Maine are capable of hosting petroleum products of consequence (Osberg et al., 1985). As a result, thermal cracking of hydrocarbons and a deep reservoir source are not factors in Penobscot Bay.

Methane can also form from the decomposition of organic matter. Decay of particulate organic matter has several pathways once into the sedimentary column. The pathway depends on the availability of preferred electron acceptors: 1) oxygen; 2) nitrate; 3) metal oxides; 4) sulfate; and 5) methane production. Aerobic decay is the first pathway. It depends on the availability of dissolved oxygen. Typically, the sediment column is oxygenated to a depth of a few millimeters. Nitrate reduction depends on the availability of nitrate. Nitrate is not available in the overlying water column and is not considered to be important. Metal oxides generally refer to the availability of manganese oxide (MnO_2) and ferric oxide (Fe_2O_3). These species are available only where the sediment column is well mixed by intense bioturbation or physical processes. Sulfate reduction is the one of the two primary pathways. It depends on the availability of sulfate (SO_4^{2-}), and yields bicarbonate and hydrogen sulfide.

$$CH_2O + \tfrac{1}{2} SO_4^{2-} \rightarrow HCO_3^- + \tfrac{1}{2} H_2S \qquad \text{(eqn. 1.1)}$$

Where CH_2O is the smallest form of particulate organic matter. When all available sulfate is consumed by the reaction, methane production begins.

$$CH_2O \rightarrow \tfrac{1}{2} CO_2 + \tfrac{1}{2} CH_4 \qquad \text{(eqn. 1.2)}$$

Once produced, methane migrates vertically through the overlying sediment column. In the presence of sulfate, methane is oxidized anaerobically.

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O \qquad \text{(eqn. 1.3)}$$

In the presence of oxygen, methane is oxidized aerobically.

$$CH_4 + O_2 \rightarrow H_2O + CO_2 \qquad \text{(eqn. 1.4)}$$

Thus, as methane migrates from a zone of production toward the surface, it passes through two zones of methane oxidation (Figure 1.12).

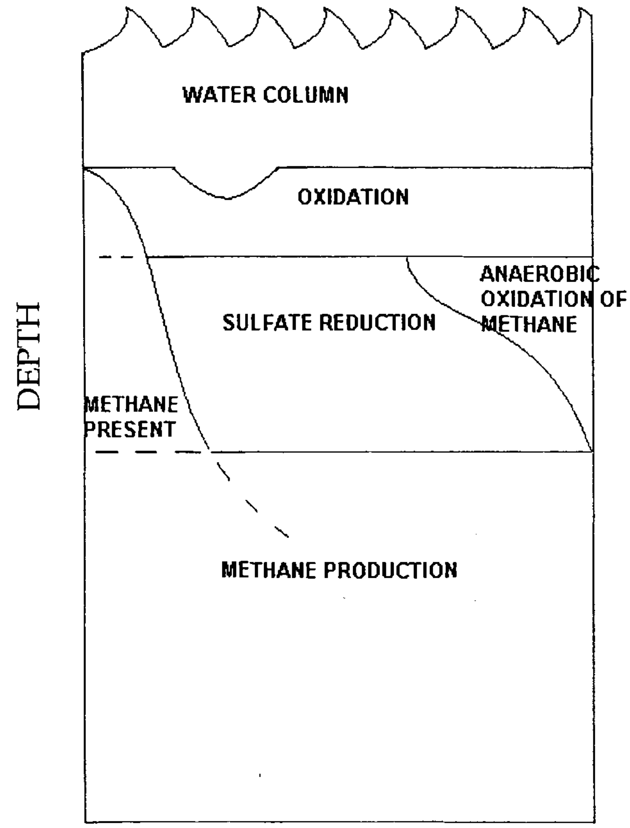

Figure 1.12. Zones of organic decay pathways and methane production and consumption within the sediment column. The pathway for decay of organic matter is controlled by the presence of preferred electron acceptors. Oxidation, the favored pathway, is active only in oxidized sediments, or generally the upper few millimeters of the sediment column. Below the zone of oxygenation, sulfate reduction becomes the dominant pathway. Once sulfate is removed from the sediments, methane production, via chemical and biological pathways, becomes dominant. Methane, once produced, migrates vertically driven by concentration and density gradients. As methane encounters sulfate in the overlying sediments, it is anaeroblically oxidized. Methane regionally depletes areas of sulfate allowing further vertical migration of subsequent methane. Methane that survives the sulfate zone encounters oxygen in the oxygenated zone and is aerobically oxidized. At times of rapid expulsion, i. e., pockmark formation, methane is vented directly from the reservoir to the water column by removing the overlying sediments.

1.5.4 Gas/Fluid Migration

Fluid migration, especially gas, interests the petroleum industry because fluids migrate based on local conditions. Understanding the migration leads to understanding of where the fluid originated and where it forms reservoirs.

Fluids migrate through earth materials driven by gradients or forces, such as buoyancy. Migration is restricted by permeability, surface tension, and wetting. In the case of gases in bubble phase, surface tension and wetting are more important and will further restrict migration of the bubble. Proposed mechanisms include diffusion and advection, pressure or buoyancy differences, and physical pumping.

Movement occurs horizontally or vertically through pore spaces or laterally along zones of increased permeability and porosity (piping). Diffusion across a concentration gradient is the simplest. Ions and molecules move from zones of higher concentration to areas of lower concentration and can have both horizontal and vertical components.

Flow based on pressure and buoyancy is common. Buoyancy forces allow fluids to migrate vertically.

Physical pumping is a bit more complicated. Cyclic loading of sediments produces a pumping force that draws fluids toward the surface (Wheeler, 1992). In the marine environment, the pumping force is generated by the pressure variations due to changes in the elevation of the water column, such as waves, tides, and storm surges.

The mechanism that creates salt and mud diapirs was suggested to include gas-charged sediments. Layers of gas-rich sediments buried under an overlying unit could be squeezed and pushed to form diapirs of gas-rich sediments in a regular pattern, similar to movement of salt driven by density differences and overlying pressure. The result would be the occurrence of pockmarks, domes, and other gas-related features along this regular pattern (Hovland and Judd, 1988).

By far, the most important mechanism in the Penobscot Bay region appears to be migration along a zone, or bed, of differing grain size. Evidence is seen on seismic reflection record in the form of gas-enhanced or bright reflectors (Figure 1.2). The reflector is enhanced by a difference in acoustic impedance resulting from methane, in bubble-phase, as well as grain-size changes. These reflectors originate from and are upslope of zones of acoustic wipeout. Pockmarks are located above gas-enhanced reflectors or they terminate at moats where till, bedrock or glaciomarine sediments crop out through Holocene muds. This suggests that enhanced reflectors and/or zones of acoustic wipeout are supplying gas for the pockmark process.

CHAPTER 2
GENERAL METHODS

Several different geophysical and geographic information systems (GIS) methods were used throughout this study. A general discussion of the equipment and methods is included with a brief methods discussion in each chapter.

2.1. Research Vessels

This project involved six days of shipboard research. The RV Friendship, captained by Tony Codega and owned by Maine Maritime Academy, was used exclusively. The RV Friendship is a converted 14-meter stern fish trawler. It has a draft of two and a half meters and a top speed of nine knots. A three-meter, double A-frame was mounted astern. It mounts hydraulic trawl and hydrographic winches. The vessel was equipped with differential global positioning satellite (DGPS) location, the Cap'n navigation software package, and depth sounder.

2.2. Geophysical Methods

Geophysical investigations were carried out with two types of equipment. Sidescan sonar was used to image the seafloor surface. Seismic reflection profiling was used to examine the stratigraphic relationships and identify areas of gas-rich sediments.

2.2.1. Sidescan Sonar

For data collected during this study, an Edgetech DF1000 digital sidescan sonar towfish was used. Archived data, acquired using an EG&G 260 analog sidescan sonar system (Rogers, 1999; Kelley et al., 1994) was also used.

The digital system consisted of two major components, the towfish and the topside processing unit. The EdgeTech DF 1000 digital towfish is capable of recording data on 100 and 500 kHz. It is equipped with a directional sensor. Optional depth and location sensors were not installed.

The topside processing unit was designed and constructed by Triton-Elics International (TE). It consists of a computer with various specialized circuit boards that convert the signal from the towfish into an image. The system is build around a 533 MHz Pentium III processor, Windows 2000 operating system, 8x CDRW drive, 8 and 20 GB capacity hard drives, an LS-120 Super Disk drive, and twin 15-inch monitors.

The towfish was tethered to the vessel via a Kevlar-jacketed data transmission cable and towed about seven meters astern of the vessel and about 3-7 m deep. The shallow water and short length of cable out eliminated the need for a winch. The cable was routed through a block attached to an A-frame. Two sets of "chinese fingers," woven rope cable grips, were used to hold the cable in place. One was placed on the cable at the required length of cable out and was the primary way of securing the towfish to the vessel. The second "chinese finger" was positioned near the opposite end of the cable, close to the point where it attached to the Triton-Elics topside unit. This served as a backup should the other "chinese finger" fail and prevented stress on the connection with the topside unit. The vessel speed was maintained between 4 and 5.5 knots. Data were simultaneously collected on 100kHz and 500kHz frequencies (Figure 2.1).

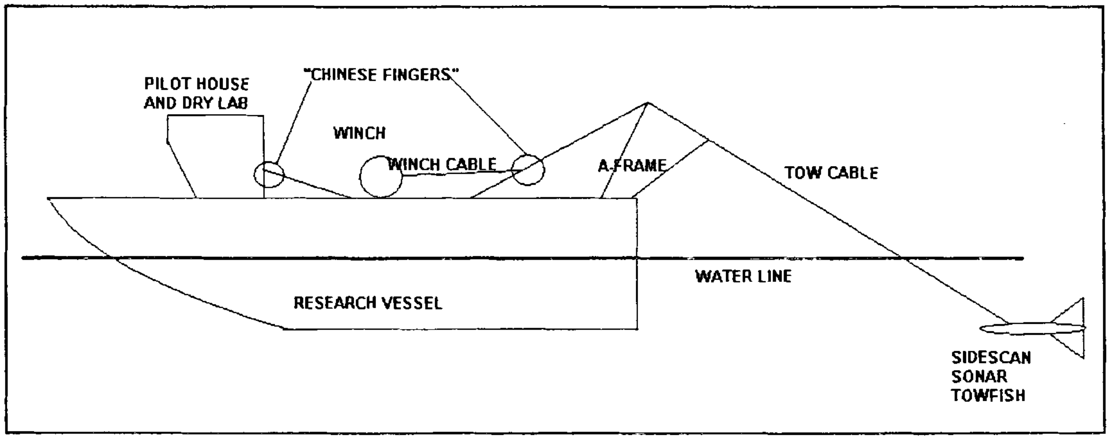

Figure 2.1. Schematic layout for sidescan sonar operations. The sidescan sonar towfish is towed behind the vessel, submerged in the water column. The depth below the surface depends on the overall water depth and acquisition range. For this study, the tow depth was shallow, about 5-7 m.

Post-processing of digital sidescan sonar data was performed on the TE topside unit with Isis Sonar v.4.54 and DelphMap, both designed by TE. Raw data were first converted to mosaic files with Isis Sonar and DelphMap. The mosaic file, an image referenced to true space, was exported in the geoTIFF format. The geoTIFF image was opened in ArcView GIS, designed by ESRI, for spatial analysis and digitizing of features (see Section 2.3. GEOGRAPHIC INFORMATION SYSTEMS METHODS)

2.2.2. Seismic Reflection Profiling

Two seismic reflection systems were used during this project. Both were surface-towed, boomer systems differentiated by the method of data processing. One system, the Ocean Research Engineering Incorporated (ORE) GeoPulse, produced an analog output while the Applied Acoustics Engineering International (AAE) boomer produced a digital output coupled to the Triton Elics topside receiver and processing computer.

The towing geometry was identical for both systems. The hydrophone array was towed from a boom to the side, enabling it to be towed outside of the wake, about three meters outboard of the rail and seven meters astern. The array was floated at or near the surface to reduce ringing noise in the record. The catamaran-mounted boomer was towed from the opposite rail approximately seven meters astern. A line was affixed to each of the two floats of the catamaran. This enabled the catamaran to be steered, like a box kite, around obstacles such as lobster pot buoys. These lines were tied off to the rail. The power cable was attached to the inboard line with duct tape to keep it at the surface and limit tangling and fouling with seaweed. The distance astern and outboard of the vessel removed the catamaran and hydrophone array from the cavitation zone created by vessel's propeller (Figure 2.2).

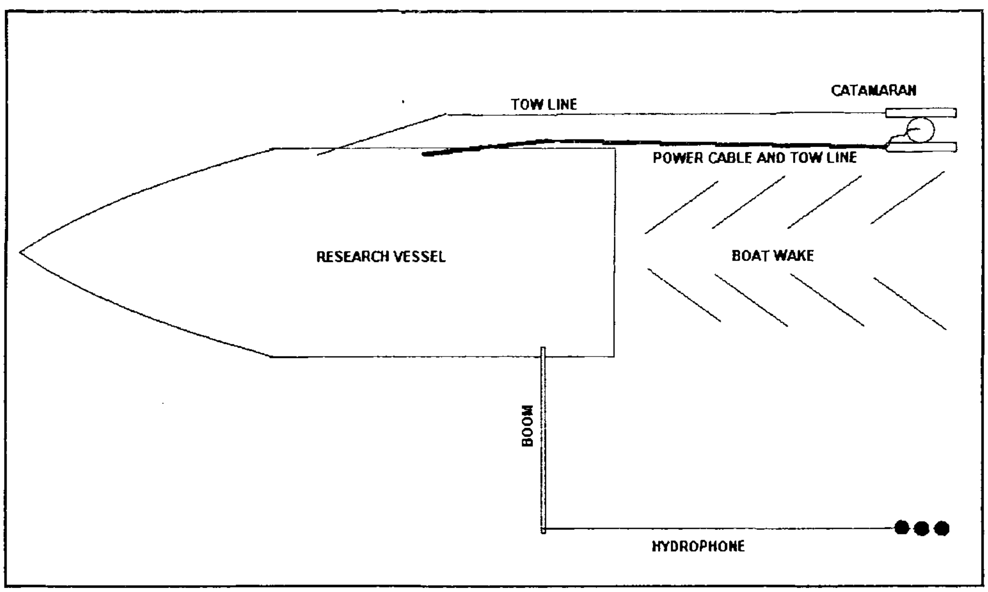

Figure 2.2. Schematic layout for seismic reflection operations, top view. All of the seismic gear used during this study was surface-towed. The catamaran-mounted energy source and hydrophone were towed from opposite sides of the vessel. A boom was used to remove the hydrophone from the vessel wake to reduce noise in the record.

2.2.2.1. Ocean Research Engineering Geopulse Analog Seismic System

The Ocean Research Engineering (ORE) Geopulse System was manufactured by ORE, Inc. It is a surface-towed, boomer system consisting of a catamaran-mounted boomer plate, an energy source, a hydrophone array, a filter and amplifier unit, and an EPC burning stylus analog printer. Data was usually filtered between 700 and 2000 Hz.

Analog records required no post-processing. Original records were photocopied onto 11"x17" paper. Original records were used to guide interpretations and subsequently archived for future use. Interpretations were drawn directly on the photocopies. Portions of records were scanned into digital image format and interpretations were digitized in Adobe Photoshop v.9.

Depth and two-way travel time for prominent reflectors were extracted from the analog record by direct measurement and assumption of a seismic velocity of 1500 m/s. Latitude and longitude were recorded for points where depths to prominent reflectors were extracted. The exact position was interpolated from time marks on the record and navigation log recorded through the Cap'n. An Excel spreadsheet was developed to convert latitude and longitude to northings and eastings with the assistance of Blue Marble's Geographic Calculator. The northings and eastings were returned to the Excel spreadsheet for use in GIS (see Section 2.3. GEOGRAPHIC INFORMATION SYSTEMS METHODS).

2.2.2.2. Applied Acoustics Engineering Digital Seismic System

Applied Acoustics Engineering, International (AAE), manufactured the Applied Acoustics System. It consists of a catamaran-mounted boomer plate, energy source, hydrophone array (20 element), and a topside processing unit.

The energy source is capable of producing 100 – 300 J pulses at intervals longer than 100 ms. The source was set to 100 J and fired at 250 ms during all cruises.

TE manufactured the topside unit, control and post-processing software. It is capable of collecting raw field data, as well as performing post-processing tasks in the lab and is the same unit used for sidescan sonar acquisition and processing. Details on the hardware of the unit were presented in Section 2.2.1. TE has designed the system to be capable of collecting sidescan sonar, seismic reflection data and numerous other geophysical and oceanographical data sets simultaneously. The acquisition of seismic data is accomplished with Delph Seismic v2.4 and post-processing is done via SeismicGIS v1.0. TE designed both software packages. Data were collected across the entire frequency spectrum in raw form. Filters and gains were applied in the lab to achieve the highest resolution possible and varied for based on water conditions, ship's speed, and towing geometry.

The digital record produced by the Applied Acoustics system required more post-processing than the ORE GeoPulse system, but needed a less watchful eye during data collection. After data collection, the record was played back through Delph Seismic in the lab on the TE computer system. During the playback, filters and gain levels can be varied to produce the optimum output. These levels stay with the file, but can be varied at anytime in the future. After the gain and filter levels have been set for the file, it is played back once again. This time, the file is geoencoded and prepared for SeismicGIS. SeismicGIS is a seismic analysis package produced by TE. It is used to map individual reflectors and suites of reflectors. Once reflectors are mapped, the reflector can be exported to an ASCII text file in the format of x, y, z, where X is northing, Y is easting and Z is two-way travel time. The ASCII file is imported into ArcView GIS for spatial analysis (see Section 2.3. GEOGRAPHIC INFORMATION SYSTEMS METHODS). Additionally, records were printed on an EPC 1086 Multiping printer. Interpretation of the record was performed as described in Section 2.2.2.1. Ocean Research Engineering GeoPulse Analog Seismic System.

2.3. GEOGRAPHIC INFORMATION SYSTEMS METHODS

Geographic information systems (GIS) software was an integral part of this project. Analysis of spatial data, sidescan sonar images, and elevation data relied on ArcView v3.2 and ArcInfo v8.0 software, designed by ESRI, Inc. In addition, Blue Marble Geographic Calculator v4.2, designed by Blue Marble Co., was used to convert coordinate data between geographic and Universal Transverse Mercator (UTM) projection systems.

GIS tasks were accomplished using three separate workstations: 1) Dell GTX 2x866 MHz processors with 10 and 20 GB hard drives, 256 MB RAM, and an 8x CDRW drive; 2) Dell GTX 1.4 GHz processor with 10 and 40 GB hard drives, 256 MB RAM, and an 8x CDRW drive; and 3) a Gateway Solo 5150 laptop 300 MHz processor with a 6 GB hard drive and 128 MB RAM. All workstations where networked to a base 10 system and operated under the Windows 2000 environment. ArcView v.3.2 was run on all three platforms and ArcInfo v.8.0 on the 2x866 Dell.

Detailed information for GIS techniques is included in Sections 3.2, 4.2, and 5.2. The remainder of this section provides a brief overview of the common techniques.

2.3.1. Analysis of Sidescan Sonar with GIS Techniques

GIS was used to analyze sidescan sonar images. Seafloor features, such as pockmarks, drag marks, and surficial sediment cover were digitized in ArcView from GeoTIFF images created in DelphMap. A database was associated with the digitized features. Linear features, such as drag marks, contain records including: ID, length, and type. Polygon features, such as pockmarks, include records for: ID, area, perimeter, radius, depth, field name and cluster name; while surficial sediment cover includes records for: ID, unit ID, unit name, and area.

Surficial geology maps, based on backscatter from sidescan sonar, were created for Chapter 5. The sidescan data were transformed as detailed in Section 2.2.1 and opened in ArcView. The protocal established by Barnhardt et al. (1998) was followed for mapping seafloor units. Their continuum of sixteen units was applied. A GIS map and database was produced various spatial analysis were run on the database.

2.3.2. Analysis of Cruise Data with GIS Techniques

ArcInfo was used mainly for creation of coverages containing tracklines from digitally logged navigation data collected by the Cap'n. ASCII text files from the Cap'n were converted to a trackline coverage with the ArcInfo "generate" command set. The result was an arc coverage containing tracklines attributed with type of gear used, navigation points, and trackline name.

2.3.3. Analysis of Pockmark Change Data with GIS Techniques

Spatial analysis, for changes to the Belfast Bay pockmark field was accomplished utilizing ArcView v3.2 GIS. GIS data, in the form of themes, from 1989 (Kelley et al., 1994) (Figure 2.3) and 1998 (Rogers, 1999) (Figure 2.4), showing the area of seafloor ensonified, pockmarks, and till outcrops for each survey, were overlain. The initial overlay showed errors in position, a result of LORAN-C positioning in 1989 and Differential GPS (DGPS) in 1998. Seafloor features (e.g., rock and till outcrops) as well as pockmark chains were used to align the coverages via rubbersheeting. The 1989 data set was rubbersheeted using the Geo Move extension, designed by Spatial-Online for ArcView, to fit the 1998 data set.

After alignment, the first step removed of all pockmarks from the overlay that did not occur in both surveyed areas (data gaps). These pockmarks were discarded from the data set since they were imaged only once.

Pockmarks were visually paired, matching one from the 1989 survey with one from the 1998 survey (Figure 2.5). Visual matching of pockmarks was carried out by using proximity to landmarks (e.g., bedrock and till outcrops), uniquely shaped clusters and chains, and direction of offset based on ship's track. Paired pockmarks were removed from the overlay to a temporary coverage, leaving only pockmarks that had changed over the 10-year period. A change was defined as new formation or filling. The

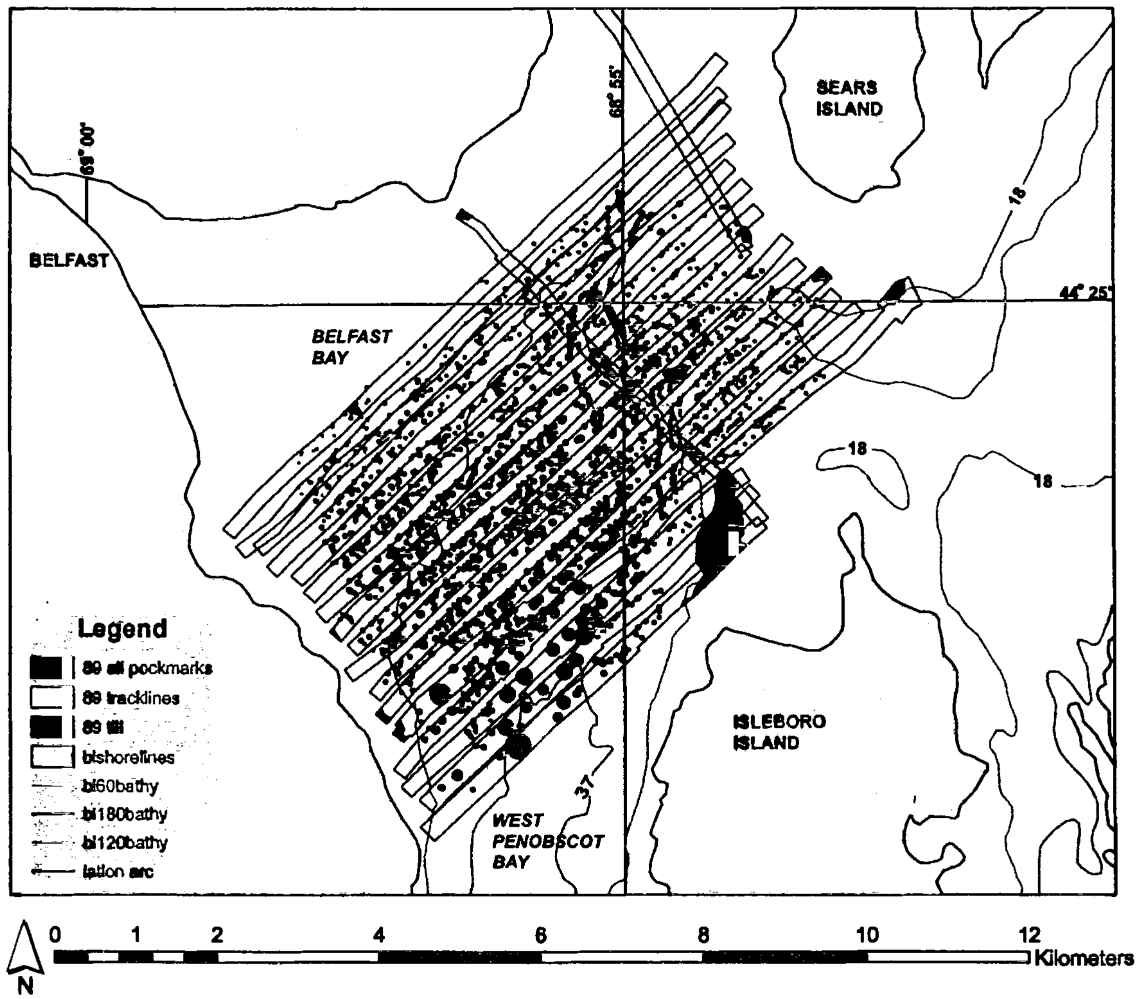

Figure 2.3. The 1989 data set. Original sidescan sonar data was digitized into ArcInfo to create a GIS map of the Belfast Bay pockmark field in 1989. Sonar coverage is outlined in gray. Survey lines did not sufficiently overlap to create 100% coverage of the area. Till outcrops are purple and pockmarks are red circles. The survey grid was laid out along LORAN-C dial readings and resulted in a generally southwest-northeast orientation of the grid (Kelley et al., 1994).

