

**A Microfossil Evaluation of Sediment Deposits on the Continental Shelf,
Merrimack Embayment, New England**

by

Stephen A. Nathan, R. Mark Leckie, and Stephen B. Mabee

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Cibicides lobatulus (Walker and Jacob) 1798 (x48)

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Stephen A. Nathan¹, R. Mark Leckie², and Stephen B. Mabee¹

¹Office of the Massachusetts State Geologist, 611 N. Pleasant St., University of Massachusetts, Amherst, MA 01003. ²Department of Geosciences, 611 N. Pleasant St., University of Massachusetts, Amherst, MA 01003

ABSTRACT

During the late Pleistocene the Merrimack River paleodelta formed as post-glacial rebound produced a local low stand in sea level. Drowned as sea level rose, the paleodelta is now being reworked by a variety of processes. This study uses benthic foraminifera as a biotic and environmental proxy to study the sand and gravel resources of the paleodelta.

Nineteen sediment samples were collected from the paleodelta along two east-west transects east of the Merrimack River. From these samples nearly 6000 benthic foraminifera, representing 62 species, were collected and identified. Although dissolution compromised the preservation of calcite tests within six samples, the resulting data is robust and allows for numerous conclusions to be drawn. Specifically, benthic foraminifera become more common distally and specific species inhabit specific areas of the paleodelta. Distribution patterns of some species have changed significantly since the late 1940s, with some species migrating landward, others, seaward. Distributions of some taxa differ significantly between the two transects, both in the present day and from the past. These differences point to the influence of, and changes in, the Merrimack River outflow upon water column nutrient delivery, productivity and food availability over the past 60 years.

Species diversity and evenness peak at the delta break, coincident with low species dominance at 50 meters water depth. Q-mode cluster analyses show three distinct assemblages, “shallow” (≤ 30 meters water depth), “deep” (≥ 40 meters), and “delta edge” (50 meters). There is no apparent correlation between foraminiferal distributions and deltaic bedforms, and in turn, sediment type. This implies that foraminiferal distributions are controlled by other environmental variables such as food.

In summary, benthic foraminiferal assemblage analyses complement geophysical techniques. Benthic foraminifera can also help assess the marine impact of, e.g., mining sediment resources, watershed development, pollution, rising sea level, and increased fishing.

INTRODUCTION

Objective

Microfossils collected from the Merrimack River delta have been studied to characterize offshore sand and gravel resources for use as construction aggregate and beach replenishment (Figure 1). Boston University characterized these marine resources using geophysical and sedimentological analyses. This paper presents and interprets the collected biotic data in light of the geophysical and sedimentological data. It demonstrates how micropaleontological analyses can complement geophysical analyses and provide information where geophysical techniques cannot. Most importantly, this paper illustrates the utility of studying benthic foraminifera as a proxy for substrate conditions pre- and post-sediment disruption (i.e., from offshore mining of sand and gravel resources). Thus, benthic foraminifera can be used to gauge biotic recovery by analyzing recolonization trends and rates.

Project tools

This study uses benthic foraminifera (testate protists) as a biotic and environmental proxy to study the sand and gravel resources of the Merrimack Embayment. Foraminifera are sand-sized, single-celled protists; they are neither animals nor plants. They occur abundantly in most marine and marginal marine environments and have long been used by geologists for purposes of biostratigraphy (age determination, correlation) and paleoenvironmental analyses (depositional environment reconstruction, paleoceanography). There are two general types of foraminifera that produce a test (a.k.a., a shell): 1) floating (planktic); and 2) bottom dwelling (benthic; Goldstein, 1999). Planktic species are more abundant in outer continental shelf and deep-sea environments and are rarely observed near the coast. Their tests are constructed of precipitated calcium carbonate (calcite). Benthic species are most abundant along marginal marine and continental shelf environments, although they are also found in the deep ocean. The tests of benthic species are composed of precipitated calcium carbonate (calcareous species) or agglutinated particles (arenaceous species). This study focuses upon benthic foraminifera.

Because benthic foraminifera do not migrate, their distributions on the continental shelf are influenced by water temperature, depth, salinity, dissolved oxygen, sea floor composition, food availability, and seasonality. In general, benthic foraminifera are either epifaunal, i.e., living on the seafloor at the sediment/water interface, or they are infaunal, i.e., living within the

seafloor sediments at depths of 1-15 cm. Their distributions trend parallel to the coast with increasing water depth and distance from the shore (e.g., Murray, 1991; Sen Gupta, 1999; Leckie and Olsen, 2003). Foraminiferal abundances can also vary seasonally (e.g., Korsun and Hald, 2000; Scott et al., 2003). Thus, the data presented in this study represents one day in the seasonal progression of changing foraminiferal assemblages in the Merrimack Embayment.