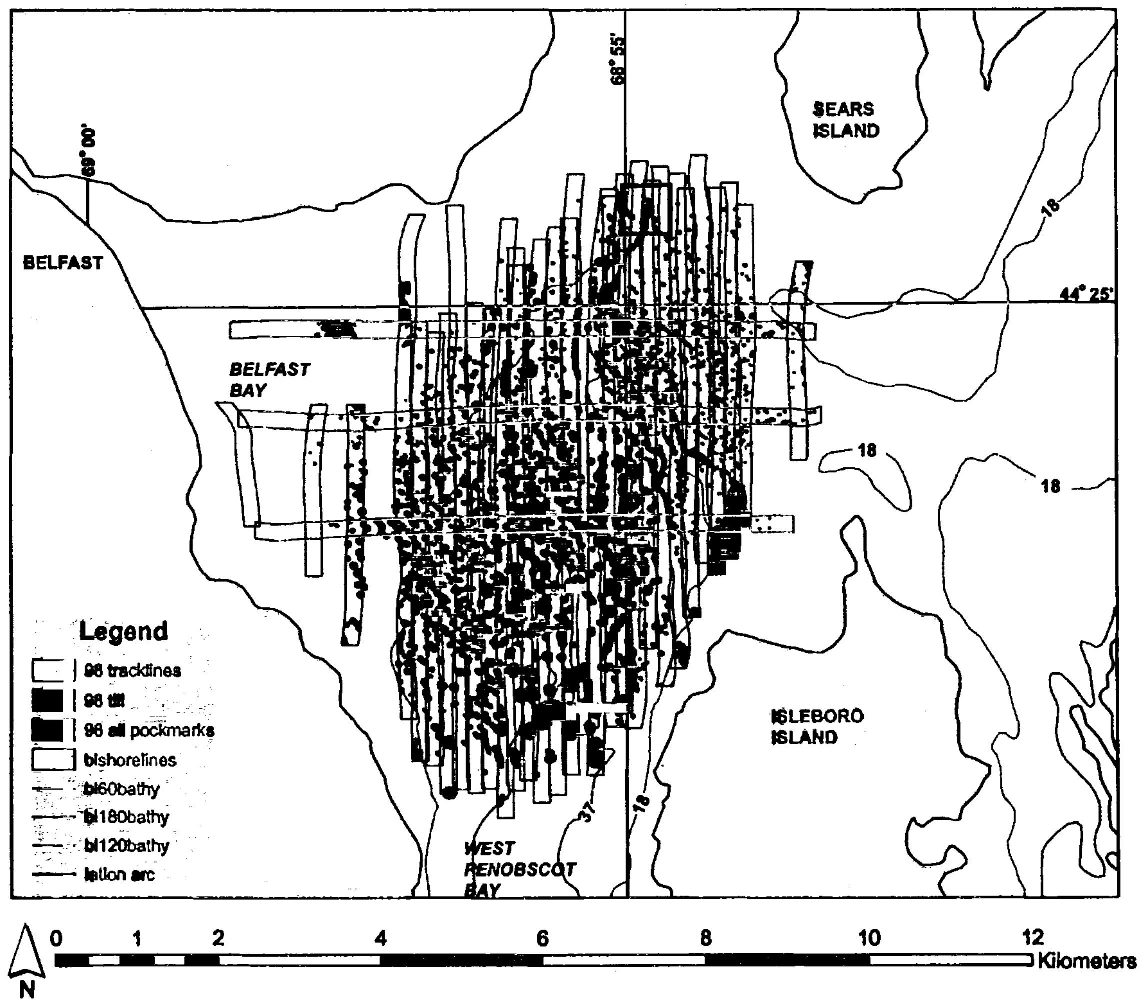

Figure 2.4. The 1998 data set. Original sidescan sonar data was digitized into ArcInfo to create a GIS map of the Belfast Bay pockmark field in 1998. Sonar coverage is outlined in gray. Survey lines overlapped enough to create 100% coverage of the area. Till outcrops are purple and pockmarks are red circles. The survey grid was laid out using differential global positioning satellite information. The grid is orientated nearly north-south (Rogers, 1999). The area within the heavy black box is shown in detail in Figure 2.5.

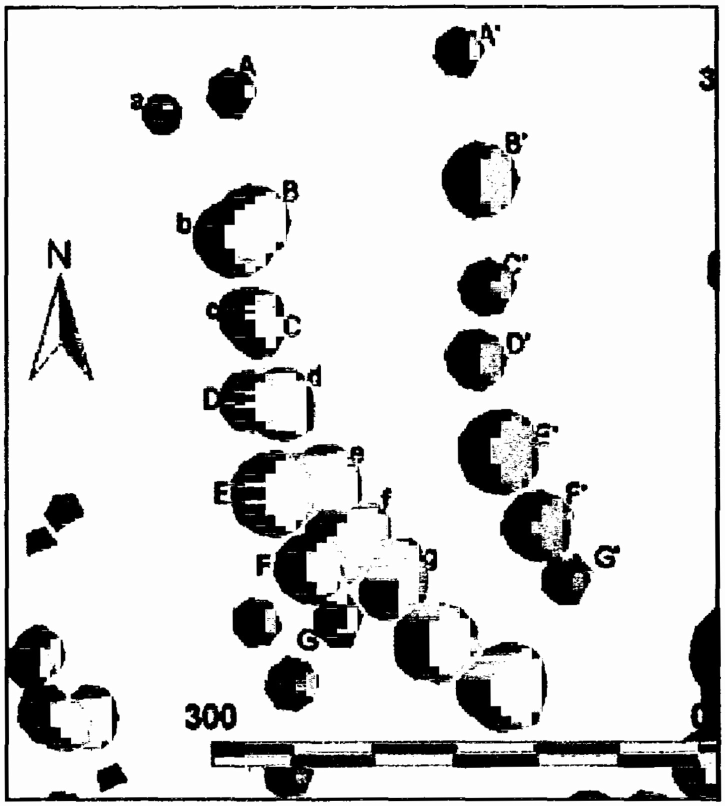

Figure 2.5. Examples of the matching process. Solid blue circles are original 1989 data (A'); solid green circles are the corrected 1989 data (A), and solid red circles are the 1998 data (a). Pockmarks identified with A, A' and a, etc. are the same feature and are examples of matches. The cluster of three pockmarks in the lower left potion of the figure is an example of a pockmark created during the time interval. Only two occurred on the 1989 record and three on the 1998. The entire area had 100% coverage by both surveys. The location of the data is shown in Figure 2.4.

resolution of the original sidescan sonar images and digitizing techniques prevented evaluating morphological changes (e.g., size and shape).

After all matches were identified and removed, only potential changes remained. Uncertainty resulted from pockmarks coalescing or potential misinterpretation of the original data. Original analog records were reinterpreted in these areas.

2.4. OTHER METHODS

All location fixes during the new research were taken with differential global positioning satellite systems (DGPS). The DGPS system consists of the U. S. government's constellation of positioning satellites coupled with land-based beacons managed by the U. S. Coast Guard. The global positioning satellite (GPS) signal was accurate to within 300 m prior turning off of selective availability in 1999. Currently, GPS is accurate to within five to ten meters. DGPS is accurate within two to five meters. The data collected by Rogers (1999) also used DGPS, but Kelley et al. (1994) used LORAN-C for data collected in 1989 and 1990. LORAN-C navigation is supported by a series of land-based towers broadcasting a signal. Signals from two towers are used to determine the position by time delay readings, two or more time delays crossing at a large angle provide geographic position. In coastal embayments, the system's signals may break down and provide erroneous readings. Nominal geographic accuracy is 100-300m, but local experience has shown that repeatability can be in the tens of meters for precision. This method is no longer widely used.

Ship's navigation and survey planning were accomplished using the Cap'n Voyager digital navigation software created by Nautical Technologies, Limited. Prior to surveys, the course was laid out in the Cap'n and saved to a 3.5" floppy disk. The research vessel was also equipped with the Cap'n integrated into the autopilot. The software logged DGPS readings directly from the ship's DGPS receiver twice a minute and plotted the ship's track on a navigational chart. The log allowed for quick creation of trackline maps in a GIS environment. Logs were opened in Microsoft Excel for editing and preparation for conversion to UTM via Blue Marble Geographic Calculator and use in GIS.

CHAPTER 3
CHANGES TO THE BELFAST BAY POCKMARK FIELD

3.1. INTRODUCTION

The Belfast Bay (Figure 3.1) pockmark field was imaged in 1989 and 1998 using analog sidescan sonar and mapped with GIS. Kelley et al. (1994) created a baseline map of the distribution of pockmarks and investigated the size of the field and pockmarks in 1989. Nearly nine years later in 1998 Rogers (1999) remapped the field and correlated pockmark occurrence to Holocene sediment thickness and presence of subsurface gas. During the years between surveys, questions arose about the level of activity of the pockmark field. Kelley et al. (1994) imaged an apparently active pockmark within the field, during the 1989 survey. Paull et al. (1999) and Ussler et al. (1999) suggested that the field was senescent and a relict feature based on a survey employing a submarine methane detector (A. Codega, personal communication, 2000).

The goal of this chapter is to further investigate the activity of the Belfast Bay pockmark field. I hypothesized that the field is active based on observations of Kelley et al. (1994) and attempted to validate the hypothesis with an in-depth GIS analysis.

3.2. DATA SOURCE AND ERRORS

3.2.1. Data Sources

This project was completed using the GIS data created by Kelley et al. (1994) in 1989 and Rogers (1999) in 1998. Reinterpretation of original sidescan sonar images from 1989 and 1998 surveys were required to verify change analysis. Additional, new high-resolution data were collected in 2000. Data from previous studies (Kelley et al., 1994;

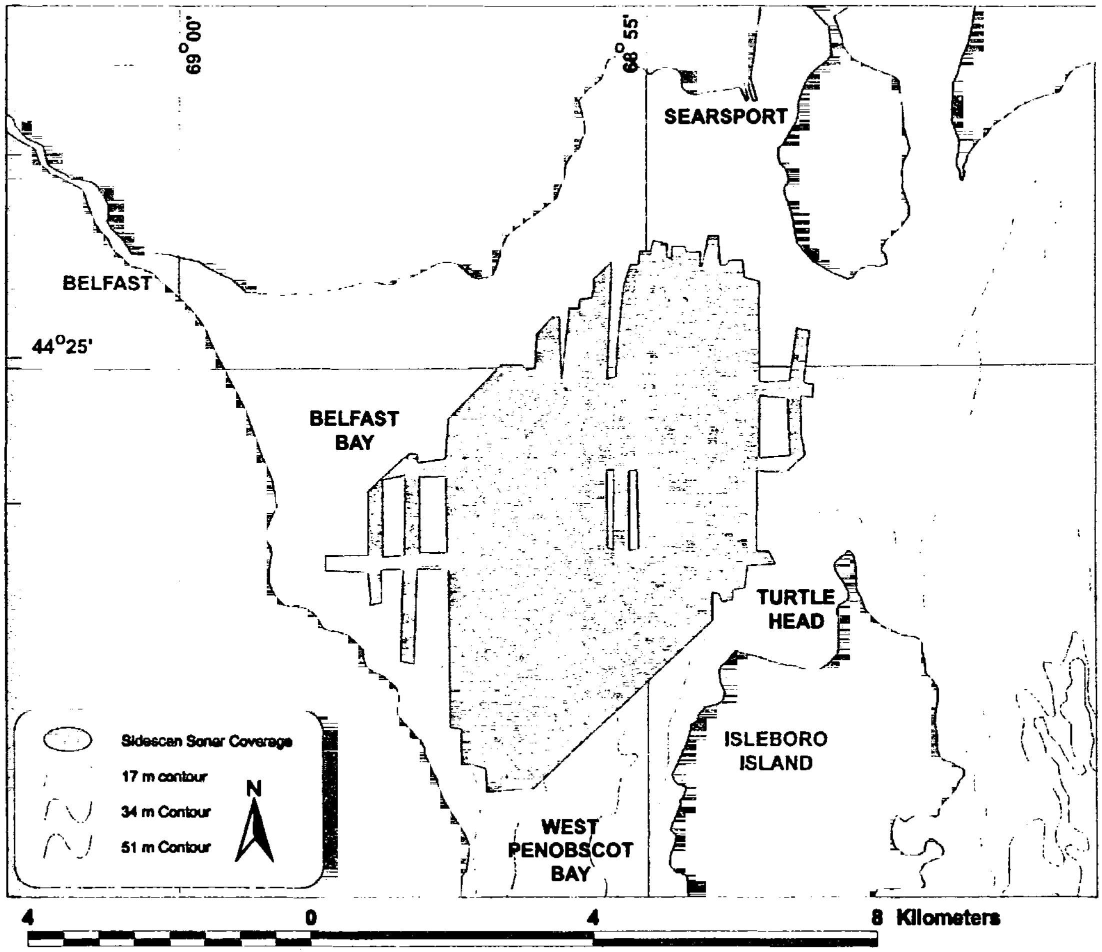

Figure 3.1. The Belfast Bay study area for change analysis. Belfast Bay is a northwest extension of Penobscot Bay (Figure 1.1). The study area for the change analysis is shaded in gray and represents the combined sidescan sonar coverage from surveys in 1989 (Kelley et al., 1994) and 1998 (Rogers, 1999). Coastline and bathymetry were simplified from NOS chart 13302.

Rogers, 1999) were not in the same area surveyed as surveyed in 2000. These new data are not considered in the analysis.

3.2.2. Errors

Error in aligning the coverages resulted from three sources: 1) the data were located with different coordinate systems; 2) the layback of the sidescan sonar towfish varied on survey lines and entire surveys by an unknown amount; and 3) the survey grids were orientated differently. Each of these errors could be accounted for, but often operated in chaotic fashion, and individual sources of error were difficult to separate from the total error. It was not feasible to attempt to correct the data by means of a single algorithm.

The 1989 data were collected and located using the LORAN-C system while the 1998 data were collected using the differential global positioning satellite (DGPS) system. LORAN-C dial readings can have an error as great as 300 m or higher inshore and close to islands, but can be corrected to +/- 50 m with software provided by NOAA. The location of Belfast Bay within Penobscot Bay inherently results in LORAN-C errors. LORAN-C has been replaced by the more accurate and precise DGPS system. The DGPS system is designed around a network of satellites and coastal beacons. The coastal beacons provide a correction factor to the satellite data to remove the government-induced errors and satellite wobble. The error in positioning has been reduced to two to five meters. As a result, the 1998 data set is more accurately located than the 1989 data, but there is no way to transform either set of navigation parameters into the other with great accuracy.

Layback is defined as the distance from the DGPS (or LORAN-C) receiver to the towfish. The positions recorded during data collection are the position of the receiver on the vessel, not the position of the towfish. If the layback is recorded, and notes are made during changes to the layback, it is easy to remove from the data during initial GIS processing. The layback was, for the most part, accounted for during the 1998 survey. There are portions of the data were the layback appears to have changed and has not been accounted for in the GIS processing. The 1989 data set does not appear to have taken layback into account. This difference between the two surveys adds tens of meters of error to the attempts to reconcile the 1989 and 1998 navigation.

Trackline orientation is often dictated by local conditions. In 1989, the survey was conducted parallel to LORAN-C dial readings, or southwest to northeast and vice versus. The survey in 1998 collected data on a north-south orientated grid. Either of these patterns is acceptable. Problems arise when the data are compared. The differing trackline orientations result in an error that is amplified by layback. If both surveys had been run with the same orientation, the error could easily be removed. The offset of trackline direction makes it difficult to determine which line's positioning was altered.

An additional source of uncertainty arose from interpretation of the analog sidescan records. This error was independent of navigation issues and resulted purely from biased interpretations. Misinterpretations of the original data could result from several items: 1) water column noise; 2) improper bottom tracking; 3) improper/inappropriate gain settings; 4) slant range; 5) grazing angle; and 6) feature size and instrument resolution. Unfortunately, the analog record is only as good as the operational control at the time of collections; digital data collected since 2000 can be reprocessed and filtered to enhance features or remove noise multiple times without corrupting the original raw data.

Water column noise results from several situations: 1) turbidity; 2) strong stratification; and 3) intense mixing. Noise in the water column can obscure the record and prevent an accurate image of the bottom. Turbidity is suspended sediments and can obscure the bottom from proper imaging with sonar. Strong stratification can create a density difference that will create noise on the record from reflection and refraction of sonar beams along the interface. Intense mixing can disturb the bottom sediments and create turbidity throughout the water column.

Bottom tracking is dependent on two major factors: water column noise and seafloor sediments. Water column noise will obscure the bottom and prevent the first return from accurately representing the actual depth below the towfish. This will result in a shallower-than-actual image. Soft seafloor sediments can allow the sonar beam to penetrate the sediments and return a deeper-than-actual image. Both of these factors will return images that are obscured toward the center of the swath. The greater the error in bottom tracking, the wider the erroneous return area is on the record. Analog records, such as those collected in 1989 and 1998, had one opportunity to properly track the bottom. In less than ideal survey conditions, bottom tracking is difficult at best and can greatly degrade the center portion of the record.

Inappropriate gain settings can yield a record that is either too dark or too light to resolve features of interest. Strength of return (i. e., darkness on record) is directly related to seafloor sediment type. Improper gain settings can hide subtle features on muddy bottoms.

Grazing angle is the angle that a sonar beam intersects the seafloor. The further from the centerline of the towfish, the greater the angle of the beam becomes. The greater angles will tend to scatter energy and return weaker signals to the towfish. Weaker signals are more difficult to interpret and resolution decreases, thus increasing the possibility of a misinterpretation.

Pockmarks have been reported to range in size from less than one meter to greater than 700 m (Hovland and Judd, 1988). Small features (i.e., lobster traps) are resolvable on the original data, but the process of mosaicking and interpretation in GIS reduces the final resolution. As a result, features below the resolution of the interpretation (about 3 m) will not be observed. Features significantly larger than the swath width, typically 200 m for this study, may not be observed, or properly interpreted.

3.3. Results

A cursory analysis of both data sets showed the pockmark field had 1888 pockmarks in 1989 (Figure 3.2) and 2262 pockmarks in 1998 (Figure 3.3). However, the area each survey covered was slightly different, with the 1998 survey encompassing a greater area. Comparison of the coverage showed that gaps existed in the area covered. After data gaps were removed and the data sets reanalyzed, the 1989 coverage contained 1702 pockmarks and the 1998 coverage contained 1777 pockmarks. After matching pockmarks was completed, 342 pockmarks occurred on the 1998 coverage without a match on the 1989 coverage (creations) and 287 pockmarks appeared on the 1989 coverage without a match on the 1998 coverage (destructions) (Table 3.1).

Table 3.1. 1989 and 1998 Pockmark Coverage Statistics. Table details numbers of pockmarks on each coverage and how the total pockmarks mapped where broken down into comparable data sets.

	1989	1998
Total pockmarks imaged and digitized	1888	2262
Data gaps	206	485
Pockmarks possible on both	1702	1777
Pockmarks only on one coverage	287	342

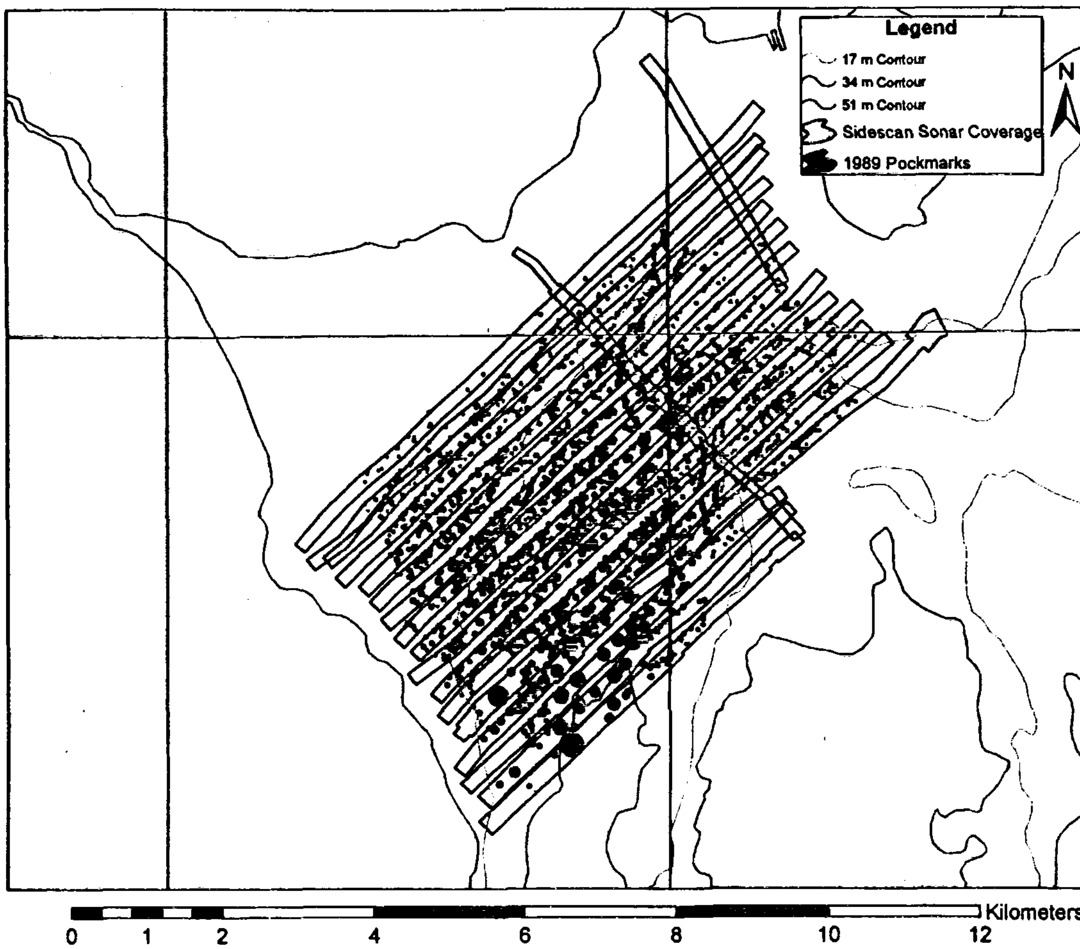

Figure 3.2. Pockmarks mapped in 1989. A GIS interpretation of the sidescan sonar collected in 1989 (Kelley et al., 1994) shows 1888 pockmarks (red) within the Belfast Bay area. Gray lines delineate sidescan sonar coverage on each survey trackline. Considerable gaps occur between tracklines. Coastline and bathymetry simplified from NOAA chart 13302.

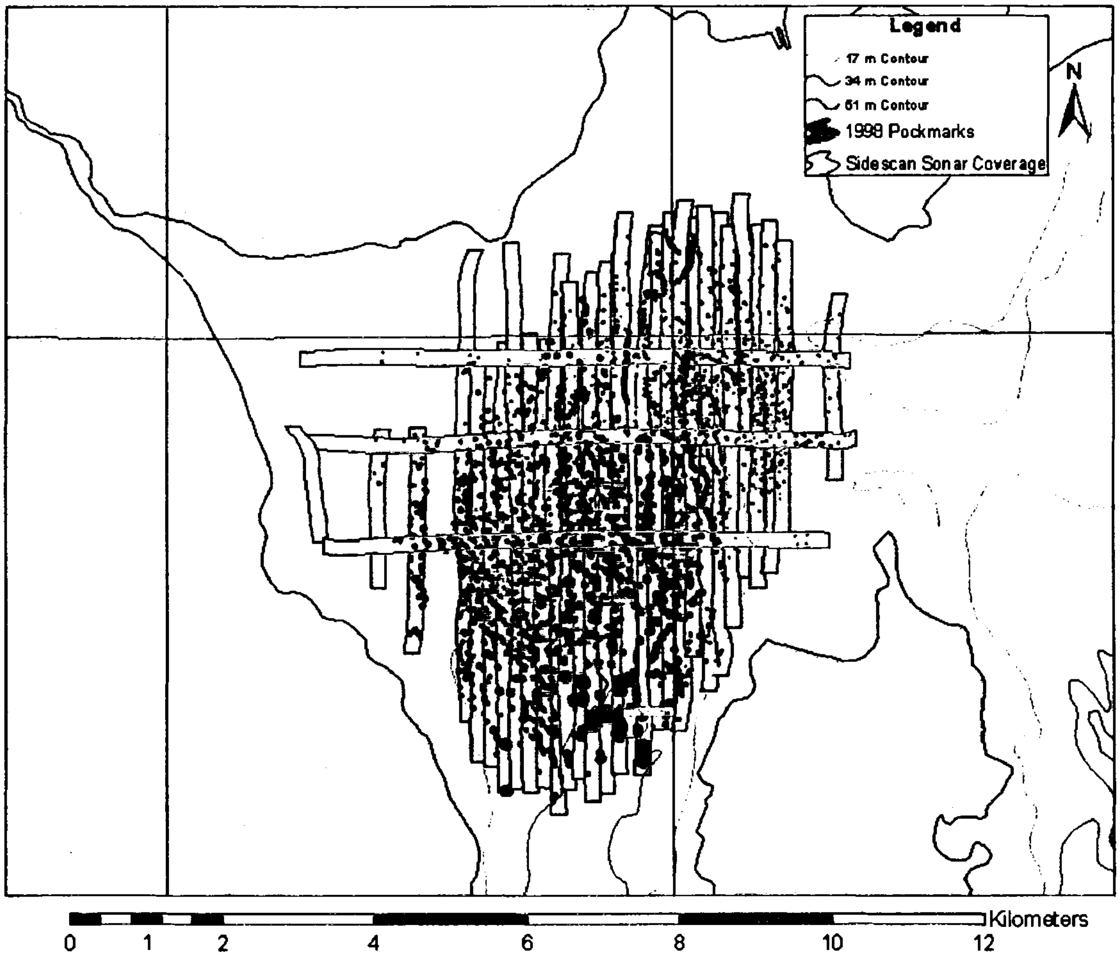

Figure 3.3. Pockmarks mapped in 1998. A GIS interpretation of the sidescan sonar collected in 1998 (Rogers, 1999) shows 2262 pockmarks (red) within the Belfast Bay area. Grey lines delineate sidescan coverage on each trackline. Unlike data collected in 1989 (Figure 3.2), trackline overlap and data gaps are rarely present within the main body of the pockmark field. Coastline and bathymetry simplified from NOAA chart 13302.

The unaccounted pockmarks on the 1989 coverage exist in places where pockmarks could have coalesced into larger features on the 1998 coverage or could have been in areas not covered by both surveys. These pockmarks were removed from the analysis.

A volumetric analysis (see Rogers, 1999 for techniques and Chapter 5, this work for further discussion) was performed on the pockmarks added and pockmarks filled. The 342 new pockmarks represent 3.4 x 10^6 m^3 of sediment removed from the seafloor and the 287 filled pockmarks represent 3.2 x 10^6 m^3 of muddy sediments added to the seafloor. The difference, 0.2 x 10^6 m^3, represents nearly 6%. Based on potential variations in pockmark morphology and inaccuracy in digitizing, this is not a significant difference.

3.4. Discussion

The resultant coverage (Figure 3.4) details the activity of the Belfast Bay Pockmark Field. At first glance, it appears as if the pockmark population in the surveyed portion of field has increased by 75 pockmarks. A more detailed analysis of pockmarks, which involved matching of pockmarks, over the 10-year period shows that 342 new pockmarks were created and 287 pockmarks were destroyed. Over the 10-year period, 35.4% of the 1998 population of pockmarks was either created or destroyed. These numbers do not include the possibility of a pockmark being destroyed and a new pockmark forming in a similar location (within about twice the original pockmark's radius). In the type of analysis conducted here, these two, unrelated pockmarks would appear to be the same pockmark. Seismic reflection evidence does suggest filled pockmarks, although they may be difficult to interpret. Seismic reflection data is based on acoustic impedance contrast. The pockmarks are formed in Holocene muds and would infill with Holocene muds. Seismic reflection data would not show a

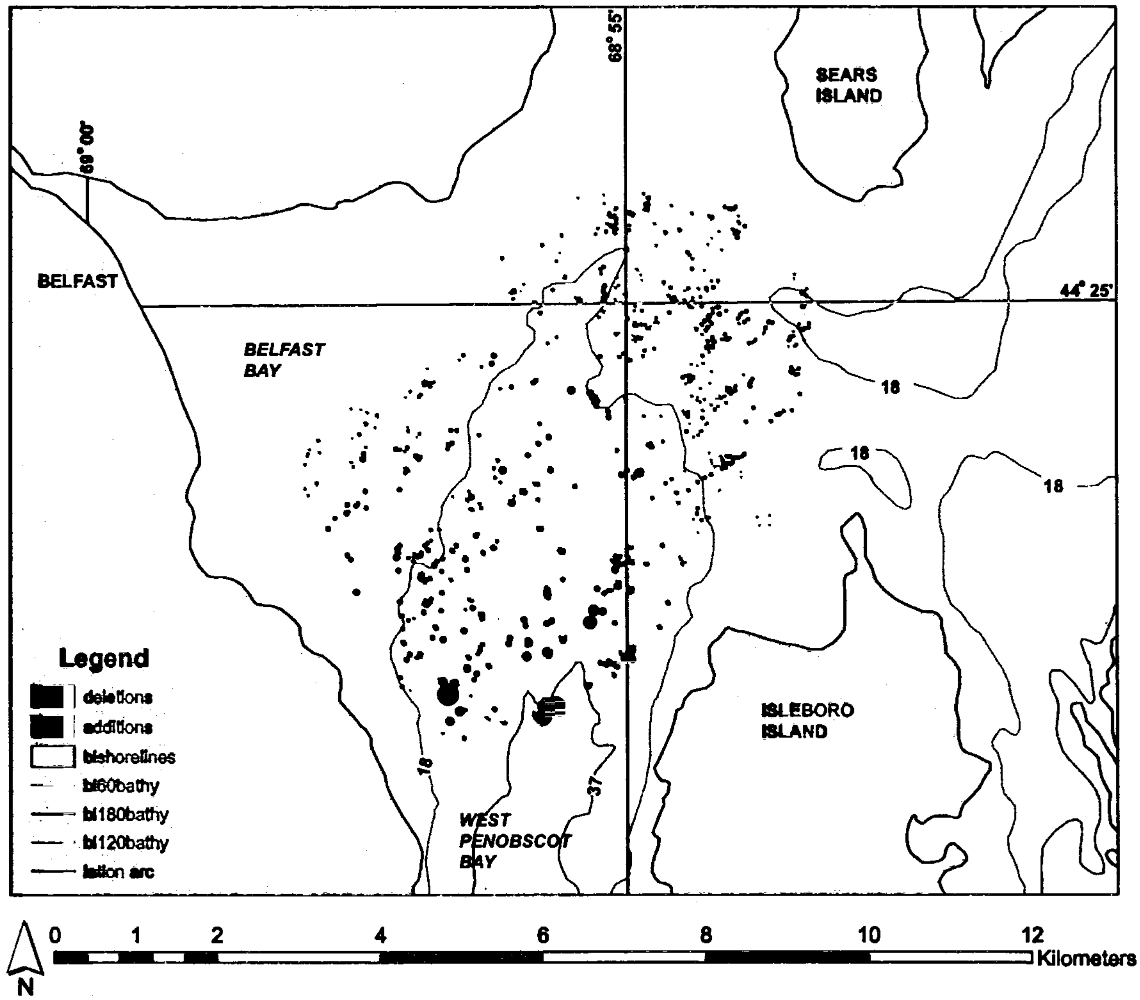

Figure 3.4. Changes to the Belfast Bay Pockmark Field. After correlation of the 1989 (Figure 3.2) and 1998 (Figure 3.3) data sets, changes to the field can be determined. A near 36% change in the 1998 field population occurred over the nine-year period. A total of 342 pockmarks were created since 1989 and 287 pockmarks were destroyed after 1989. The field shows zones of changes. Areas of new pockmark creation occur in the northwest, southeast and central portions, while pockmark destruction dominates in the northeast and southwest portions of the field.

contrast unless a surface of differing density, water content, or grain size occurred on the surface of the pockmark before it filled.

The volumetric analysis shows that more sediment was removed from the seafloor than added. (3.4×10^6 m^3 removed, 3.2×10^6 m^3 added). The difference of 0.2×10^6 m^3 represents material that has been transported out of the system or stored in the intra-pockmark areas. Movement of material out of the system would suggest an overall erosive trend in Belfast Bay. If the sediment is stored in intra-pockmark areas, the system is only redistributing its resources. Data at this time are unable to resolve the fate of the 0.2×10^6 m^3 of muddy sediment.

The results of the statistical and graphical analysis demonstrate that the Belfast Bay field is active. It is also creating more pockmarks over a 10-year period than are destroyed. The field increased its gross population in the area surveyed by 55 pockmarks, or 3.2%.

Close examination of the final coverage (Figure 3.4) shows patterns in the activity levels throughout the bay such as zones of creation, destruction, or no changes. The zones where pockmark creation is greater than pockmark destruction are found in the northwestern, southeastern, and central portions of the field. The zones where destructions outnumber creations occur in the northeastern and southwestern portions of the field. Zones of no changes occur where the pockmarks mapped in 1989 retained their form and no new pockmarks were added or older ones deleted. This condition is found in the south central portion of the field.

Paull et al. (1999) and Ussler et al. (1999) argued that Belfast Bay is senescent. In order for the field to be senescent, no new pockmarks can be created in a given time interval. The population would decline through filling and erosion of pockmarks. Belfast Bay shows no such trend. In fact, the opposite is true. More pockmarks are being created than destroyed.

The southern portion of the field contains several of the largest pockmarks within Belfast Bay. The comparison mapping shows several of these large-scale features (greater than 300 m in diameter) have disappeared between surveys. This represents a potential problem. It is difficult to believe the filling of features of this size in ten years. The few isolated large-scale features in the southern portion might be due to sources of possible misinterpretation discussed above.

The activity level occurring in the Belfast Bay pockmark field is potentially significant. More work is needed to determine how long this activity will remain, the effect of rising sea level, and how anthropogenic factors will influence the field's activity. Additional work is required to determine or estimate the amount of methane present, already released, and amount that can still be generated.

CHAPTER 4
ANTHROPOGENIC CHANGES IN BELFAST BAY

4.1. Introduction

Previous researchers have shown pockmarks can be generated by many different natural triggers as well as anthropogenic factors. Known natural triggers are earthquakes (Field and Jennings, 1987; Soderberg and Floden, 1992; Hasiotis, et al., 1996), waves, and storm surges (Hovland and Judd, 1988). Anthropogenic triggers include any activity that places a load, either static or dynamic, on the seabed. Ellis and McGuinness (1986) closely examined a pockmarked seabed in the Arabian Gulf associated with a deep hydrocarbon deposit. Over the course of their survey, they noticed pockmarks had formed in an area where gassy sediments were recognized on an earlier survey. The new pockmarks were in close proximity to a hydrocarbon production platform. They attributed the pockmarks to gas and pore-fluid escape due to static loading of the seafloor, resulting in compression and dewatering/degassing of the sediments. Ellis and McGuinness (1986) suggest that any load, including anchoring or drag fishing, could trigger pockmark formation, but fail to provide any examples or proof that this occurs.

Belfast Bay is home to a large fishing and commercial shipping fleet. Areas of the bay are regularly fished for lobsters, scallops, and ground fish. Fishing techniques include trapping, diving, and dragging. Trapping and diving have virtually no impact on the seabed and will not be considered further.

Large cargo vessels travel through the bay enroute to Searsport on the northern shore of the bay or up the Penobscot River to Bangor. Occasionally, vessels will anchor within the bay to await free berths or appropriate tide and sea conditions. The United

States Coast Guard has designated an oil transfer and anchorage area for these vessels in Belfast Bay and it lies within an active section of the pockmark field (Figure 4.1).

During a drag fishing operation, a vessel drags a net held open by two large D-shaped doors across the seabed (an otter trawl). Sidescan sonar images in areas that are heavily dragged show deep, parallel furrows in the seafloor sediments from the passage of these doors. The furrow reworks the upper region of the sediment column, potentially altering the pressure regime in the sediment column.

Anchoring large vessels can leave marks on the seabed similar to drag fishing. One or more long, linear furrow initiating from the same location, spreading from the initiation point and eventually fading are characteristic of anchoring and often referred to as "plumose structures" (Fader, 1988; Fader 1991). Multiple furrows from one initiation point are a result of changes in tides, wind and current direction, and waves.

Belknap and Kelley (1999, unpublished proposal) hypothesized that anthropogenic actions, such as drag fishing and anchoring, can act as triggering events for pockmarks. This project was designed to test these ideas.

4.2. Data Sources

A combination of previously collected and newly acquired sidescan sonar records were used. The previous data was collected, post-processed, and interpreted by Rogers (1999) during 1998. New data was collected during one field day in August 2000 with an Edgetech DF 1000 digital sidescan sonar towfish and Triton-Elics topside control and processing unit.

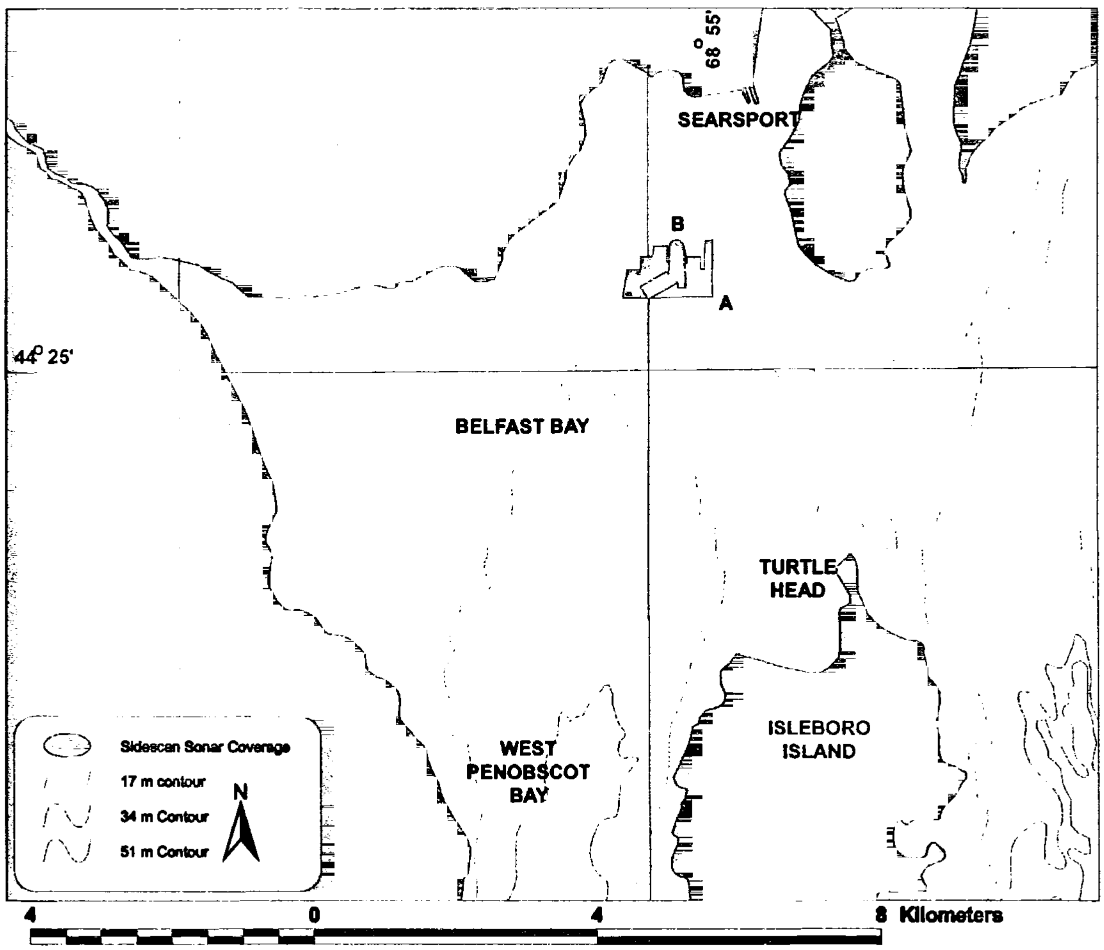

Figure 4.1. The Belfast Bay study area for anthropogenic forcings. Belfast Bay is a northwest extension of Penobscot Bay (Figure 1.1). The study area for the anthropogenic forcings is shaded in gray. Polygon A represents data collected in 1998 (Rogers, 1999) and polygon B is data acquired during August 2000. Coastlines and bathymetry simplified from NOS chart 13302.

Data were collected at 50 m range on 100 and 500 kHz frequencies. The data were post-processed with the Triton-Elics unit and mosaicked with a 0.1 m resolution. Features from the sidescan sonar images were digitized and analyzed for spatial changes with ArcView 3.2.

4.3. Results

The August 2000 fieldwork resurveyed an area of 13,725 m^2 that was originally surveyed by Rogers (1999) in 1998 (Figure 4.2). Three classes of features were mapped from the sidescan sonar data sets: pockmarks, anchor drag marks, and other drag marks. The August 2000 survey mapped 80 pockmarks, 87 anchor-drag marks, and 197 other drag marks (Figure 4.3). The 1998 survey mapped nine pockmarks and 82 other drag marks. Anchor drags were not distinguishable from other drags in this data set and have been combined into other drag marks (Figure 4.4).

The 1998 data shows nine pockmarks while 80 occur on the 2000 data set. Of those nine, from 1998, only five are matched with comparable pockmarks from 2000. Four pockmarks were filled, and 75 pockmarks that where not present in 1998 data were mapped. Possible explanations include: 1) the scale of resolvable events; 2) new pockmark creation; and 3) pockmark filling. While the ultimate resolution of both types of sidescan sonar is similar, the output produced by the digital system is far superior. The digital output of equipment used in 2000 is capable of resolving features with a diameter of less than one meter. The mosaicked and GIS-interpreted analog output of the equipment used in 1998 was capable of resolving features with a diameter of between

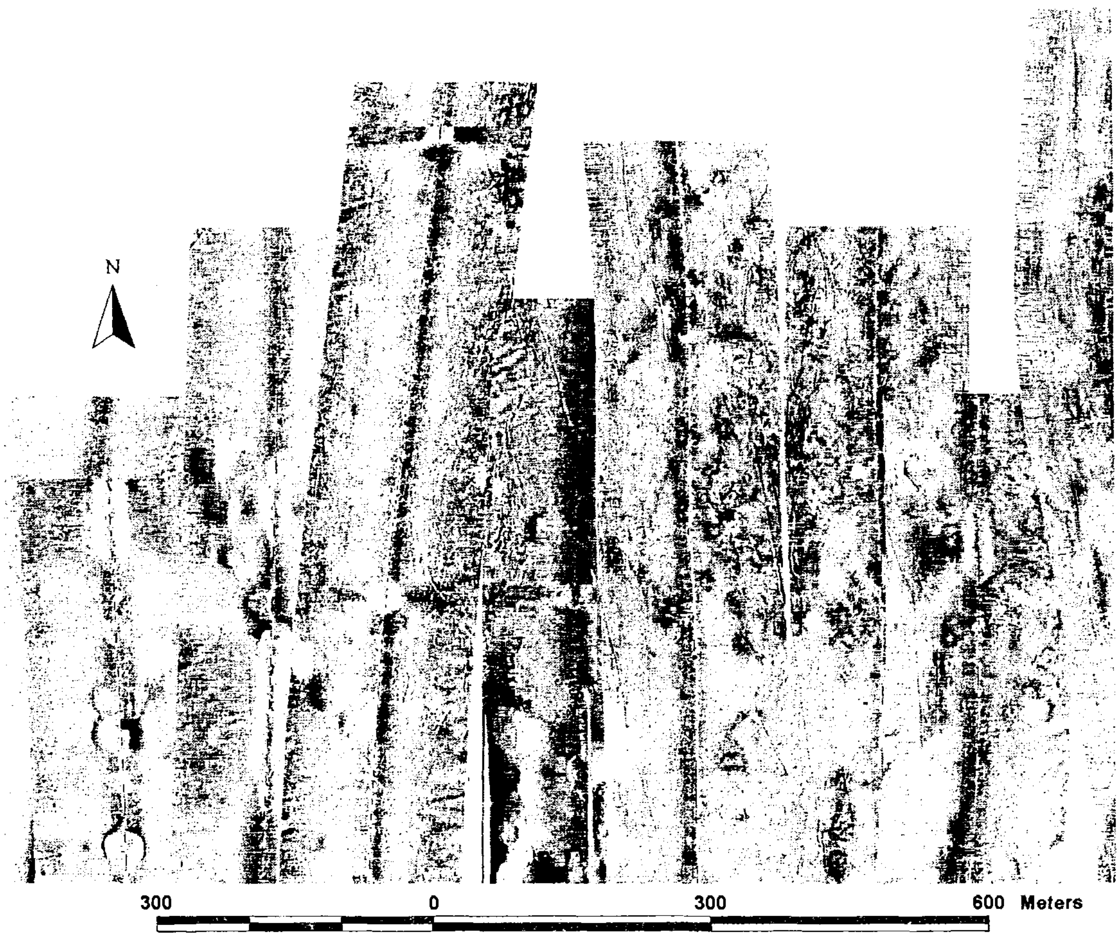

Figure 4.2. A Portion of the 1998 sidescan sonar mosaic in Belfast Bay. Rogers (1999) created a mosaic of sidescan sonar images. The area was resurveyed in 2000 to determine changes to the seafloor on a short timescale and determine anthropogenic forcings. Location of the image is shown on Figure 4.1, polygon A.

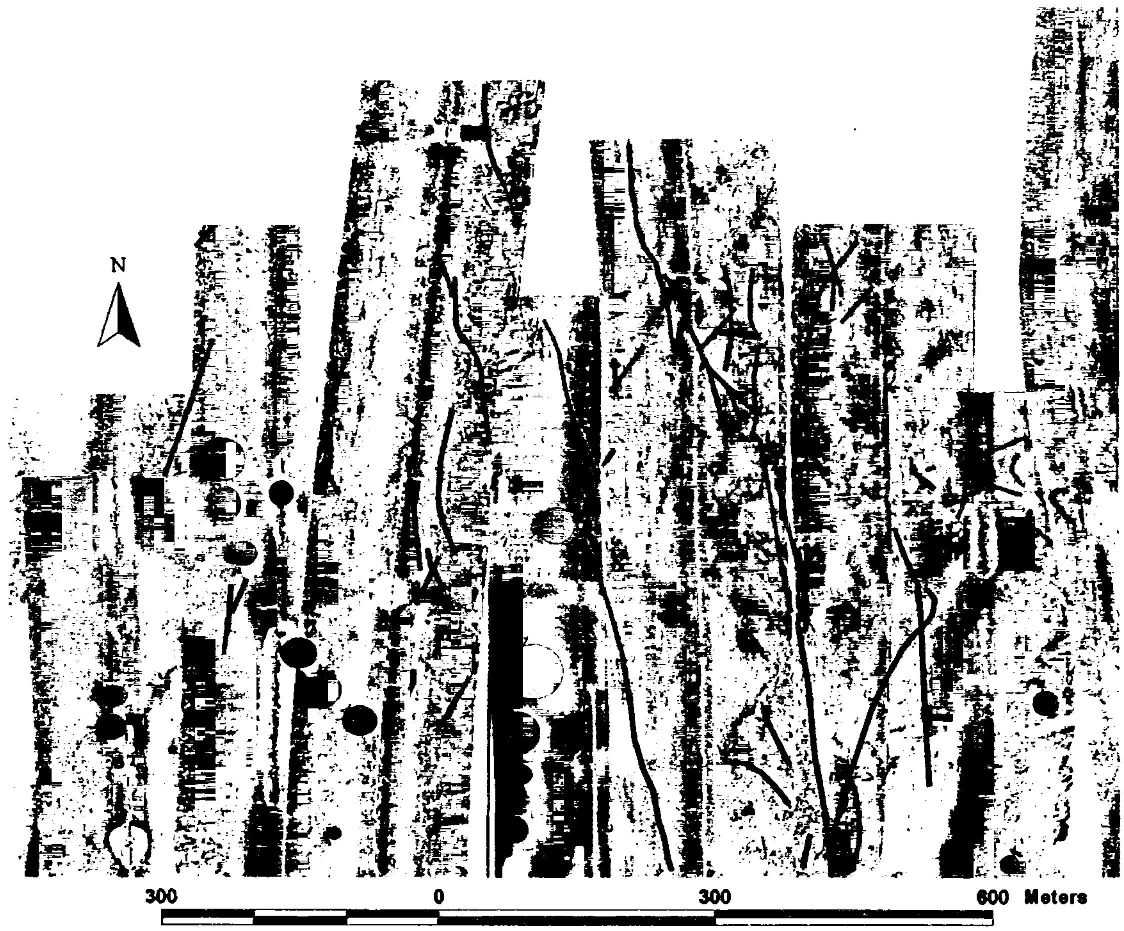

Figure 4.3. Interpreted sidescan image from 1998. The original sidescan sonar image was interpreted in GIS. Pockmarks were digitized in red and drag marks in blue.