In this study benthic foraminiferal distributions and abundances are coupled with geophysical and sedimentary analyses to: 1) develop a model of foraminiferal distribution patterns to assess depositional environments and establish a modern base-line; 2) ground-truth geophysical techniques such as side-scan sonar; and 3) test the applicability of using foraminifera as a biotic monitor of sea floor pollution and as a proxy of post-disturbance ecosystem recovery from sand mining operations (e.g., Scott and Lipps, 1995; Yanko et al., 1999).

A similar study by Phleger (1952) and Parker (1952) will be used to compare the foraminiferal distribution patterns observed by this study. The much larger study by Phleger (1952) and Parker (1952) spanned the western Gulf of Maine, from Cape Ann to Portsmouth, NH and seaward from the coastline to Jeffreys Ledge. They examined foraminiferal abundances and distributions using hundreds of seafloor sediment samples collected mostly during the summer of 1946.

Geographic location, form and history

A prominent submarine feature of the Merrimack Embayment is the “paleodelta” of the Merrimack River (i.e., hereafter referred to as the delta). The delta is approximately 8 km east of the modern Merrimack River outlet, with the delta edge currently at a water depth of approximately 50 m (Oldale et al., 1983). The delta is approximately 20 km long from north to south and 7 km wide from east to west (Oldale et al., 1983; Figure 2).

Hein et al. (2007) have shown that reworking of the Merrimack River delta and braided river plain has produced four distinct sedimentary zones along the inner shelf (from 10 to 50 meters water depth). The first zone is centered east of the river. It is a large, featureless sand sheet comprised of coarse-grained sands that are discontinuously overlain with finer sands (Hein et al., 2007; Figures 3 and 4). The second zone is comprised of asymmetrical bedforms orientated north-northwest (the direction of dip). They are located near the delta break, have

average wavelengths of 500 meters, and average amplitudes of 1.9 meters (Hein et al., 2007). The third zone is located to the south and inshore. It has westward-orientated asymmetrical bedforms, with average wavelengths of 250 meters and amplitudes of 1 meter. The last zone is farther south, approximately 4 kilometers north of Cape Ann. Bedforms in this fourth zone are orientated north and have average wavelengths of 500 meters with average amplitudes of 1 meter (Hein et al., 2007).

As the last glacial period waned the Earth's crust along the coastline of northern New England was depressed after having borne the enormous load of the icesheet. Deglaciation and global sea level rise resulted in flooding (transgression) and deposition of glaciomarine sediments in these coastal areas (e.g., Bloom, 1963; Oldale et al., 1983; Kelley et al., 1993). Subsequent rebound of the crust allowed the coastline to advance seaward (regression). Rivers such as the Merrimack began to downcut the glaciomarine sediments and build the Merrimack River delta eastward. This relative lowstand in sea level occurred approximately 12,000 years before present and is estimated at -45 meters relative to modern sea level (Oldale et al., 1983). By 5,000 years before present, sea level rise had drowned the delta, but slowed enough to permit the establishment of barrier beaches such as Plum Island (Kelley et al., 1993). Radiocarbon studies of the delta suggest that it is the source of beach sands at river mouths and that offshore there is little modern sediment (Kelley et al., 1993).

Oceanographic conditions

Within the Massachusetts Embayment sea surface temperatures change seasonally. Seasonal sea surface temperatures range from a low of approximately 4°C in February to a high of 17-18°C in August (Pathfinder, 2005). In February and March the water column is isothermal but it becomes strongly stratified by August. At this time the thermocline is at 40-50 meters water depth and bottom temperatures have warmed to approximately 5.5°C (Phleger, 1952; Parker, 1952; Pathfinder, 2005).

Seasonal changes in salinity are generally uniform across the study area (Phleger, 1952; Parker, 1952; GoMOOS, 2007). The Gulf of Maine Ocean Observing System (GoMOOS, 2007) Buoy B (Station 44030, Buoy B0102), western Maine shelf, is located 50 kilometers north of the Merrimack River. The buoy records bottom waters as consistently saltier than the upper water column (GoMOOS, 2007). In winter the water column is isohaline and at its saltiest,

approximately 31.75-32.5 ‰. From early spring to early summer surface water salinity drops to 29 ‰, increasing to about 30.5-31 ‰ by October, with the water column becoming isohaline again by early December (GoMOOS, 2007). Bottom water salinity changes from 31.5 ‰ in mid summer to 32.5 ‰ during the winter (GoMOOS, 2007).