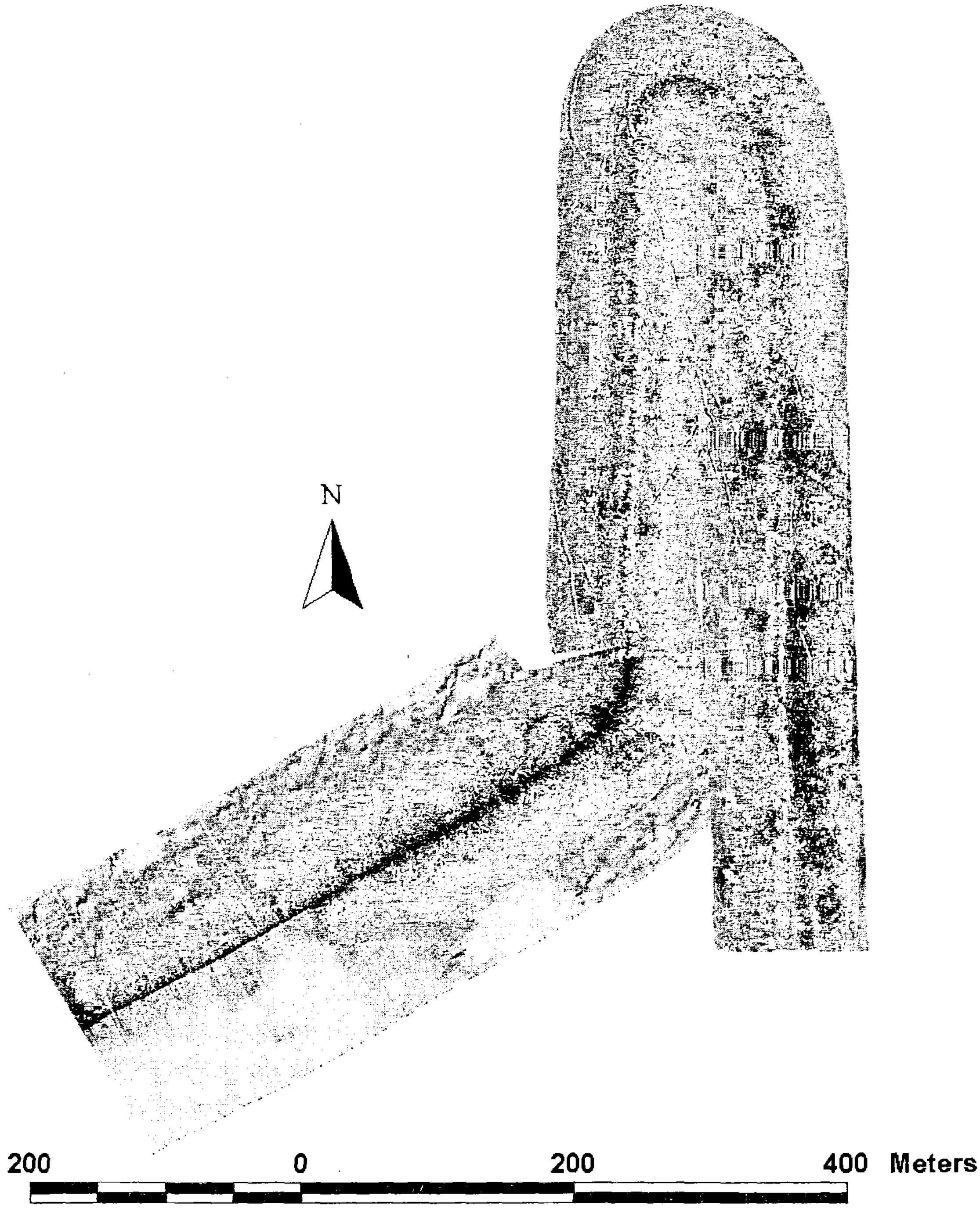

Figure 4.4. Sidescan sonar image collected in 2000. This image was collected over the same area as the 1998 image (Figure 4.2). Location of the image is shown on Figure 4.1, polygon B.

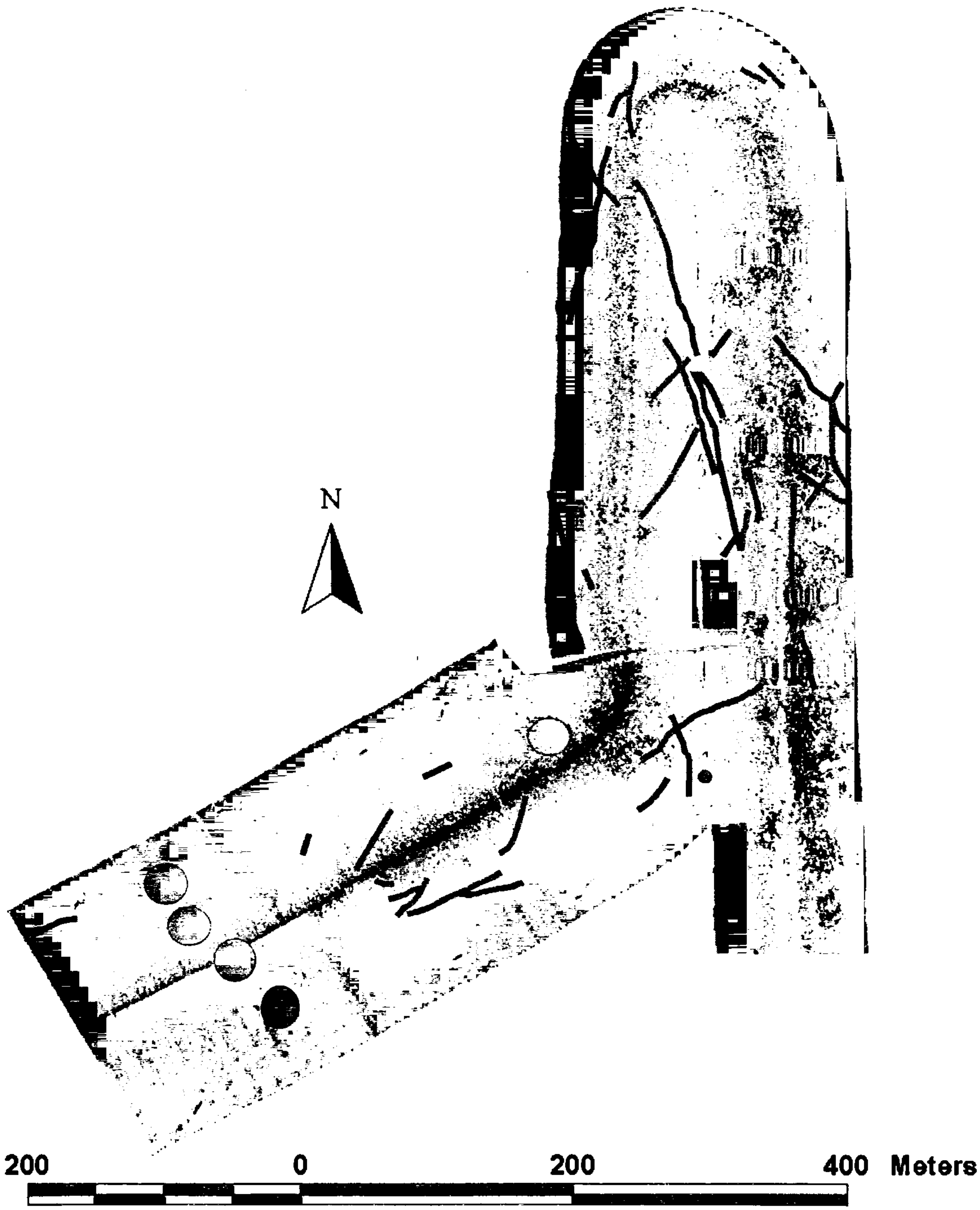

Figure 4.5. Interpretation of 2000 sidescan sonar image. The image was interpreted in GIS. Pockmarks are red and drag marks are blue. The scale prevents showing all drag marks on the image. Only the most prominent are displayed.

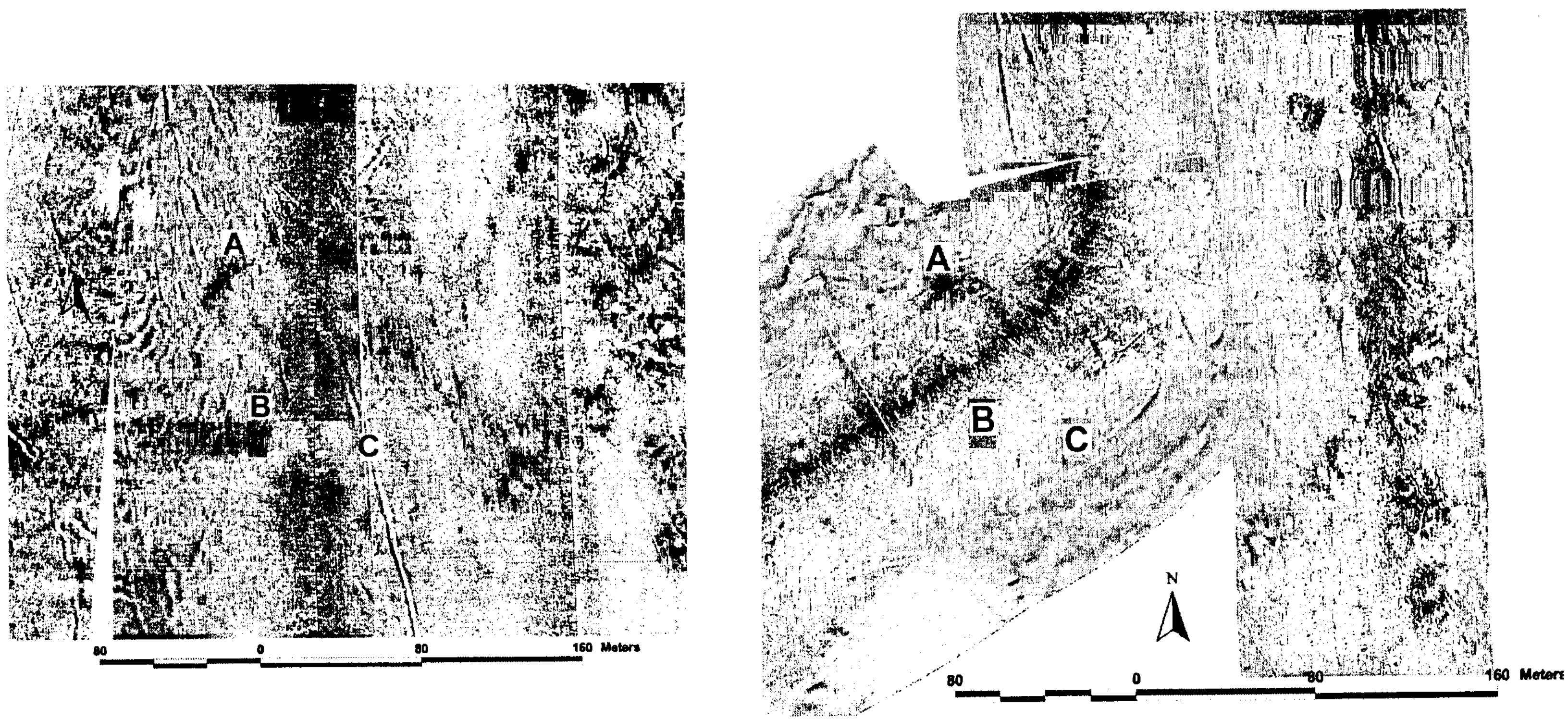

Figure 4.6. Comparison of raw sidescan sonar images. The image on the left is from 1989 and the right from 2000. Letters A, B, and C refer to the following features: A pockmark, B, pockmark, and C a drag mark. The letters are in the same geographic location on both images.

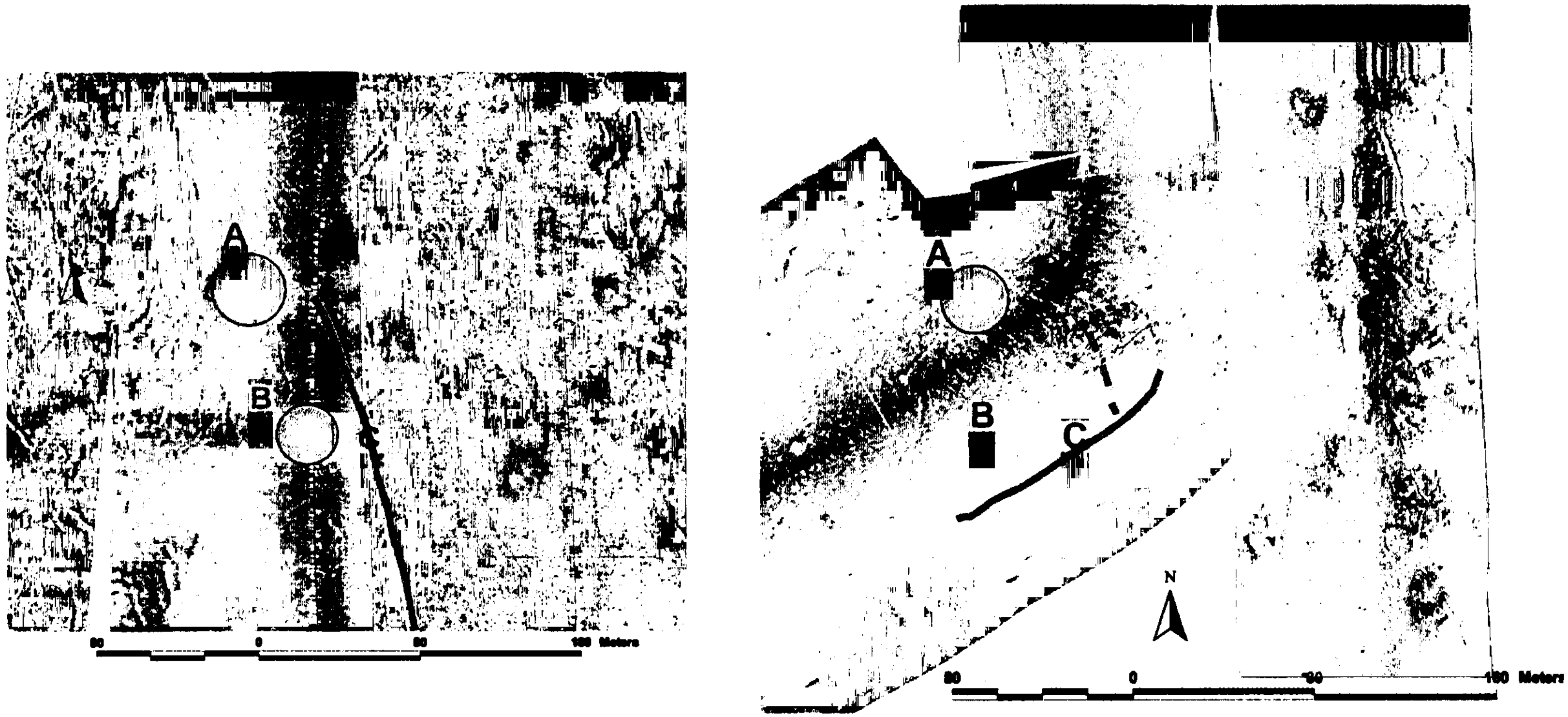

Figure 4.7. Interpreted sidescan sonar images. The image on the left is from 1998 and the right from 2000. Red represents pockmarks and blue represents drag marks. At A, a pockmark is visible on both images. At B, a pockmark is visible on the 1998 image only. At C, a north-south drag mark is visible on 1998 and an east west drag mark is visible on the 2000 image. This series shows evidence for change to the seafloor over a two-year time period.

four and five meters and linear features. The discrepancy in populations is attributed mainly to the resolution of the equipment, although I do not rule out pockmark creation and filling as an alternative to resolution differences. Small (< 5 m) pockmarks occur throughout the survey area. In places, these features are crossed by drag marks that were present on the 1998 survey. On the 2000 survey, the drag mark is not present and the pockmark is present. This suggests a distinctive chain of events: 1) drag mark was created; 2) 1998 survey took place; 3) drag mark filled; 4) pockmark created; and 5) 2000 survey took place.

Evidence for filled pockmarks exists in the southwestern portion of the survey area. Four pockmarks occur on the 1998 record that have no expression on the 2000 record. The only explanation is the features were filled with sediment in the intervening two years (Figure 4.5).

The filling of such large features over a short period of time can seem unrealistic when examining the volumes of material that are transported. Each of those four pockmarks are approximately 25 m in diameter and 4.1 m deep. Each pockmark would require 18,363 m^3 to be completely filled, for a total of 73,452 m^3 of muddy sediment. Where does this sediment come from? There are three potential sources: 1) sediment carried via the Penobscot River from areas upstream; 2) local resuspension of sediment through wave-seafloor interaction; and 3) the formation or maintenance of pockmarks elsewhere in the basin.

Anchor drag marks are defined as any drag mark that terminates in a broad bulbous mark, or has a plumose-type structure. Other drag marks are any marks on the seafloor that do not qualify as anchor drag marks. These could be the result of tow cables from tugs and barges interacting with the seafloor, or any type of drag fishing (e.g., quahog, mussel and scallop dragging).

Pockmarks can be seen in close association with both types of drag marks. A single pockmark located at the terminus of a drag mark is called a "tadpole". A series of pockmarks located anywhere along a drag mark is called "beaded". Both types of associated pockmarks are found in Belfast Bay.

Beaded pockmarks are chains of pockmarks that form along a visible lineation on the seabed (Figure 4.6). Iceberg furrows, scarps, and fissures have been reported as source lineations (Hovland and Judd, 1988). The high-resolution data set from Belfast Bay suggests that drag marks from fishing and anchoring should be added to source lineations.

Tadpole pockmarks form at the end of an anchor or other type of drag marks (Figure 4.6). The pockmarks form at the initial or terminal end where the tool is place or removed from the seafloor. Pockmarks in the size range of three to five meters have been recognized at terminal ends of drag marks. This is too large to be attributed to the pit from an anchor.

As the beaded or tadpole pockmarks increase in size, they destroy the evidence of the drag mark that was the point of initiation. Sediment from eruption and reworking by waves fills or erodes the drag mark.

Activities that create drag marks alter the sediment thickness in the creation of the drag mark. As the mark is created, sediment is removed from the area where the object was drug and redistributed to the sides of the object. Changing the sediment thickness alters the pressure regime expressed on the underlying gas pocket. Removal of sediment lowers the pressure. As the pressure is lowered, the pocket becomes overpressurized. An anchor impacting the seafloor has a similar effect. The rapid loading of the seabed by the anchor increases the local pressure, thus allowing more gas to accumulate in the pocket. When the anchor is removed, the overlying pressure is rapidly reduced and pockmark formation can progress due to the disequilibrium pressure state. A similar mechanism has been suggested for North Sea pockmarks that occur only along drag marks created by icebergs.

Figure 4.7 shows a time series of a small portion of seafloor within the study area. Two sidescan images from 1989 (A and C) and 2000 (B and D) show how rapidly the seafloor in Belfast Bay is changing. The letters A, B and C identify features on the seafloor. In all four images, the letters are in the same place. A shows a pockmark that remains consistent through the two-year interval while B shows a pockmark that was filled during the two-year interval. C shows a roughly north-south orientated drag mark on the 1989 image (A and C), but that feature is subdued, only marginally recognizable in the 2000 survey. The 2000 data also show a roughly east-west drag mark at C that is not present during the 1998 survey.

It appears, from this initial study, that any activity that interacts with the seafloor could initiate pockmark formation. The conditions must be favorable, as they are in Belfast Bay, for the activity to induce a pockmark. More research is needed to determine what percentage of the Belfast Bay Pockmark Field is the result of anthropogenic activities and if this is significant.

4.4. DISCUSSION

The seafloor in the area of Belfast Bay is a dynamic environment. The seafloor sediments are disturbed by formation of pockmarks and the activities of society. Activities like dragging and anchoring appear to have the ability to disturb the equilibrium of the seafloor to allow pockmarks to form. The close correlation of small (<5 m) pockmarks and drag marks point to a relationship. Features like tadpoles and beads demonstrate the relationship between pockmarks and drag marks, and ultimately to the processes creating the drag marks.

At the resolution of the sidescan sonar, it is difficult to determine the difference between a gas-escape pockmark and a pit created by an anchor. Anchor pits occur at the terminal end of anchor drag marks. This could reduce the number of "pockmarks" in an area, but only if those features interpreted as pockmarks occur at the terminal end of an anchor drag. This argument does not effect the interpretation of beads.

The dynamics occurring in Belfast Bay result from a combination of societal and pockmark processes. These processes potentially impact the sediment transport and benthic habitat of the bay.

Additional investigations are required to determine the differences between anchor pits and pockmarks and the temporal relationship of the creation of the drag and the formation of pockmarks. Further research is required to determine what, if any, effects the combination of these processes have on the ecology of Belfast Bay.

CHAPTER 5
SEAFLOOR MAPPING OF THE BLACK LEDGES AREA

5.1. Introduction

Belfast Bay is not the only location within Penobscot Bay to host large concentrations of pockmarks. Reconnaissance lines from researchers working in Penobscot Bay show scattered pockmarks at various locations (Belknap and Kelley, unpublished data, 1984). One area, the Black Ledges (Figure 5.1), was chosen for a more intensive investigation.

The Black Ledges area was chosen for several reasons: 1) initial sidescan sonar reconnaissance lines showed pockmarks in dense clusters, but did not image the entire field; 2) initial seismic reflection profiling lines show pockmarks hosted within a thin Holocene sedimentary unit; 3) the area does not experience heavy commercial boat traffic or bottom trawling; and 4) the islands in the area provide a sheltered location for fieldwork close to a port facility.

The purposes for studying another pockmark field in Penobscot Bay are to: 1) determine if the processes creating the field are the same; 2) determine if the field's composition is similar to the Belfast Bay pockmark field; and 3) identify additional stages of the evolutionary model (Chapter 6, this work).

5.2. Data Sources

The mapping phase of this project involved data collection with high-resolution sidescan sonar and two marine seismic systems. Data analysis was conducted with ArcView and ArcInfo GIS software as well as Triton-Elics post processing software for sidescan sonar and seismic systems.

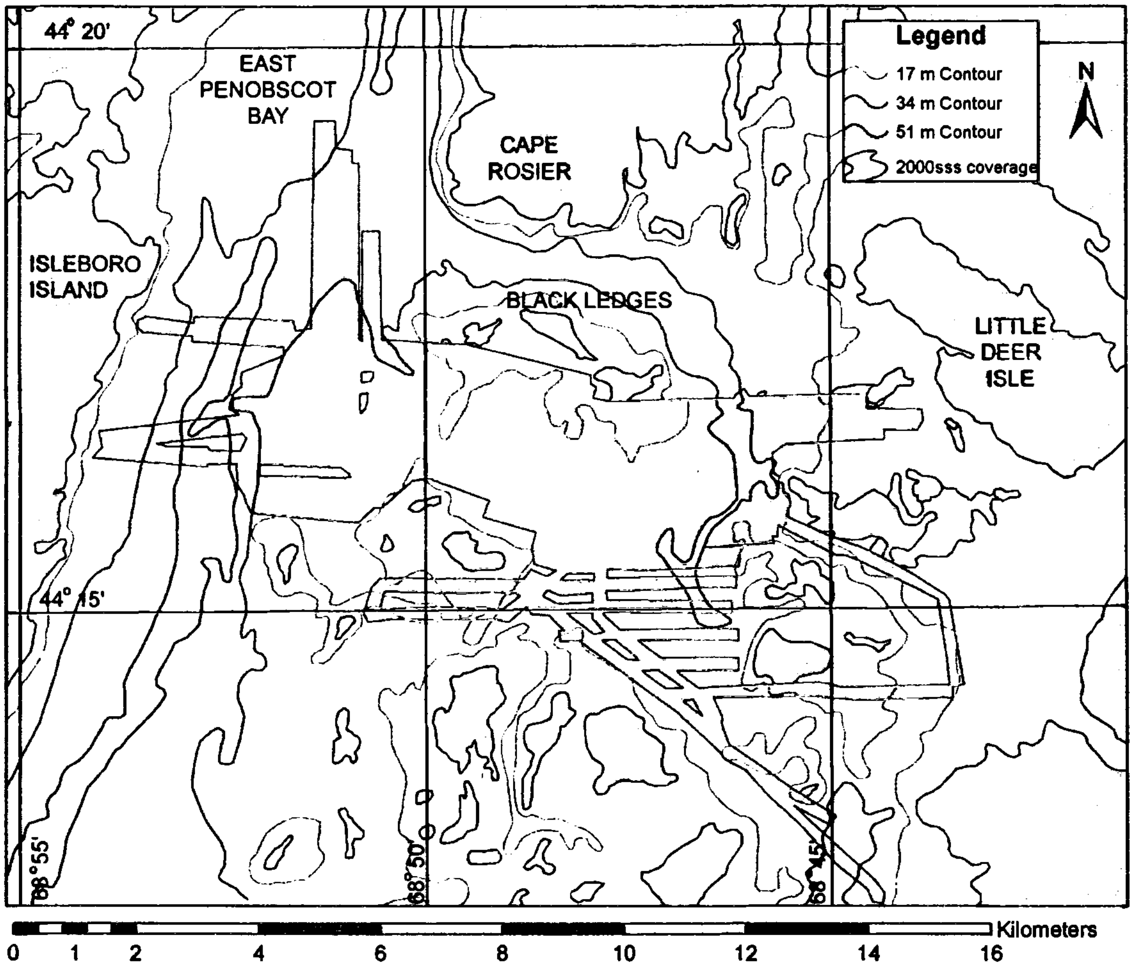

Figure 5.1. The Black Ledges study area. The Black Ledges are a series of islands and ledges located in East Penobscot Bay (Figure 1.1). The area in gray represents 100% sidescan sonar coverage. Boxes A and B (Figures 5.4 and 5.), and line A-A' (Figure 5.) are referred to later in the text. Coastline and bathymetry are simplified from NOS chart 13302.

Sidescan data were collected over three days in August 2000 and one day in January 2001. The sidescan sonar was deployed from the RV Friendship's stern A-frame and towed at about five knots. Survey range was maintained at 100 m (200m swath width) for the majority of the survey. A few reconnaissance lines were collected at 200 m range (400 m swath width). Data were recorded digitally in Q-mips format through Isis Sonar v. 4.54 for sidescan sonar. Seismic reflection data were collected simultaneously with sidescan sonar data on two of the August 2000 and one January 2001 survey days. The August survey used the Ocean Research Engineering boomer system (ORE) while the January survey used the Applied Acoustics Engineering boomer system (AAE) and Triton-Elics topside unit. Analog data from the ORE system produced paper records and were photocopied for analysis. Digital data from the AAE were recorded in XTF format through Delph Seismic for seismic reflection profiling. Raw field data are archived to CD-ROM media for use in the lab and subsequently removed from the local hard drive. A total of about 5.5 GB of data was collected during the surveys, representing approximately 38 km^2 of sidescan imagery and approximately 120 km of seismic reflection lines (Figure 5.2).