Chlorophyll a (ChlorA) is the pigment used by photosynthetic organisms to capture the energy of sunlight for growth. Because photosynthetic organisms are at the base of the food chain, all higher organisms are dependent on them. Thus ChlorA concentrations in the water column are a strong indicator of biological productivity within the study area (e.g., how abundant or scarce fish are in the water column). Unlike temperature and salinity, ChlorA varies greatly, both seasonally and spatially across the study area (SeaWifs, 2005). Seasonal ChlorA values in the study area are at a low in February and August; approximately 2-3 mg/m³ near shore and about 1 mg/m³ to the eastern limit of the study area. Peak ChlorA concentrations occur in April (about 10 mg/m³), reach a low by August and then increase to an intermediate high in October.

The effects of long shore transport upon the barrier islands of the Merrimack Embayment, particularly Plum Island, demonstrate that near shore currents and wave action produce a coastal flow that is primarily to the south and southeast. The deeper water, Northern Shelf (coastal) Current, flowing south, may produce a counter-clockwise gyre within the Gulf of Maine (Buzas and Culver, 1980). Bottom currents in the Merrimack Embayment are more uncertain. The GoMOOS Buoy B (western Maine shelf) has recorded bottom currents of 20-30 cm/sec in 60 meters of water during spring tide conditions and greater speeds during storm conditions (Hein et al., 2007). Bottom currents and their speed across the Merrimack River delta sand sheet are unknown (Hein et al., 2007).

Sample Recovery

On September 6, 2005, seafloor sediment samples were collected from the Merrimack Embayment, north of Cape Ann, aboard the University of New Hampshire research vessel *Gulf Challenger* (Figures 1 and 2). Cloudless, sunny skies, with temperatures near 24 °C prevailed, while the sea was calm and intensely green in color (indicating high biological productivity). Seafloor sediment samples from a total of 19 sites were recovered along two parallel east-west transects across the inner shelf and the Merrimack River delta. Sampling every 10 meters of water depth out to 103 meters, the northern transect yielded nine samples while the southern

transect yielded ten samples. The northern transect was located east of the Merrimack River outlet, while the southern transect was located 5 km south, offshore from Plum Island. The two transects sampled the Merrimack River delta surface, delta break, and the delta front (analogous to topset, foreset, and bottomset deposits, respectively, in a geologic context), which ranged from coarse sand and gravel to mud. The collected samples were processed and analyzed for their microfaunal characteristics by the Office of the Massachusetts State Geologist and the Department of Geosciences, University of Massachusetts Amherst. Geophysical and sedimentological analyses were completed by Boston University (see Methods).

The data obtained in this study is compared to the data collected by Phleger (1952) and Parker (1952). To facilitate this historical comparison of foraminiferal distributions, 15 sites of the hundreds studied by Phleger (1952) and Parker (1952) in the Gulf of Maine are regarded as “comparable” to the 19 sites examined in this study because of their close geographic proximity to one another (Figure 5). However, the locations of these 15 sites are not an exact match to 19 sites of this study; some have offsets ranging from tens of meters up to 2 km. The concept of “comparable” also tries to minimize differences in water depth and sediment type that exist between the “comparable” sites of Phleger (1952) and Parker (1952) and those in this study. Yet, the differences in location, water depth, sediment type and other factors need to be kept in mind when making comparisons between the two studies.

METHODS

Nineteen sediment samples from the Merrimack River delta were recovered using either a Shipek corer or a small box core device, depending on the nature of the sediments. Both devices collected relatively undisturbed samples. Portions of each sample were set aside for grain size analyses (by Boston University) and for microfaunal analyses (by the University of Massachusetts). The portion set aside for microfaunal analysis was separated into two sub-samples. One sub-sample was collected from 0 to 2 cm depth while the second sub-sample was collected from 2 to 5 cm depth. These sub-samples ranged in volume from approximately 100 cm³ to 200 cm³, and were placed in 250 cm³ Nalgene bottles. To preserve the foraminifera within each sample, a 4 % formalin solution was added to all bottles and shaken (a 1:9 mixture of 38 % formaldehyde and water, respectively). Approximately one tablespoon of Borax was added to each sample and the bottles were shaken again to make an alkaline solution. The samples were stored in a freezer until processed at a later date.