5.3. Results

The mapping project collected 38 km^2 of sidescan sonar and 120 km of seismic reflection data, revealing a complex seafloor around the Black Ledges. A mosaic of the field area was created from the sidescan data (Figure 5.3). Combining the sidescan mosaic with seismic reflection data, the seafloor sediments were characterized (Figure

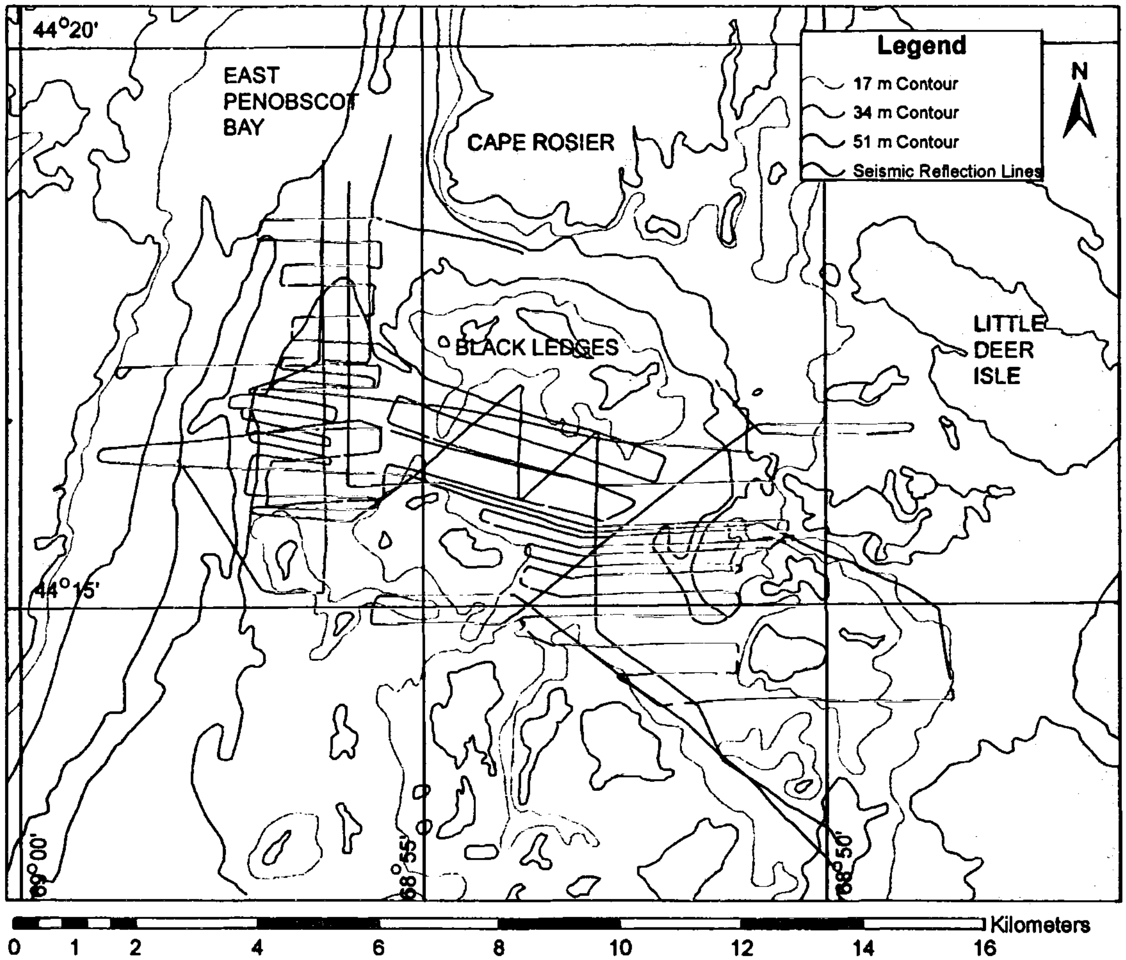

Figure 5.2. Seismic reflection data coverage. A total of approximately 120 km of seismic reflection profiling data were collected. The black line indicates the ship's track during seismic reflection data collection. Coastline and bathymetry are simplified from NOS chart 13302.

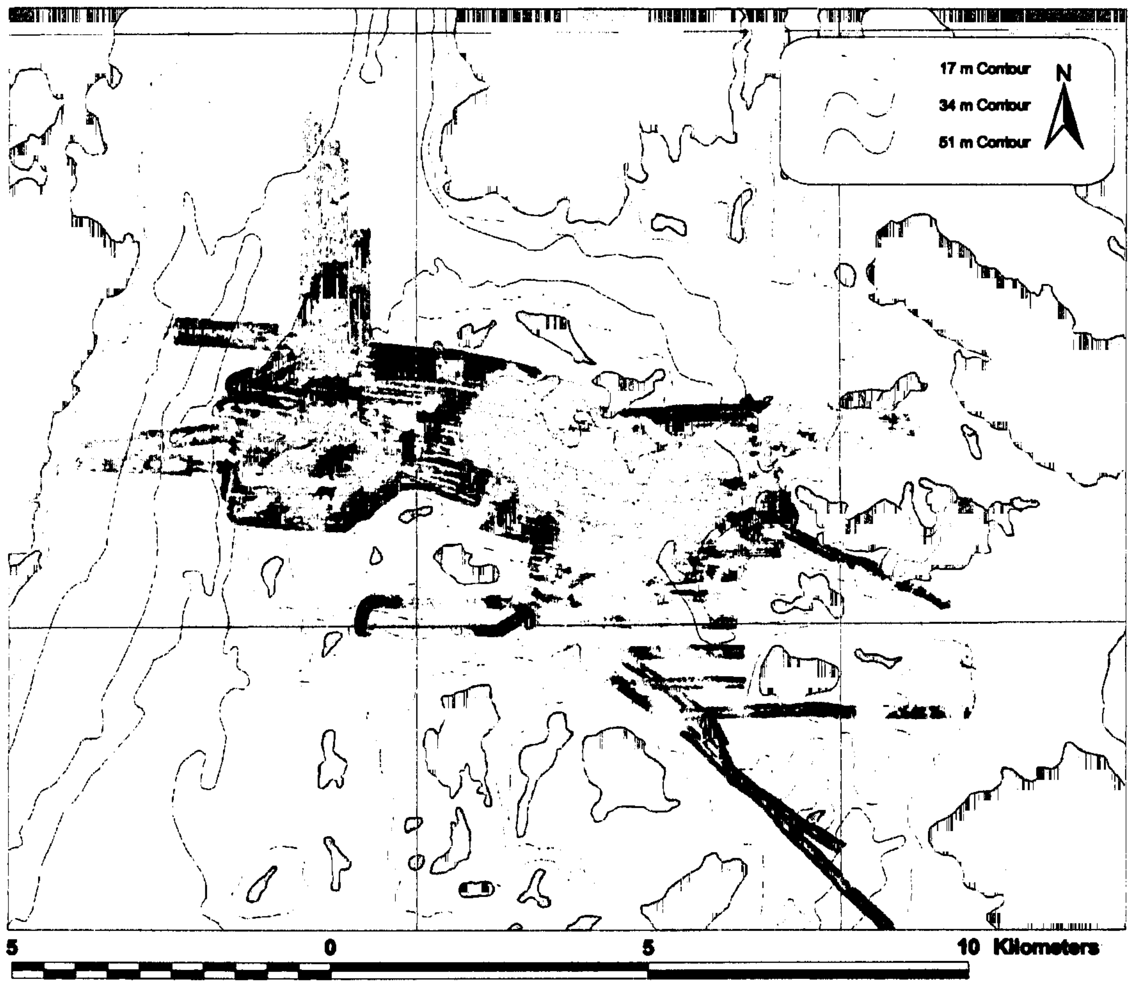

Figure 5.3. Sidescan sonar mosaic of the Black Ledges area. Sidescan sonar images were mosaicked to create an image of the seafloor. Areas of mud or finer grained sediments appear as light grays and gravel and rock appear as dark gray to black. Individual muddy basins are clearly visible as are regions of pockmarked seafloor. Coastlines and bathymetry are simplified from NOS chart 13302.

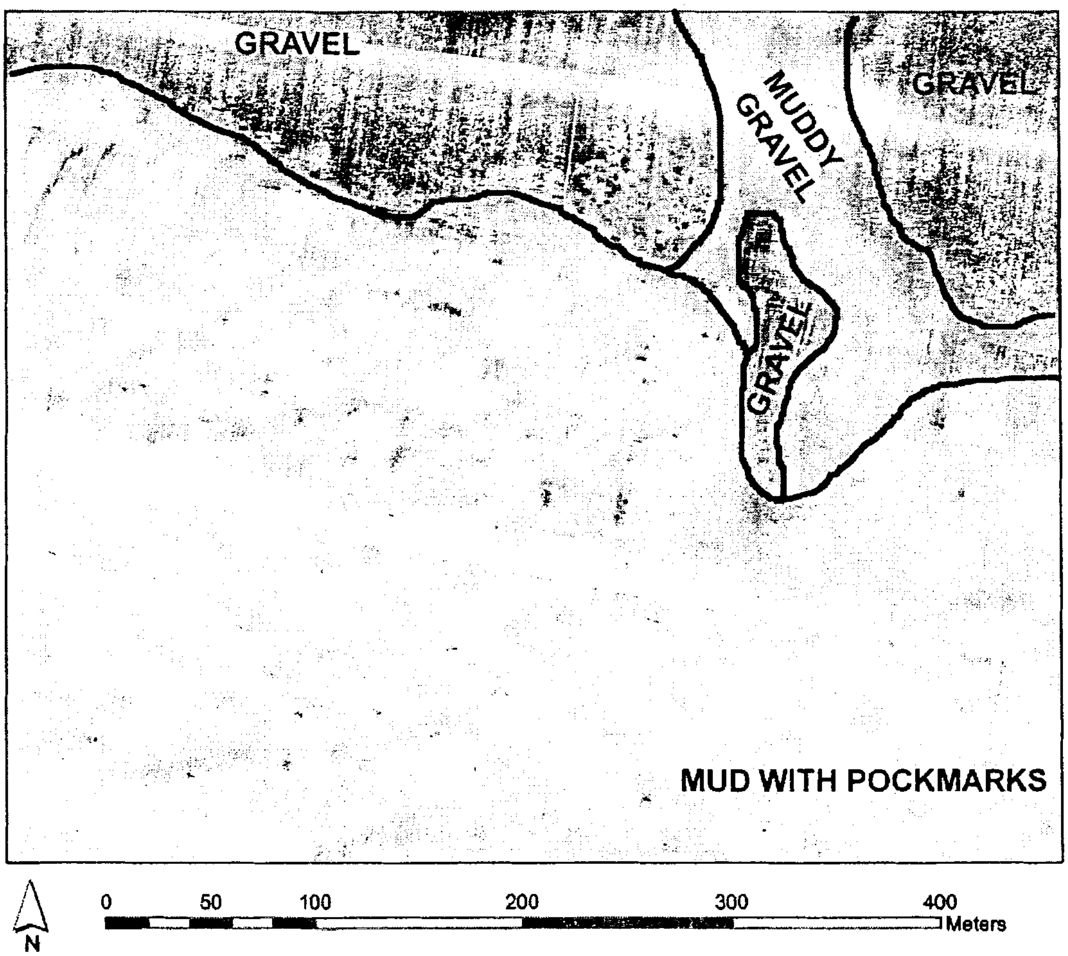

Figure 5.4. Sample of surficial mapping from sidescan sonar images. Sidescan sonar images are interpreted based on image color, a proxy for amount of sonic energy scattered versus energy reflected. Lighter areas absorb or scatter more energy and are interpreted as fine-grained sediments (muddy or muddy gravel). The darker areas are gravel or gravelly mud. This image also shows small (~25 m) pockmarks. Location of the image is identified in Figure 5.1 as box A.

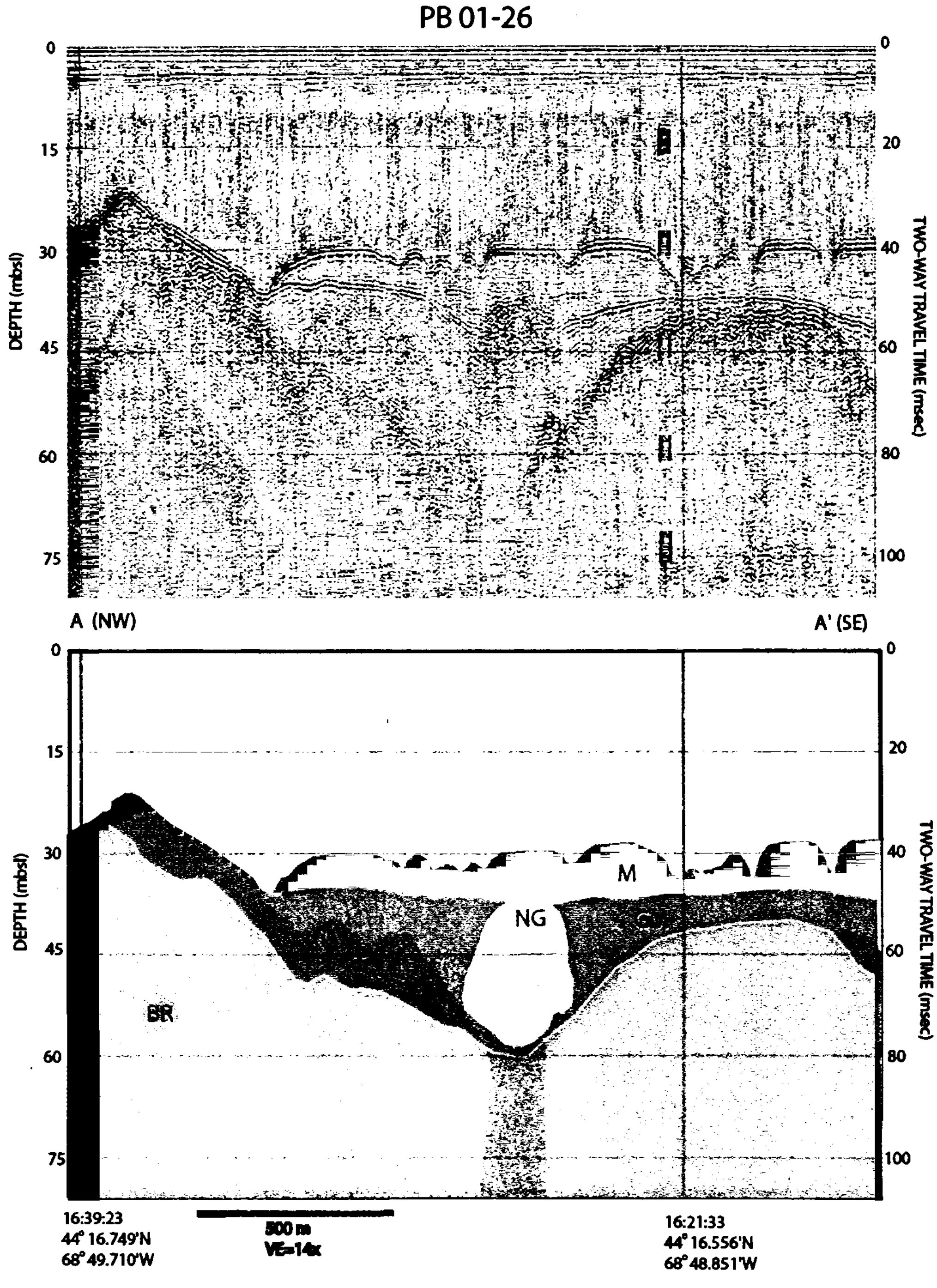

Figure 5.5. Seismic line PB0126. A representative seismic profile from the Black Ledges shows stratigraphic relationships and typical unit thicknesses within the study area. The seismic profile line shows bedrock (B, red), till (T, purple), glaciomarine (GM, blue), Holocene mud (M, gray), and natural gas (NG, green). The upper image is uninterpreted data and the lower image has been interpreted. Location of original line is shown on Figure 5.1 as line A-A'.

5.4). The protocol and units (Table 5.1) developed by Barnhardt et al. (1996a, b) was followed. Twelve of the 16 seafloor sediment classifications were present. Units containing sand were not observed.

Table 5.1. Seafloor classification scheme. A classification for seafloor surficial geology was developed by Barnhardt et al. (1998). Sixteen members representing rock (R), gravelly rock (Rg), sandy rock (Rs), muddy rock (Rm), Gravel (G), rocky gravel (Gr), sandy gravel (Gs), muddy gravel (Gm), sand (S), rocky sand (Sr), gravelly sand (Gs) muddy sand (Sm), mud (M), rocky mud (Mr), gravelly mud (Mg), and sandy mud (Ms) was used to interpret sidescan sonar images.

R	Rg	Gr	**G**
Rs	Rm	Gs	Gm
Sr	Sg	Mr	Mg
S	Sm	Ms	**M**

Seismic reflection profiles revealed a thin (<7 m) Holocene sediment cover in discrete muddy basins underlain by glaciomarine sediments, occasional till, and bedrock. Till was found to be thickest on the southeastern slopes (Figure 5.5), in agreement with Thompson and Borns (1985). Natural gas was observed within the sediment. It was found in one of two forms: gas-enhanced reflectors and acoustic wipeout.

Gas-enhanced reflectors typically followed reflectors interpreted as the Pleistocene-Holocene unconformity and other prominent reflectors within the Holocene sediments. These reflectors were found on the flanks of depressions cut into the glaciomarine sediments. The enhanced reflector at the unconformity could be due to a lag deposit, or grain-size changes. This has been discounted in most occurrences due to the presence of acoustic wipeout at the base of the depression and enhanced reflectors emanating from the zone of wipeout. Also, the enhanced reflector is not found at the same elevation throughout the area, as would be expected if it were a lag deposit related to transgression. The enhanced reflectors also underlie pockmarks or terminate in moats where the Holocene sediments pinch out against a Pleistocene or bedrock outcrop (Figure 5.5). This suggests the enhanced reflectors are a pathway for the migration of natural gas and might be the source of fluid for the overlying pockmarks.

Acoustic wipeout is typically found within depressions cut into the glaciomarine (Figure 5.4 and 5.5). The wipeout is a result of gas, in bubble phase within the sediments. Bubbles attenuate the seismic energy at concentrations as low as 2% per volume (R. Parrott, personal communication, 2002). The stratigraphic record below the bubble front is obscured. Acoustic wipeout zones are small and not regionally extensive.

A spatial analysis was conducted on the surficial units (Figure 5.6, Table 5.2). Mud and muddy units clearly dominate the system, accounting for 67.5% of the surveyed area. Gravel and gravelly units are secondary accounting for 24.0% of the area. The remainder, 8.5%, is rocky.

The sidescan sonar mosaic shows several discrete muddy basins bounded by gravelly and rocky units (Figure 5.3). The muddy basins were found to host large numbers of pockmarks (Figure 5.7). In all, seven individual fields were mapped (Figure 5.8). The fields were named using the phonetic alphabet (Alpha, Bravo, Charlie, Delta, Echo, Foxtrot, and Golf). Each field is separated from the others by a break in muddy sediments, or in the case of Charlie and Delta, a lack of sidescan coverage.

The seven fields contain 3,528 pockmarks and cover a total of 9.8×10^6 m^2 of seafloor. All of the pockmarks encompass an area of 7.5×10^5 m^2, or 7.7% of the seafloor. The density of pockmarks for all of the fields combined is 361 pockmarks/km^2.

Table 5.2. Surficial Geology of the Black Ledges Area. The results of the spatial analysis utilizing ArcView and ArcInfo GIS are present in tabular form. NP means the unit was not observed at the map scale in the Black Ledges area.

Unit	Symbol	Area (m^2)	% of Total
Mud	M	22,073,207	59.45
Rocky Mud	Mr	148,993	0.40
Gravelly Mud	Mg	2,856,339	7.69
Sandy Mud	Ms	NP	NP
Sand	S	NP	NP
Muddy Sand	Sm	NP	NP
Gravelly Sand	Sg	NP	NP
Rocky Sand	Sr	NP	NP
Gravel	G	6,884,112	18.54
Muddy Gravel	Gm	1,655,292	4.46
Sandy Gravel	Gs	NP	NP
Rocky Gravel	Gr	360,101	0.96
Rock	R	12,870	0.03
Muddy rock	Rm	17,441	0.05
Sandy Rock	Rs	NP	NP
Gravelly Rock	Rg	3,118,558	8.39
Total		37,126,883	99.97

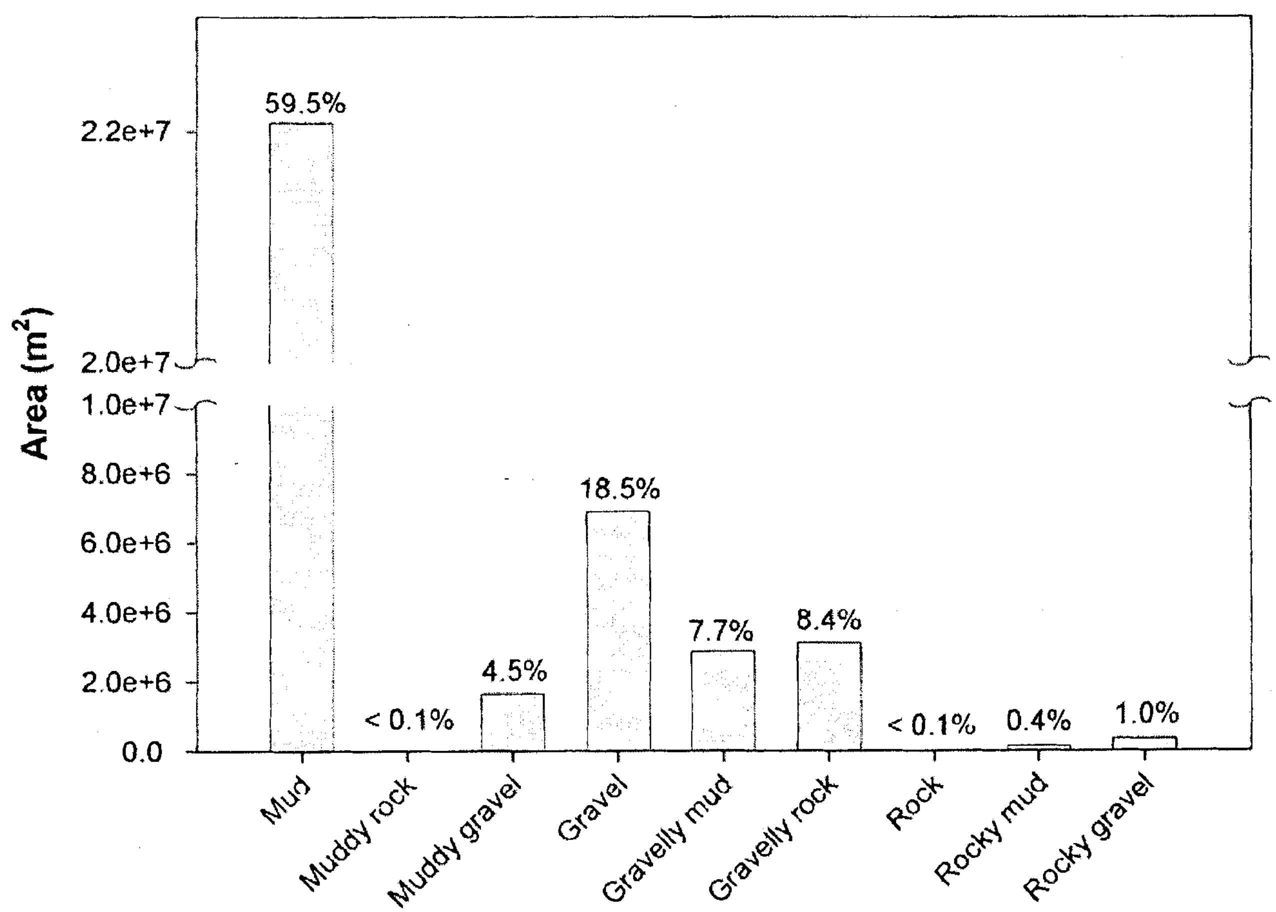

Figure 5.6. Distribution of surficial sediments in the Black Ledges. Spatial analysis was performed on the surficial map produced from the sidescan sonar mosaic (Figures 5.3 and 5.4). Mud and muddy sediments dominate the surficial geology of the Black Ledges and sand was not mapped.

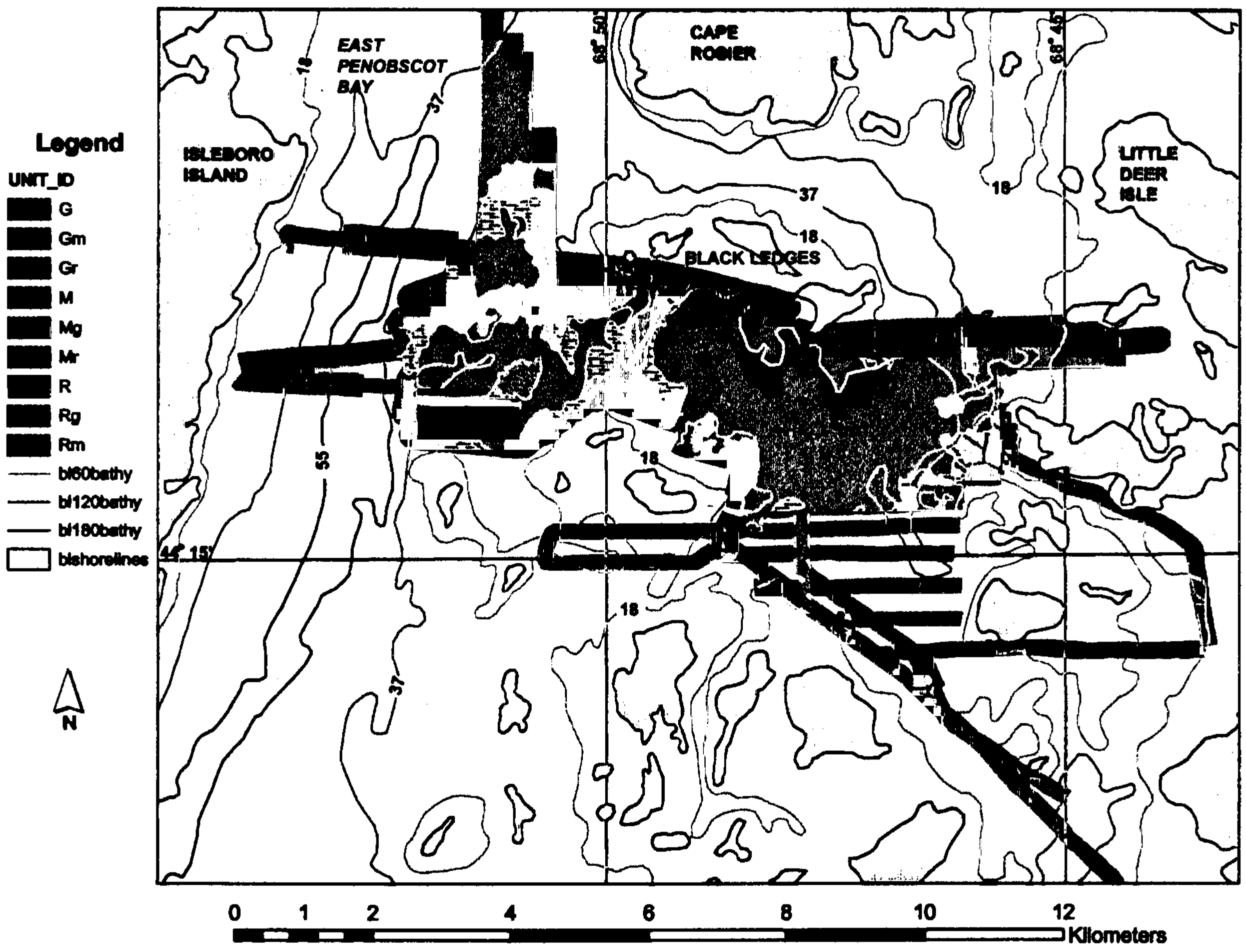

Figure 5.7. Surficial geology map of the Black Ledges Area. The sidescan sonar image was interpreted (as in Figure 5.4). The result is a map detailing the surficial sediment type in the area. A classification scheme developed by Barnhardt et al. (1996a and b; 1998) was applied. Colors represent primary surficial type, blue is mud dominated, green is gravel dominated, and red is rock dominated. The hatch pattern represents secondary surficial unit and are detailed on the map legend. Sand was absent at the map scale presented.

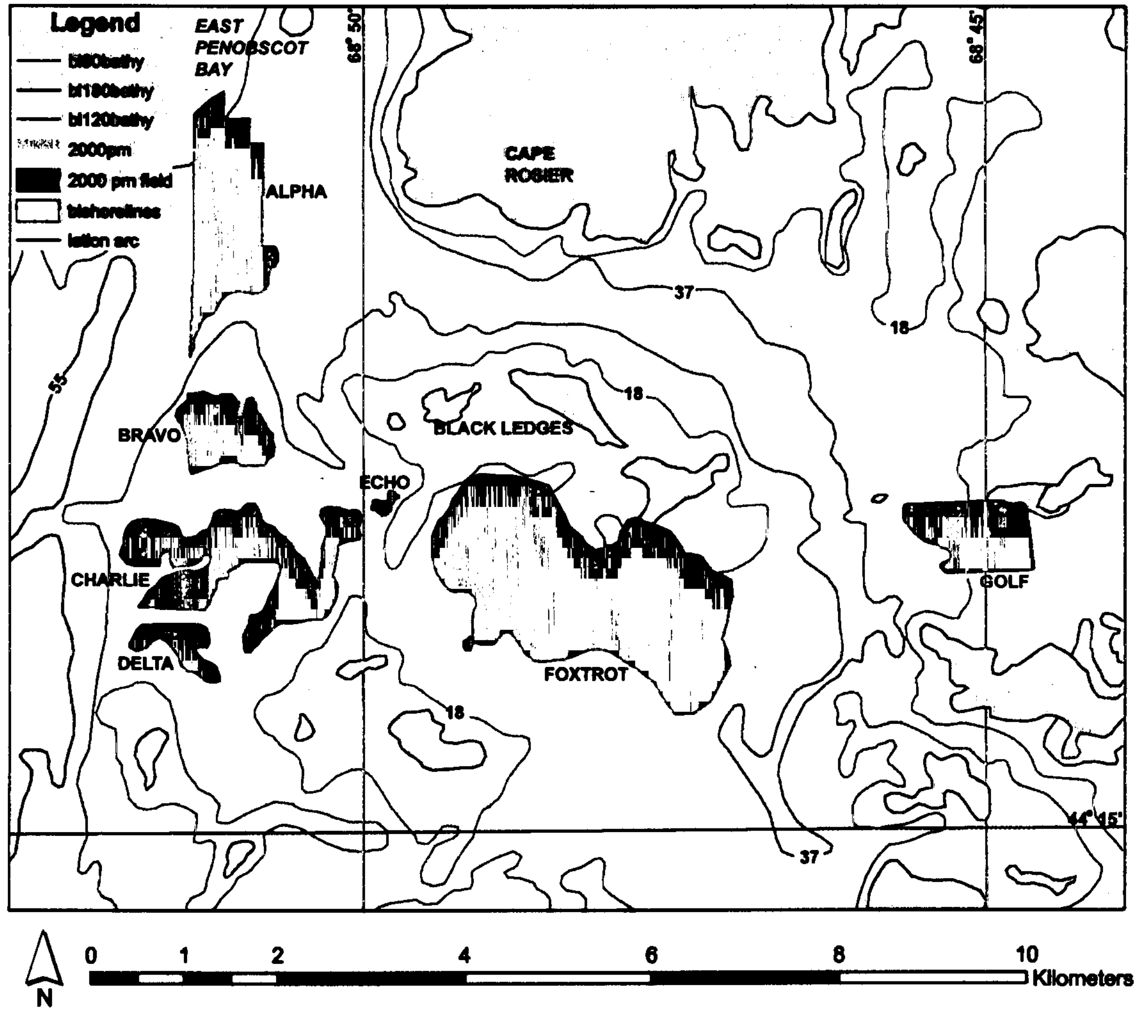

Figure 5.8. Map of the seven pockmark fields. The map shows the location of the seven pockmark fields. Associated names are referred to in the text and follow the phonetic alphabet (i. e., Alpha, Bravo, Charlie, Delta, Echo, Foxtrot, and Golf).

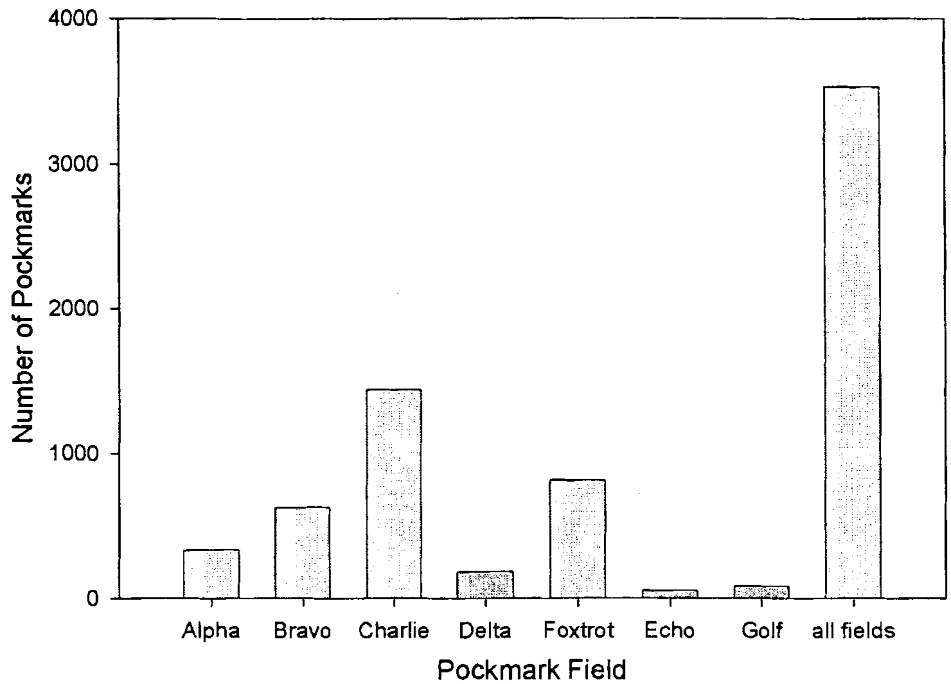

Figure 5.9. Pockmark field populations. The populations of pockmarks larger than 3 m were digitized into a GIS and spatial analyses were performed on each field. The populations are displayed by field.

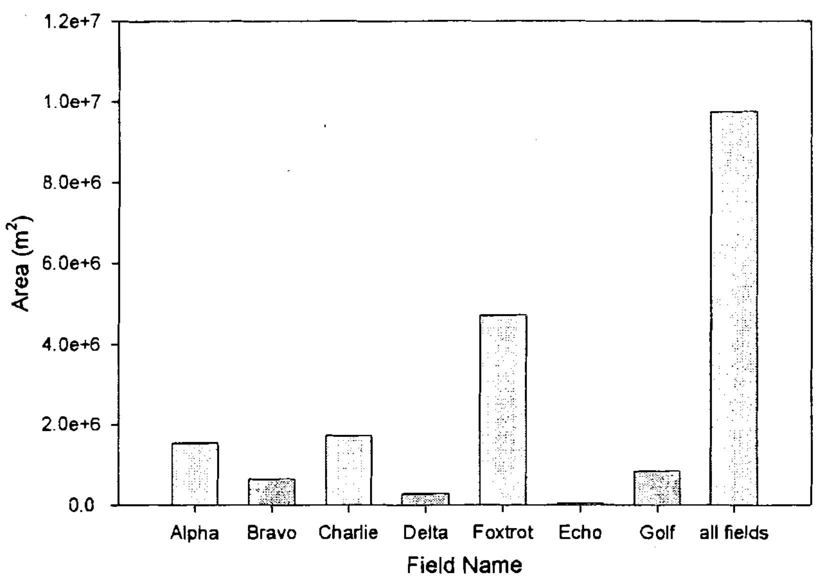

Figure 5.10. Pockmark field area. The GIS data set was used to determine the area of each field. Foxtrot is the largest and Echo is the smallest. The final column shows total area of pockmarked seafloor.

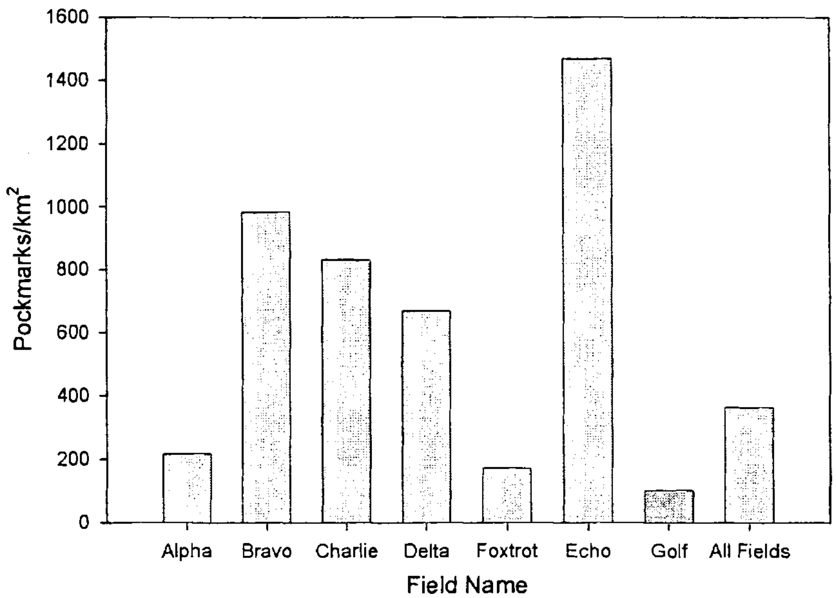

Figure 5.11. Density of pockmarks by field. Spatial analyses showed the density of pockmarks in the Black Ledges area. The smallest field, Echo, has the greatest density, nearly 1500 pockmarks per km^2. Note that Charlie and Delta are probably contiguous in the field, so similar densities would be expected

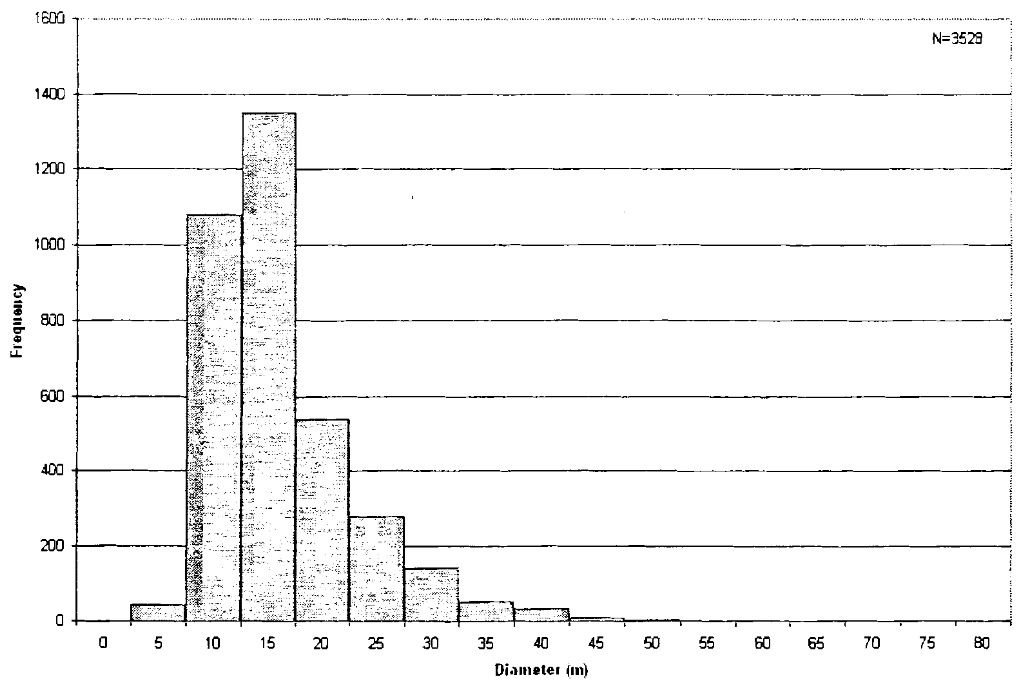

Figure 5.12. Distribution of pockmark size for all pockmarks at the Black Ledges. Spatial analyses determined the distribution of pockmarks by diameter. Classification was with 5 m classes. The most frequent size class was 15 m. Features smaller than 5 m do exist, but were below the resolution of the mosaicking processes.

The maximum pockmark diameter is 75.4 m and the minimum is 3.8 m. The minimum diameter is governed by the resolution of the sidescan sonar and the pixel size during mosaicking. The mean is 13.7 m (Figures 5.9, 5.10, 5.11, 5.12, and Tables 5.3 and 5.4).

Field Alpha contains 332 pockmarks. It encompasses 1.5 x 10^6 m^2 of seafloor. The 332 pockmarks cover 2.2 x10^5 m^2, or 14.2%. The pockmark density is 216 pockmarks/km^2. The maximum pockmark diameter is 37.2 m and the minimum is 10.2 m. The mean is 19.7 m (Figure 5.13, Table 5.3 and 5.4). There are two clusters within the field. The northern section, deeper than the 37 m isobath, contains elliptical pockmarks (Figure 5.14). These are the only observed elliptical pockmarks within Penobscot Bay. The survey grid did not image the entire field. Field boundaries on the north, east and western sides were not imaged.

Field Bravo contains 627 pockmarks. It encompasses 6.4 x 10^5 m^2 and the pockmarks cover 5.8 x 10^4 m^2, or 9.1%. The pockmark density is 983 pockmarks/km^2. The maximum pockmark diameter is 23.24 m and the minimum is 5.1 m. The mean is 10.4 m (Figure 5.15, Table 5.3 and 5.4).

Field Charlie contains 1438 pockmarks. It contains the largest population of the seven fields surveyed. It encompasses 1.7 x 10^6 m^2 and the pockmarks cover 1.6 x 10^5 m^2, or 9.3%. The pockmark density is 830 pockmarks/km^2. The maximum pockmark diameter is 30.6 m and the minimum is 3.8 m. The mean is 11.4 m (Figure 5.16, Table 5.3 and 5.4).

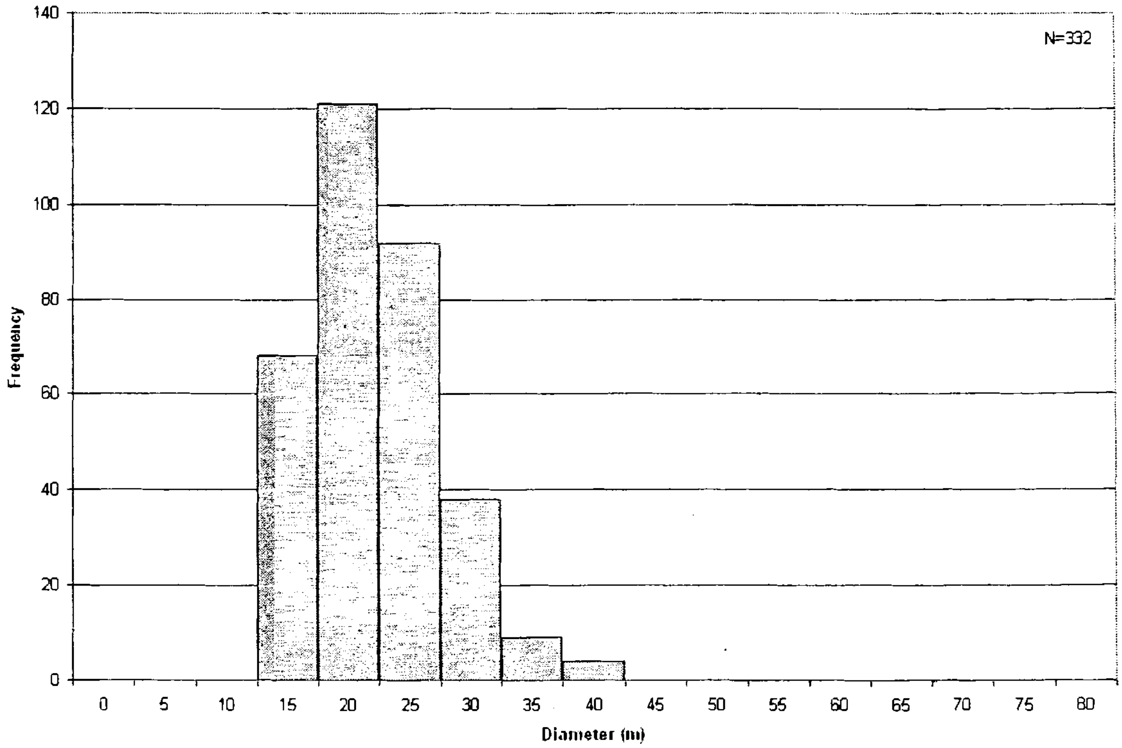

Figure 5.13. Distribution of pockmarks, by size in field Alpha. Spatial analyses determined the distribution of pockmarks by diameter. Classification was with 5 m classes. The most frequent size class was 20 m.

Table 5.3. Pockmark field areas and densities. Spatial analyses performed on the GIS database provided a method for calculating pockmark densities within each field.

Field	**Area (m^2)**	**Pockmarks**	**Pockmark Density (pm/km^2)**
Alpha	1,535,112	332	216
Bravo	637,275	627	984
Charlie	1,731,499	1,438	831
Delta	272,135	182	669
Echo	36,092	53	1472
Foxtrot	4,711,495	812	172
Golf	832,908	84	101
All Fields	9,756,516	3528	362

Table 5.4. Diameter statistics for the Black Ledges pockmark fields. The maximum, minimum and mean diameters for each field was determined from the GIS database.

Field	Mean Diameter	Maximum Diameter	Minimum Diameter
Alpha	19.7	37.2	10.2
Bravo	10.4	23.2	5.1
Charlie	11.4	30.6	3.8
Delta	11.9	20.4	5.7
Echo	7.9	14.3	3.8
Foxtrot	17.7	75.4	4.8
Golf	23.5	60.2	8.0
All Fields	13.7	75.4	3.8

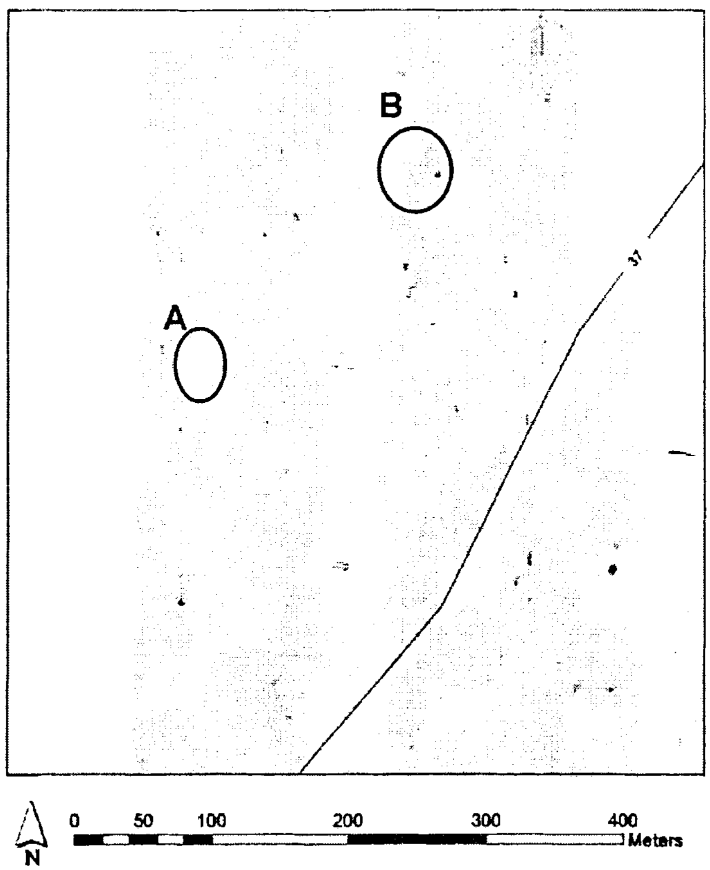

Figure 5.14. Elliptical pockmarks of field Alpha. Elliptical pockmarks occur on the northern edge of field Alpha. These features are aligned parallel to subparallel to the 37 m isobath and azimuth 045°. Models of currents in Penobscot Bay (Xue and Brooks, 2000) suggest these features are created by current scour caused by residual currents aligned along 045°.

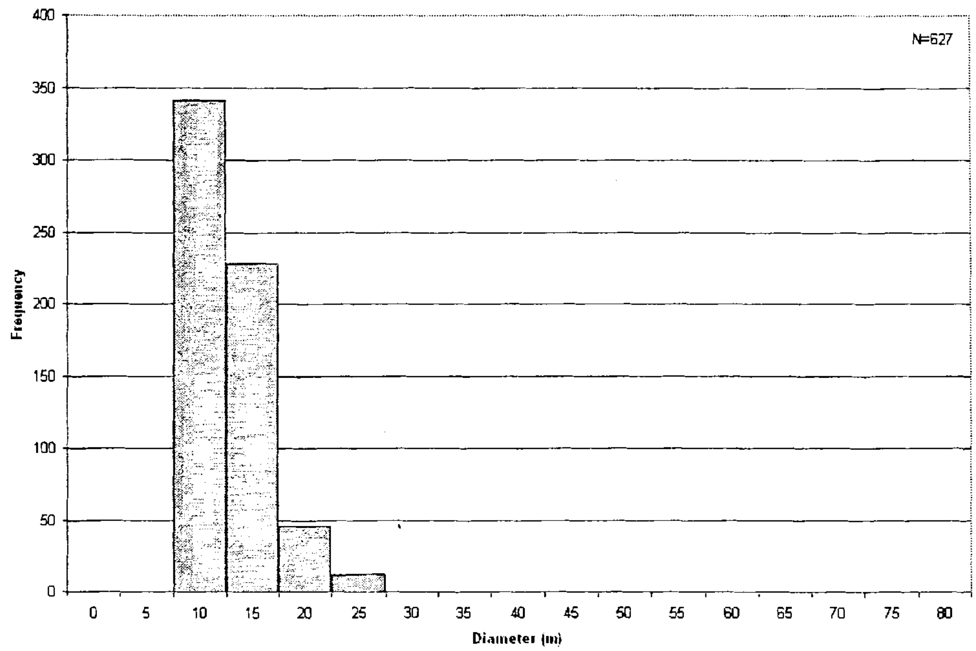

Figure 5.15. Distribution of pockmarks, by diameter in field Bravo. Spatial analyses determined the distribution of pockmarks by diameter. Classification was with 5 m classes. The most frequent size class was 10 m.

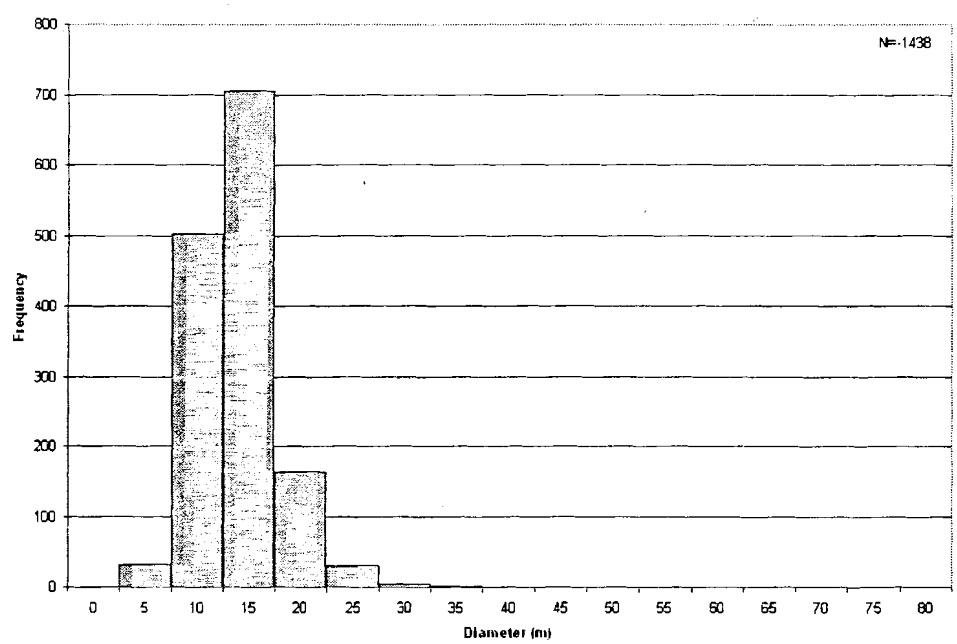

Figure 5.16. Distribution of pockmarks by diameter in field Charlie. Spatial analyses determined the distribution of pockmarks by diameter. Classification was with 5 m classes. The most frequent size class was 15 m.

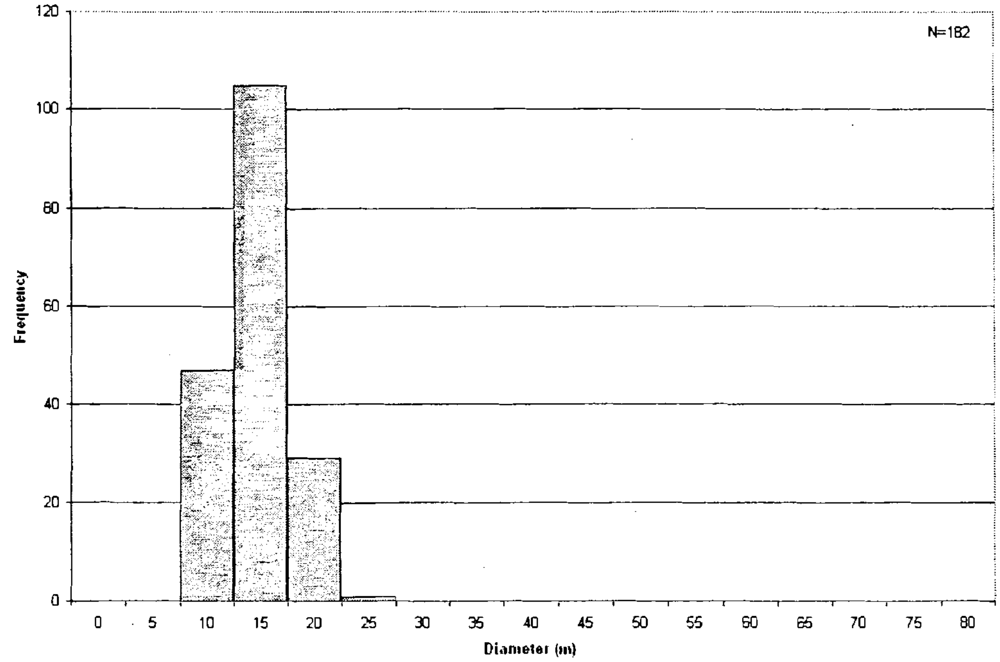

Figure 5.17. Distribution of pockmarks by diameter in field Delta. Spatial analyses determined the distribution of pockmarks by diameter. Classification was with 5 m classes. The most frequent size class was 15 m.

Field Delta contained 182 pockmarks. It encompasses 2.7 x 10^5 m^2 and the pockmarks cover 2.2 x 10^4 m^2, or 7.9%. The pockmark density is 668 pockmarks/km^2. The maximum pockmark diameter is 20.4 m and the minimum is 5.7 m. The mean is 11.9 m (Figure 5.17, Table 5.3 and 5.4). A gap in sonar coverage exists between fields Charlie and Delta. It is probable that the fields are one continuous feature.

Field Echo contained 53 pockmarks. It was the smallest field surveyed, encompassing 3.6 x 10^4 m^2 and contained the fewest pockmarks. The pockmarks covered 2.8 x 10^3 m^2, or 7.7%. This field has the highest pockmark density, 1,468 pockmarks/km^2. The maximum pockmark diameter is 14.3 m and the minimum is 3.8 m. The mean was 7.9 m (Figure 5.18, Table 5.3 and 5.4).

Field Foxtrot contains 812 pockmarks. It contains the largest pockmark surveyed in the Black Ledges area. The field encompasses 4.7 x 10^6 m^2 and the pockmarks cover 2.5 x

10^5 m^2, or 5.3% of the seafloor. The pockmark density is 172 pockmarks/km^2. The maximum pockmark diameter is 75.4 m and the minimum is 4.8 m. The mean was 17.7 m (Figure 5.19, Table 5.3 and 5.4).

Field Golf contains 84 pockmarks. It comprises four clusters of pockmarks separated by unpockmarked, muddy seafloor. The field encompasses 8.3 x 10^5 m^2 and the pockmarks cover 4.4 x 10^4 m^2, or 5.3%. The pockmark density is 100 pockmarks/km^2. The maximum pockmark diameter is 60.2 m and the minimum diameter is 8.0 m. The mean was 23.5 m (Figure 5.20, Table 5.3 and 5.4). The survey did not image the entire field. The boundaries on the north and southern sides were not imaged.

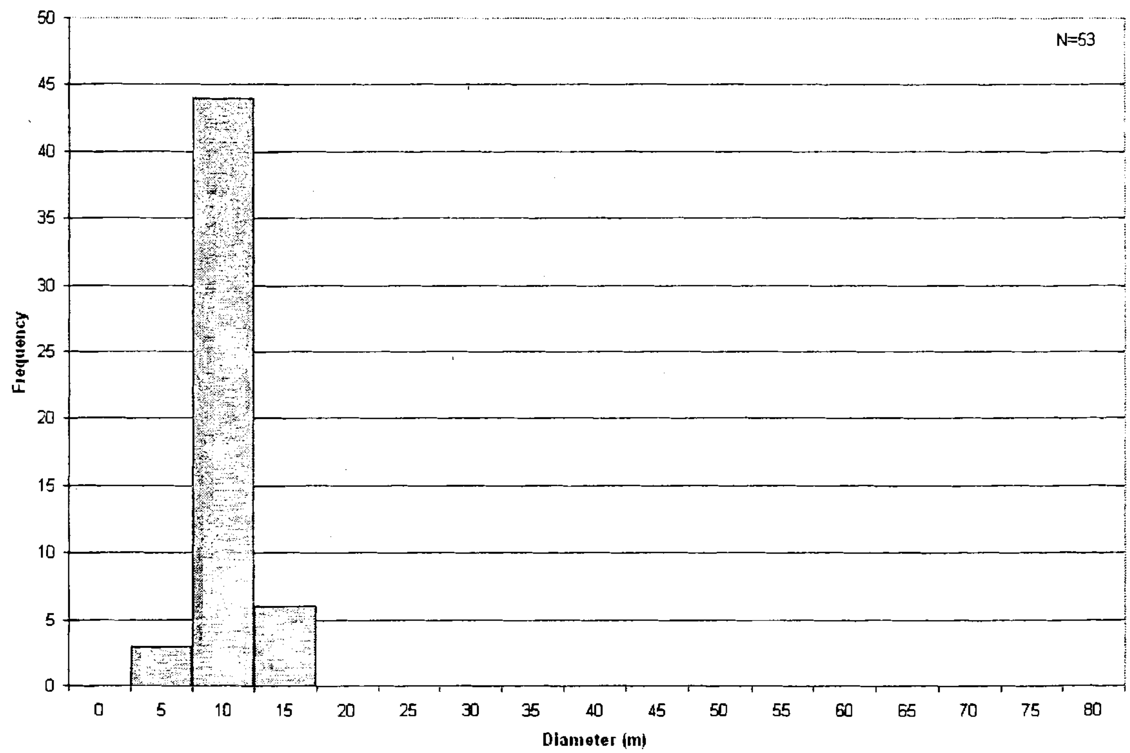

Figure 5.18. Distribution of pockmarks by diameter in field Echo. Spatial analyses determined the distribution of pockmarks by diameter. Classification was with 5 m classes. The most frequent size class was 10 m.

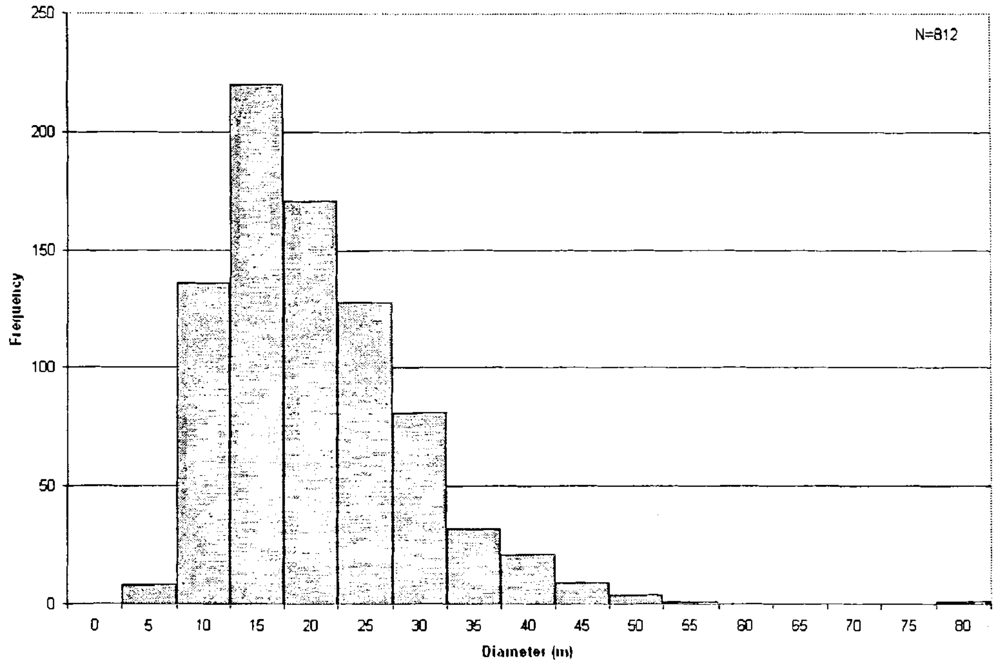

Figure 5.19. Distribution of pockmarks by diameter in field Foxtrot. Spatial analyses determined the distribution of pockmarks by diameter. Classification was with 5 m classes. The most frequent size class was 15 m.

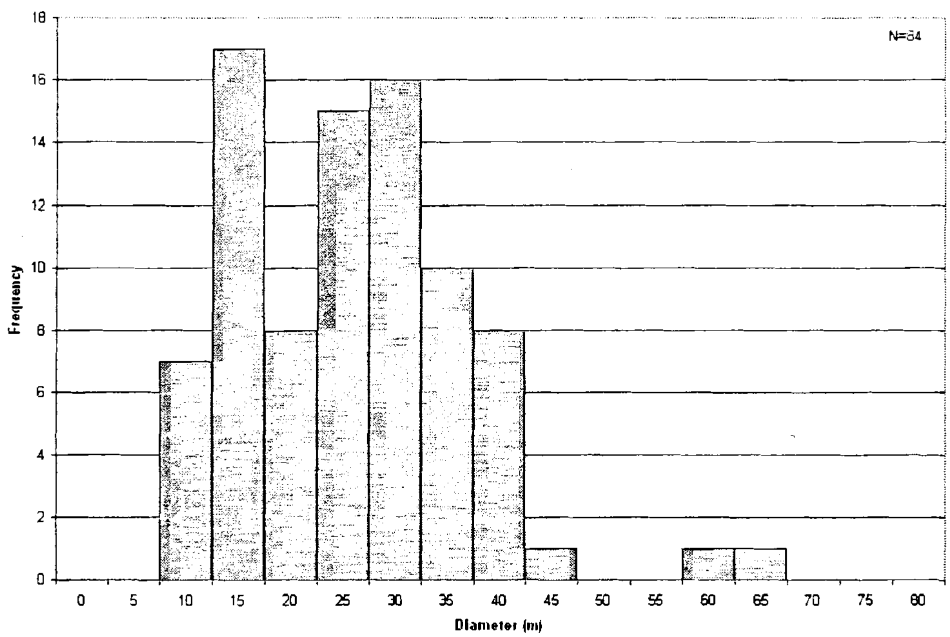

Figure 5.20. Distribution of pockmarks by diameter in field Golf. Spatial analyses determined the distribution of pockmarks by diameter. Classification was with 5 m classes. Field Golf is polymodal, with greatest populations in classes 15, 25, 30 m.

The elliptical pockmarks observed in field Alpha suggest modification by currents. Fader (1991) observed morphologically similar features on the Scotian Shelf and attributed the origin to current-modified gas-escape pockmarks. The elliptical features in field Alpha all occur deeper than the 37 m isobath and are parallel or sub-parallel to the isobath. The long axis of the ellipse trends roughly along an azimuth of 045°. Three-dimensional models of the circulation in Penobscot Bay suggest the near-bottom currents in the area are approximately parallel to the axis of the elliptical pockmarks with the U_1 velocity between 0.0 and 0.2 m/s north, the V_1 velocity between 0.0 and 0.2 m/s east and no Z_1 velocity after detiding the data (Xue and Brooks, 2000). U_1 and V_1 are the horizontal components of current velocity with U_1 in the north-south direction, with positive toward the north, V_1 in the east-west direction with positive toward the east, and Z_1 is vertical component of velocity with positive toward the surface.

The remainder of the pockmarks are either normal or eyed (Figure 5.7). Eyed pockmarks (Fader, 1988; Kelley et al., 1994) have a hard return in the center. This return is the result of several possibilities. 1) The pockmark has excavated down to the underlying Holocene-Pleistocene unconformity. The glaciomarine sediments and the lag deposit thought to form at the unconformity has a higher backscatter than the Holocene mud. This has been confirmed to occur with seismic reflection profiling (Figure 5.4 and 5.5). 2) A lag deposit forms within the pockmark during excavation. As the gas and pore water escapes, any particles too large to be removed by the escaping fluid will fall back into the pockmark and accumulate in the center of the pockmark. 3) Communities of organisms specialized to take advantage of the source of laible carbon from the methane inhabit the bases of pockmarks in some areas (Fader, 1991; Hovland and Judd, 1988).

Submersible dives in the Belfast Bay Pockmark Field did not observe vent communities within pockmarks (R. Arnold, unpublished report, 2002) and there is no indication that the Black Ledges should be different.

The width-to-depth ratios of the Black Ledges pockmarks is similar to those of the Belfast Bay pockmark field. From a sample of 15 pockmarks with diameters from 25 m to 70 m that were crossed directly over the center by both sidescan sonar and seismic reflection profiling, the widths and depths were plotted. Rogers (1999) reported a power function as a relationship for width and depth. His measurement was based on 269 pockmarks with diamters from 25 m to 250 m in the Belfast Bay area and yielded the following relationship:

$$\text{Relief} = 0.3755(\text{Diameter})^{0.7432} \qquad \text{eqn. 5.1}$$

The data collected from the Black Ledges (Figure 5.21) can be expressed by the following empirical relationship:

$$\text{Relief} = 0.10(\text{Diameter})-0.23 \qquad \text{eqn. 5.2}$$

The relationships are slightly different. The range of data and size of sample set was smaller for the Black Ledges than for Belfast Bay. The relationship has an r^2 value of 0.622. This is acceptable, considering small sample size and small data range. Rogers' (1999) power law (eqn 5.1) was applied to the data set. Linear regression was performed on the set. This was expected since the values were determined from an equation. In the diameter range of 20 – 80 m, the power law approximates a straight line

$$\text{Depth} = 0.10(\text{Diameter})+1.55 \qquad \text{eqn 5.3}$$

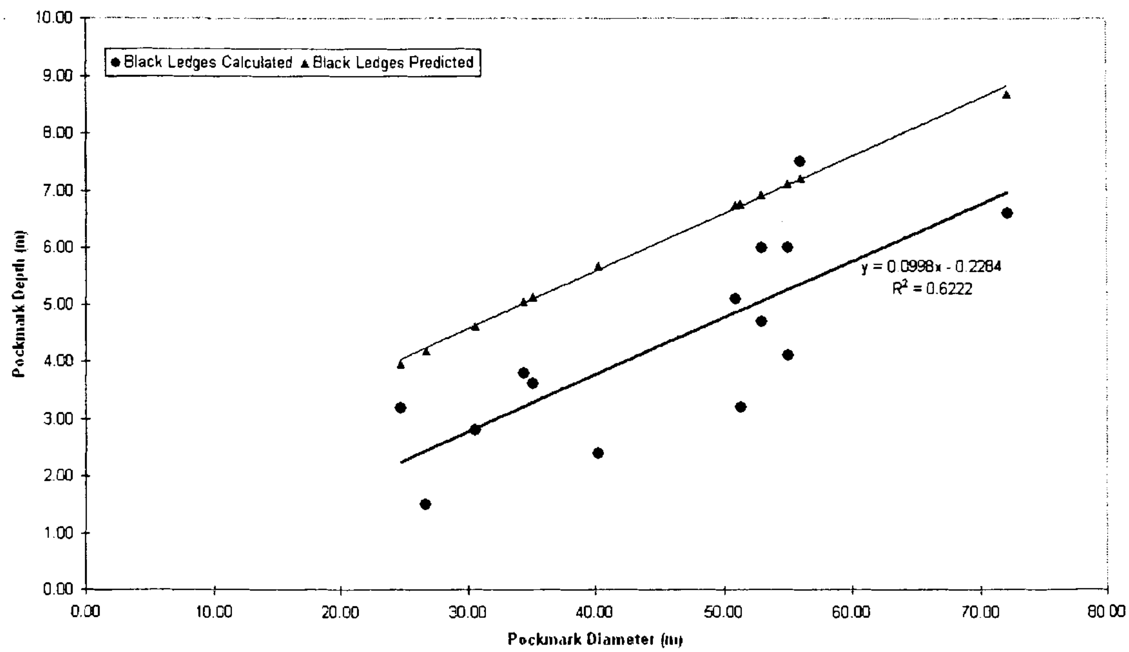

Figure 5.21. Pockmark relief versus pockmark diameter. Fourteen direct pockmark crossings were plotted to determine the relationship between depth and diameter in the Black Ledges pockmark fields. Triangles are depths predicted with the Rogers (1999) power law relationship, circles are measured width versus depth in the Black Ledges area.

The slopes of the approximations are identical, but the intercept values vary. Similar slopes suggest the features are of the same shape, but of differing portions of the model sphere. Rogers (1999) model (intercept = 1.55) suggests a larger portion than data presented here (intercept = -0.23) (Figure 5.21). The model differences represent 20 to 40% in depth approximations, with larger variation for smaller diameters.

Rogers (1999) calculated the volumes based on am empirical relationship derived from multibeam bathymetry of the pockmark field.

$$V = 1/6\ \pi h(3r^2+h^2) \qquad \text{eqn 5.4}$$

where V is volume, r is the pockmark radius, and h is depth of the pockmark. This represents the volume of $1/10^{th}$ of a sphere. The differences in modeled depth between Belfast Bay and the Black Ledges suggest the Belfast pockmarks represent a greater portion of the sphere than those found in the Black Ledges. Thus, a model for the Black Ledges would represent less than $1/10^{th}$ of a sphere. Three-dimensional data is unavailable at this time to produce an accurate representation of the exact section of a sphere.

The the portion of a sphere model lies between the end members of a cone:

$$V = 1/3\ \pi r^2 h \qquad \text{eqn 5.5}$$

and a cylinder:

$$V = \pi r^2 h \qquad \text{eqn 5.6}$$

Given a pockmark with a radius and depth, the $1/10^{th}$ sphere model yields a volume 1.5 times that of the cone model and 0.5 times that of the cylinder model (Figure 5.22, Table 5.5). The cylinder model is unlikely. Soft, unconsolidated, water saturated sediments cannot maintain slopes of 90^o. Without intensive three-dimensional observations, the exact shape of the pockmark is unknown, but this appears to be a close approximation.

The volume of muddy sediments and pore water removed from the Black ledges area by pockmark processes is $2.1 \times 10^6\ m^3$ (by eqn 5.1 and 5.4) or $2.1 \times 10^6\ m^3$ (by eqn 5.2 and 5.4). This may seem like a large volume, but when spread out over the entire area where pockmarks are present, the blanket would be on the order of 0.21 m thick. A change of seafloor elevation of this magnitude would be difficult to measure without the highest resolution multibeam bathymetric devices available.

Table 5.5. Comparison of pockmark volume models. Results from three models for three-dimensional morphology (eqn 5.4, 5.5, and 5.6) are presented below. Diameters range between 2 and 20 m. Depth was calculated from eqn 5.2. Graphical results are presented in Figure 5.21.

Diameter	Depth	Volume – Portion of Sphere	Volume – Cone	Volume - Cylinder
2	0.63	1.117	0.658	1.975
4	1.05	7.220	4.407	13.221
6	1.42	21.610	13.403	40.209
8	1.76	47.121	29.508	88.523
10	2.08	86.337	54.423	163.268
15	2.81	259.885	165.513	496.539
20	3.48	568.642	364.388	1093.164
25	4.11	1044.370	672.059	2016.178
30	4.70	1716.775	1108.199	3324.596
35	5.27	2614.037	1691.477	5074.430
40	5.82	3763.123	2439.774	7319.321
45	6.36	5190.014	3370.320	10110.960
50	6.88	6919.856	4499.799	13499.396

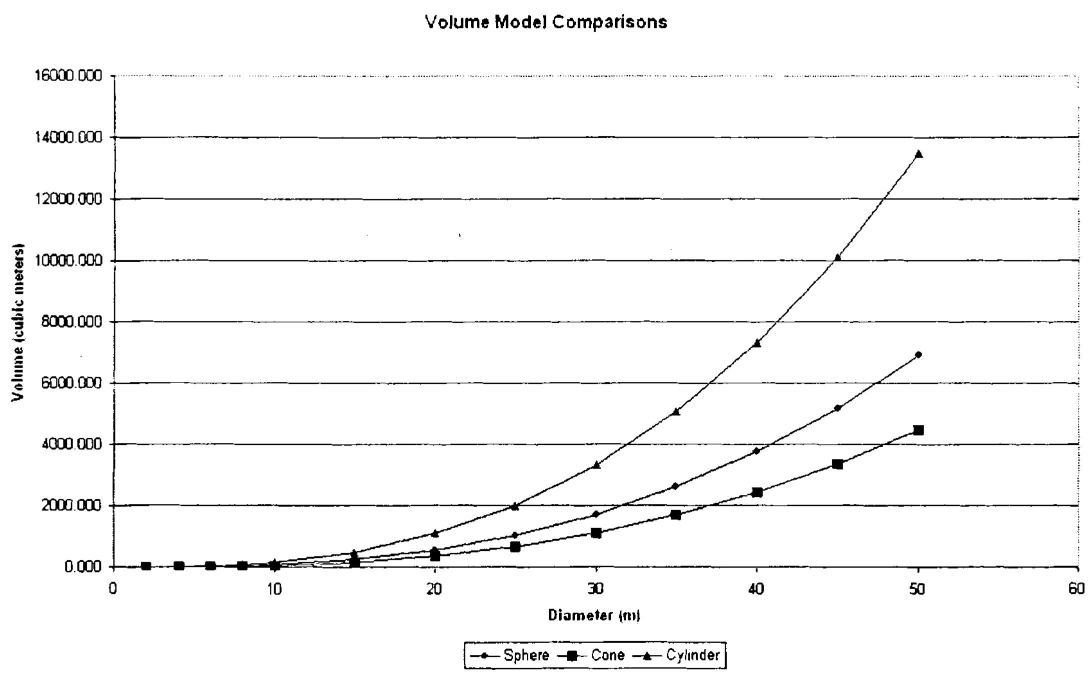

Figure 5.22. Pockmark model volume comparisons. The three models for pockmark volume are presented graphically. The portion of a sphere model (circles) falls between the end members of a cone (squares) and a cylinder (triangle). Large errors could arise from estimating volumes with the portion of a sphere model since the exact three-dimensional morphology is unknown at this time.

The pockmark process does represent a mechanism for redistribution of sediment within system. It could have major implications in areas with contaminated sediments.

5.4. Discussion

The seafloor of the Black Ledges is a complex environment. Muddy sediments with subordinate gravel dominate surficial units. Rock is sparse, occurring in small patchy areas and sand was not observed. The large areas of muddy sediments suggest a low current regime at the seafloor in more than half of the area surveyed.

The muddy areas host large concentrations of pockmarks. Concentrations found here are as great as four times higher than in Belfast Bay. Features are smaller than in Belfast Bay, with a mean diameter of 13.7 m in the Black Ledges compared to 57 m in Belfast. The smaller features allow for the nearly four-fold increase in density. The pockmarks are arranged in seven densely populated fields, unlike one field in Belfast Bay. Outcrops of till, glaciomarine, or bedrock bound each field. A total of 7.7% of the muddy seafloor is covered with pockmarks.

The presence of elliptical pockmarks in Field Alpha is correlated to the local current action. This suggests the pockmark process is no longer active enough to maintain the circular and current activity has enhanced the pockmark into an elliptical form.

The muddy basins show acoustic wipeout in the deepest central portions of the basins and gas-enhanced reflectors are common. The combination of these two observations indicates the presence of gas in bubble form. Direct sampling has identified the gas as methane (H. A. Christian, unpublished report, 2000). The close association of the pockmarks and the underlying gas features suggests the pockmarks are forming from gas escape, as in Belfast Bay. Belfast Bay hosts large areas of acoustic wipeout (Rogers, 1999). The lack of large-scale acoustic wipeout in the Black Ledges suggests less gas is present in the system.

The features in the Black Ledges area are similar in morphology to those in Belfast Bay. The identical slopes of approximation suggest similarity. Rogers (1999) showed considerable varibility over his large data set. The Black Ledges set was smaller and confined to the smallest diameters measured by Rogers. The features in the Black Ledges are also closely spaced and often collalesce. A lowering of the seafloor by several meters in pockmarks fields is observed on seismic reflection profiling and could contribute to the differences.

CHAPTER 6
EVOLUTIONARY MODEL OF SHALLOW-WATER POCKMARKS AND POCKMARK FIELDS

6.1. INTRODUCTION

Although pockmarks have been studied in a variety of locations worldwide, most research concentrates on their existence or processes of formation. Only Hovland and Judd (1988) devote considerable effort to the life cycles and evolution of pockmarks. Their work is primarily on pockmarks formed from thermogenic gases.

The pockmarks observed throughout Penobscot Bay appear in different locations, and have differing morphologies. The conceptual model attempts to link the occurrences and morphologies to the proposed life cycles and the processes, which dominate the environment of occurrence. In addition, it expands upon the previous work of Kelley et al. (2000).

6.2. SOURCE OF THE MODELS

A conceptual model was developed from review of previous work and current research. Data from previous research in Penobscot Bay (Rogers, 1999; Kelley et al., 1994; Knebel and Scanlon, 1985) and elsewhere (Hovland and Judd, 1988) was compared with the results of the current study (Chapters 3, 4 and 5, this work). The differences observed in the pockmarks of Belfast Bay and the Black Ledges required explanations. The most effective way to explain the differences observed in Belfast Bay and Black Ledges is through differing stages of evolution or differing dominant processes (Figure 6.1).

The model is presented as a flowchart. Numerical simulations have not been applied in this study.

6.3. Evolutionary Model

Kelley et al. (2000) proposed a conceptual model for pockmark source fluid in Belfast Bay and did not discuss current and future evolution of pockmarks. Their model was used as the first portion of this conceptual model.

The model begins with the retreat of the most recent glaciation. The retreating kilometer-thick Laurentide Ice Sheet (LIS) caused isostatic changes that greatly affected local relative sea level. During deglatiation, local sea level first rose to about 70 m above present. Isostactic adjustments then lowered sea level to a lowstand about 60 m below present at 10.8 kya (Figure 1.6). This lowstand was followed by continuous sea-level rise of varying rates to the present. Surfaces were exposed for varying lengths of time. During this time, lake and wetland formed in topographic lows. These features remained until sea level rose to drown the surface. The length of time any feature was present before drowning is dependent on the elevation below present sea level and the rate of sea-level rise. Organic sediments from these drowned lakes and wetlands are proposed to be the source of methane for pockmark formation (Kelley et al., 2000). Holocene fine-grained sediments accumulated above the organic sediments as sea level rose. Methane was produced as a result of anoxic decay of organic-rich material. Methane, trapped under fine-grained sediments, accumulates and develops pressurized pockets. Pockmarks developed as gas escaped to reduce the pressure formed in the shallow subsurface (Figure 6.2).

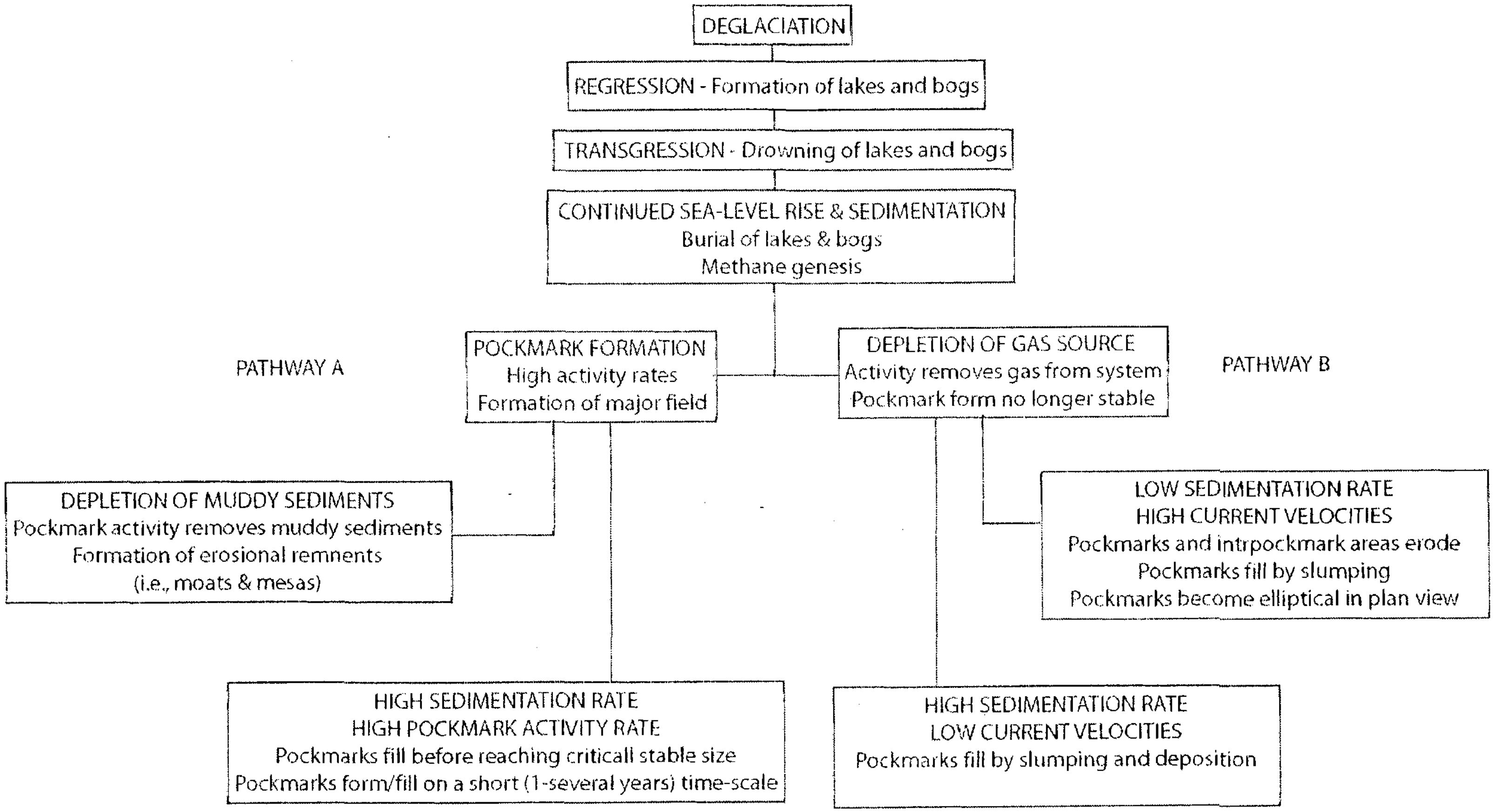

Figure 6.1. Pockmark and pockmark field conceptual model. A flowchart representing the possible pathways for evolution resulting in observed forms of pockmarks in Penobscot Bay. Flow is top-bottom, with italics boxes as potential sub stages. The model is broken down into two major pathways. A) Is the scenarios where gas is not a limiting factor on the evolution of the field. The field is actively producing new pockmarks. B) Is the scenario where gas is a limiting factor. Pockmarks are no longer produced and the form of the pockmark is dictated by sedimentation rates and current activity.

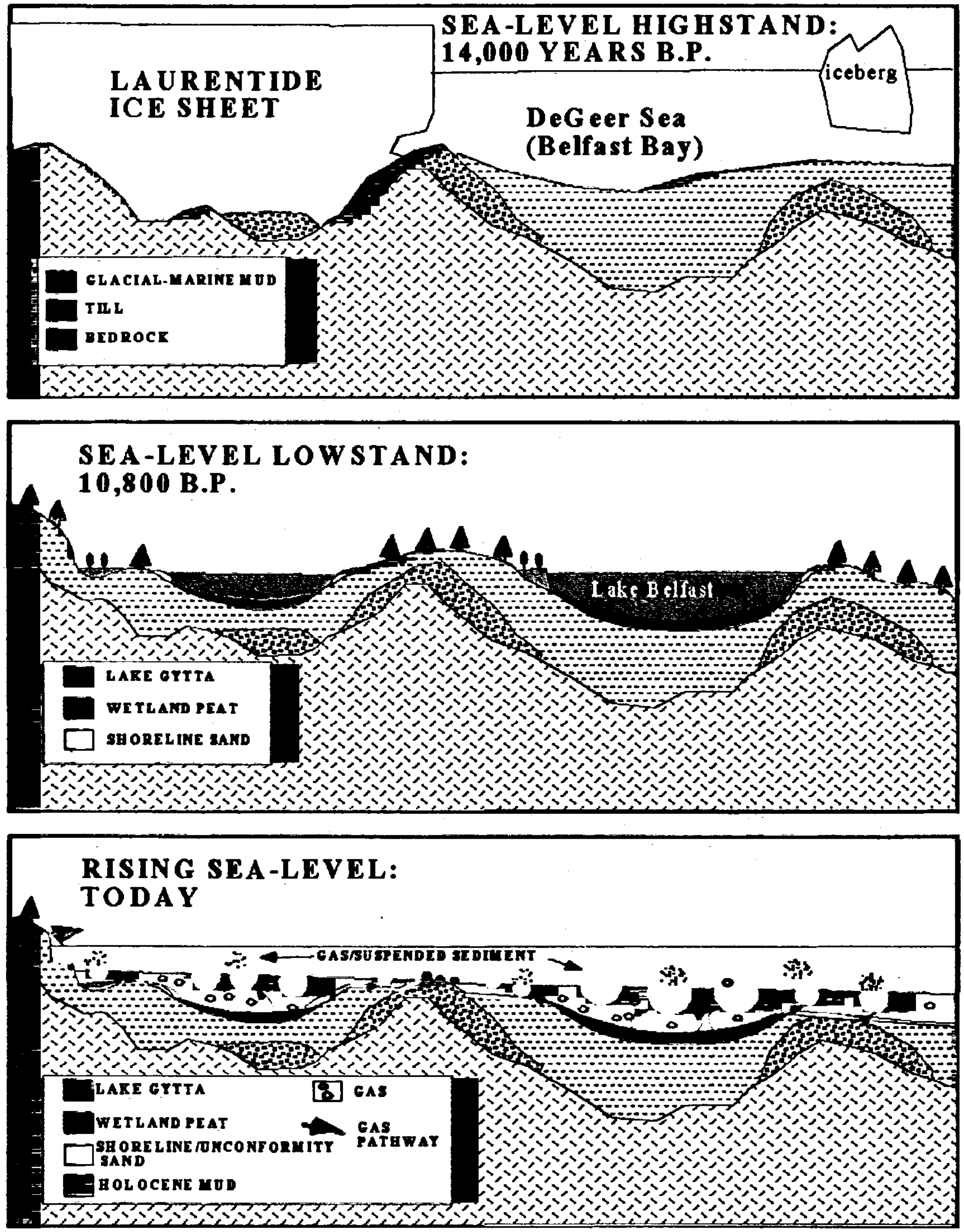

Figure 6.2. Conceptual model for deposition of source material and initial field development in Belfast Bay. Kelley et al. (2000) presented a model for the deposition of methane-generating material in glaciated New England estuaries. This model was the starting point for the conceptual model. After Kelley et al., 2000.

The evolutionary model expands upon the Kelley et al. (2000) model. The evolutionary model picks up where their model stops, the past several thousand years to the present, and into possible future trends.

During the present time, the differences expressed in the pockmarks and pockmark fields are a result of a combination of different stages of evolution and different dominant processes. The first major step in the evolution is the development of a pockmark field. High levels of activity, due to high rates of methane production and pressure increases, begin the excavation of pockmarks and the pockmark process exceeds the sedimentation rates and/or current scour to allow pockmarks to develop. Once the field has begun to develop and matures, several different paths are available, based on local conditions. These are broken down based on the whether or not gas is a limiting factor.

6.3.1. Gas-Nonlimited Scenarios

When gas is not a limiting factor and the field is active, two major pathways exist: 1) high pockmark activity and low sedimentation; or 2) high pockmark activity and high sedimentation. The effect of current velocity is undetermined at this time. Pockmark activity might be frequent enough to mask the current influences by enlarging the pockmark and erasing a current overprint. High current velocities would tend to erode the Holocene sequence, and eventually expose the Holocene-Pleistocene unconformity. Presently, there is no evidence for an eroding Holocene sequence in Belfast Bay. The fields in these stages are very active and the seafloor appears to be in a nearly constant state of change.

Extremely active pockmarks and low sedimentation rates remove muddy sediments. Pockmarks coalesce into moats, leaving pillars or mesas of muddy sediment that are highly gas charged. Southern Belfast Bay is an example of this stage of evolution.

High pockmark activity and high sedimentation rates form pockmarks, but sedimentation fills them in. Pockmarks may be created and filled on a seasonal or longer time scale. Eastern Belfast Bay shows this stage of development. Many small pockmarks and an area of high rates of change characterize it. The seafloor is resurfaced frequently (Chapter 4, this thesis).

6.3.2. Gas-Limited Scenarios

When gas is a limiting factor or the field is senescent, four major pathways exist: 1) high sedimentation rates and low current activity; 2) low sedimentation rates and high current activity; 3) high sedimentation and high current rates; or 4) low sedimentation rates and low current velocities. Few if any new pockmarks are formed. Processes other than gas escape dictate the form of the pockmark.

During times of high sedimentation rates and low current velocities, pockmarks will tend to fill in under a blanket of sediment. What little gas is left in the system is insufficient to maintain the pockmark form. Current velocities are low enough to not modify the circular nature of the pockmark. This scenario has not been observed in Penobscot Bay.

When sedimentation rates are low and current velocities are high, pockmarks will tend to become modified into an elliptical form (Figure 5.13). Currents will erode sidewalls of pockmarks to form ellipses aligned parallel to the dominant current direction. Pockmarks will not fill by sedimentation, but could be modified by slumping of sidewalls to create irregular morphologies. Portions of this scenario have been recognized in an isolated area of the Black Ledges (Chapter 5, this thesis).

If sedimentation rates are high and current velocities are high, pockmarks will be modified by a combination of processes. The pockmarks can become elliptical and fill at the same time. Evidence in Belfast Bay suggests filling occurs (Chapter 3, this thesis). Elliptical pockmarks are found in the Black Ledges (Chapter 5, this thesis), but the sedimentation rates are unknown and the current velocities are low (Xue and Brooks, 2000)

During times of low sedimentation rates and low current velocities, pockmarks will tend to be modified by slumping. The lack of gas emissions will not maintain the circular form. The high-angle side slopes will seek a more stable position and slump, filling the pockmark and creating an irregular morphology. Slumping in pockmarks has not been recognized in Penobscot Bay, but is known to occur in muddy sediments in other Maine embayments (Belknap et al., 1986; Kelley et al., 1989).

An entire field does not have to be in the same stage at a given point in time. Depending on local conditions, as seen in Belfast Bay, a single field may contain zones in different evolutionary stages. The shift between stages may occur, especially between the two stages of high pockmark activity and between the four stages of low pockmark activity. The shift from high activity to low activity should occur only once, and in one direction, unless a new source of gas is tapped. Conversely, the variation could be related to the volume of natural gas present and the Holocene sediment thickness.

6.4. Discussion

Examination of sidescan sonar records collected previously in Penobscot Bay (Rogers, 1999; Kelley et al., 1994) and data collected for this study (Chapters 3, 4 and 5, this thesis) shows differences throughout Penobscot Bay. The differences in pockmark morphology and field characteristics are attributed to several items: 1) the thickness of the Holocene sedimentary sequence; 2) exposure to currents; and 3) water depth.

The Holocene sedimentary thickness appears to control the size of pockmarks by limiting the depth to which excavation can occur (Rogers, 1999). Belfast Bay is home to the largest known pockmarks in Penobscot Bay. They approach 300 m in diameter and 35 m deep. The thickness of the Holocene sediments in this area are 35 m or greater. Across Penobscot Bay at the Black Ledges, pockmarks are generally less than 50 m in diameter and five meters deep. The Holocene thickness here is no greater than five meters. Nearly all of the pockmarks in this area are eyed, signifying that they penetrate the entire Holocene sequence and are floored by Pleistocene sediments (Figure 5.4) (Chapter 5, this thesis).

North and west of Green Ledge, in the Black Ledges area, pockmarks are elliptical. Just to the south of this area, pockmarks are circular. The pockmarks appear to be modified by current actions in the main channel of East Penobscot Bay. Stronger currents in deeper water have modified the circular form to an ellipse with a major axis of roughly 045° T.

Nearly all stages of the model are observed in Penobscot Bay. There is some confusion about the existence of the stages of gas depletion. The differences observed could be attributed to several of the four stages of gas depletion.

The Belfast Bay field exhibits both of the high pockmark activity stages. The southern portion of Belfast Bay and upper portion of West Penobscot Bay are in the high pockmark activity, low sedimentation stage. Sidescan sonar images show mesas of mud and moats. Relief in the area exceeds 30 m vertically. Several areas are scoured clean of mud, down to the Holocene-Pleistocene unconformity. Seismic reflection profiling data indicate that large quantities of gas remain in the subsurface. The results from Chapter 3 of this work show this area of the field is still generating new pockmarks.

The eastern portion of Belfast Bay is in the high pockmark activity, high sedimentation stage. The results from Chapters 3 and 4 of this work show large numbers of filled and new pockmarks created over a nine-year period as well as a shorter two-year period. Changes to the population of the pockmark field are not the only seafloor feature indicating high sedimentation rates. The results of Chapter 4 of this work show that none of the drag marks or other seafloor features visible are apparent two years later, indicating a complete resurfacing of the seafloor over the period. Erosion of the seafloor could also explain the changes over the two-year period, but the lack of modification to the pockmarks suggests against it.

The remainder of Belfast Bay is somewhere in between the two end members of the high pockmark activity scale. It is apparent that the high activity stages are a continuum and the high sedimentation and low sedimentation phases are extreme end members.

The depleted gas stages of the evolutionary model are found in the Black Ledges pockmark fields. It is, at times, difficult to determine which processes dominate the evolutionary trend of the pockmarks.

The northern section of field Alpha is in the low sedimentation, high-current-velocity stage. The pockmarks within the cluster are elliptical, aligned with a good approximation of the current direction in the area. No current meter data are available to verify the current direction at this time.

The rest of the Black Ledges pockmark fields is somewhere within the other three stages. Once again, these are discrete end members on a continuum that might not be resolvable with the current data.

This model is a good starting place. It puts the processes affecting the pockmark fields into perspective and provides a framework. The framework will assist in planning future research on present day pockmark processes in Penobscot Bay, as well as other nearshore and estuarine occurrences of pockmarks.

CHAPTER 7
ITEMIZED CONCLUSIONS

1. **The Belfast Bay pockmark field is active.** Results from Chapter 3 (this work) conclusively show recent activity in the field. Nearly 36% of the 1999 population changed in a 10-year period. These changes consisted of 287 pockmarks filled and 337 pockmarks created. Evidence for activity of shorter time scales (< 2 years) exists (Chapter 4, this thesis). Four pockmarks were filled and nearly the entire area of study was resurfaced over a two-year period.

2. **Anthropogenic activities can trigger pockmark formation.** Results from Chapter 4 (this thesis) link pockmarks to drag marks on the seafloor. Tadpole and beaded pockmark forms are a direct result of disturbances of the seafloor by drag fishing and anchoring. These interactions can only be seen through high-resolution, investigations. As the pockmarks progress in development, the influences from anthropogenic activities are not evident. The redistribution of sediments from the pockmark process obscures the linkage.

3. **Belfast Bay is not the only location within Penobscot Bay to host large concentrations of pockmarks.** Results from Chapter 5 (this thesis) show large concentrations of pockmarks in the Black Ledges area. Initial investigations suggest these pockmarks are formed in the same method as those in Belfast Bay, by gas escape. This is the fifth area studied along the Maine coast that hosts large concentrations of pockmarks. Other locations include: Passamaquoddy Bay (Fader, 1991), Blue Hill Bay,

Somes Sound (Kelley et al. 1995), and Belfast Bay (Knebel and Scanlon, 1985; Kelley et al., 1994; Rogers 1999). Pockmarks appear to be the rule in glaciated, muddy estuaries along the Maine coast.

4. **The pockmark process is effective at redisrubting sediments within estuaries.** As a pockmark forms, muddy sediments are placed into suspension. Evidence exists that shows a total of about 5×10^6 m^3 of muddy sediments and pore water have been redistributed in Belfast Bay (Chapter 3, this thesis). This material has been moved within a 10-year period. In addition to this sediment in Belfast Bay, the pockmarks in the Black Ledges represent the removal of 2×10^6 m^3 of muddy sediment and pore water (Chapter 5, this thesis) over the course of the field's development. Whether this sediment remains in the pockmarked basin and fills pockmarks, adds to the total thickness as a blanket through deposition, or the sediment remains entrained within the water column and is carried out of the pockmarked basin is currently unknown.

5. **Pockmarks and pockmark fields appear to follow an evolutionary progression based on current environmental conditions.** The conceptual model presented in Chapter 6 (this thesis) suggests pockmarks and fields follow an evolutionary progression. The state of progression is based on the local conditions, including: currents, sedimentation rates, and available methane. This model can be applied to pockmark fields to suggest what conditions are governing the evolution of the pockmarks and the rates of activity.

CHAPTER 8
SUGGESTIONS FOR FUTURE WORK

The work presented in this thesis continues research conducted by others at the University of Maine and Maine Geological Survey (Kelley et al., 1994; Rogers 1999). There are many questions about pockmarks that still remain unanswered. Future work should focus in three areas: 1) identifying the source of methane, 2) the process by which pockmarks form and evolve, and 3) comparing the features found in Penobscot Bay with those in other areas such as Passamaquoddy and Blue Hill bays.

The source of methane has yet to be identified in Penobscot Bay. Kelley et al. (2000) suggest organic-rich sediments from paleo-wetlands and lakes as a potential source. Alternatives include organic detritus disseminated throughout the Holocene sediment and migration of methane from deeper sources. The stratigraphic position of the source material has implications to field evolution and potential for continued and future development.

Several theories have been presented for pockmark formation in Penobscot Bay. The exact mechanisms are still being debated. A detailed study involving time-series investigations, remote sensing, seafloor instrumentation, and computer simulations is needed to determine the mechanisms.

Penobscot Bay is host to at least eight pockmark fields. Studies conducted in other bays along the Gulf of Maine coast have revealed other estuarine pockmark fields. A comparative study involving geophysical data collection and direct sampling of sediments and pore fluids should be undertaken to determine if these fields are similar and controlled by the same processes.

The suggested future investigations would lead to a greater understanding of estuarine pockmarks. Once an understanding of the processes involved is gained, applications and impacts on the environment can be investigated. These include, but are not limited to biologic productivity and climate change through release of greenhouse gases.

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BIOGRAPHY OF THE AUTHOR

Allen Gontz was born in Lebanon, Pennsylvania on 17 September 1970. He was raised in Palmyra, Pennsylvania and graduated from Palmyra Area Senior High School in 1989. After graduation, he attended Virginia Tech for two and a half years as a civil engineering major. He left without graduating to complete four years with the United States Army in the Army Corps of Engineers. He served in Operations Restore Hope and Restore Comfort, Somalia, Africa in 1993 and 1994. He has also served with the 82nd Airborne Division as a paratrooper. After completing his tour of duty, he returned to Pennsylvania to attend Lock Haven University of Pennsylvania. He graduated in 1999 with a Bachelor's of Science in Environmental Biology with a concentration on Ecology and a Bachelor's of Science in Applied Geology. In the fall of 1999 he entered Geological Sciences graduate program at the University of Maine.

After completing his degree, Allen will be continuing his education at the University of Maine. He will be pursuing a Doctorate Degree in Geological Sciences. Allen is a candidate for the Master of Science degree in Geological Sciences from The University of Maine in May, 2002.