In their study, Phleger (1952) and Parker (1952) differentiated between living and dead foraminifera. They found a “good correlation” between the geographic distributions of live foraminiferal tests of each species and all tests of that species (for sediments containing mud). In light of these results we did not use preservation techniques or processing procedures that differentiated between living and dead foraminifera.

All samples were processed by first thawing, measuring the sample pH, and then soaking in a 10 % solution of H₂O₂ for several days (with the pH adjusted to at least 8 by adding Borax). It should be noted that six samples had acidic pH levels after thawing. These samples were immediately adjusted to a pH of at least eight by the addition of Borax prior to soaking (Table 1). The sediment mixture was then washed over a 63 micron screen, and the residues were dried in an oven at 60°C. The residuals were then passed through a 2000 micron (2 mm) sieve. These sand sized residues (63 to 2000 microns) were later examined for the species present (simple diversity or species richness), relative abundance, and preservation.

The residuals of each processed sample were repeatedly split with a microsplitter until a volume of sediment was obtained that, when spread evenly onto a picking tray, produced a single layer of particles. All foraminiferal tests on the tray (both benthic and planktic) were then removed and affixed to a gummed microscope slide for later sorting, identification, and counting. Other biogenic particles on the tray (e.g., macro and microfossils) as well as inorganic particles

(mineral grains, etc.) were removed to the gummed slide in representative numbers. Because the foraminifera in any one tray were typically scarce, the above process was repeated until at least 300 foraminiferal tests were collected onto the gummed slide. Broken tests that comprised more than half of the organism were counted as a whole test. In some cases a large fraction of the sample or its entire volume was examined. In one sample, T2-20, foraminifera were so rare and sand grains were so voluminous that several days of examining the sample yielded only 75 tests.

The species observed in the Merrimack Embayment and their relative abundances in each sample are recorded in Table 1. The distributions of the key species observed in this study are briefly discussed in the Results section. How each species was recognized is discussed in the Taxonomic Notes at the close of this paper.

Statistical analyses of species abundances were made by using the software program, PAST (PAAlaeontological STatistics, ver. 1.72; 2007). The results of multivariate techniques such as Q-mode cluster analysis are described in the Discussion section.

RESULTS

Test preservation was found to be very good to excellent in all samples. Some calcite tests were glassy in appearance and/or green in color due to the recent sequestering of chloroplasts from photosynthetic organisms. Tests of agglutinated and calcite species were typically complete; it was uncommon to observe broken tests or to find tests that appeared to be reworked. Reworked refers to tests that appear to be very old (i.e., having a worn/degraded appearance and perhaps dating from the last glacial period) and/or being transported from a different locality.

It was observed that benthic foraminifera became more abundant relative to other sand-size particles with increasing water depth. This is based on the number of fossils per gram of sample residuals that were greater than 63 microns but less than 2000 microns (2 mm) in size.

The abundances and distributions of the 62 species identified in this study are presented in Table 1. The abundances and distributions of 27 of these 62 species are described below because: 1) they illustrate the key points addressed in the discussion section; and 2) they account for more than 91 % of all tests collected from all samples. The 27 species are described in alphabetical order and only benthic taxa are considered since planktic species were observed in trace numbers.

Adercotryma glomeratum (H.B. Brady)

A. glomeratum is observed from intermediate to deep water depths (>30 m) along both transects and it is the second most numerous species observed in this study. Along both transects, counts of *A. glomeratum* increase with water depth, reach a peak at approximately 92.5 meters, and then diminish slightly at the deepest site.

Ammodiscus catinus Höglund

Ammodiscus catinus is found in nearly all water depths except the shallowest sites (T1-1, T2-20, approximately 10 meters) and at roughly 71 meters. It is much more abundant along Transect 1 and has peak abundances at 30 meters water depth.

Buccella frigida (H. B. Brady)

Along Transect 1 *Buccella frigida* occurs in samples collected from 9.8 meters to 71.5 meters water depth, with a peak abundance at 50.6 meters (10.3 % of the assemblage in sample T1-5). *B. frigida* also occurs at Site T1-10, the deepest site. *B. frigida* is much less abundant along Transect 2, extending only to 50.6 meters (Site T2-15).

Buliminella elegantissima (d'Orbigny)

Occurrences of *Buliminella elegantissima* are rarely more than a single test in any one sample. Yet, it occurs at enough sites to imply a preferred distribution of shallow to intermediate water depths (<60 m).

Cibicides lobatulus (Walker and Jacob)

Abundances of epifaunal *Cibicides lobatulus* peak at the shallowest sites along each transect (T1-1, T2-20, approximately 10 meters) and then rapidly decline with depth. *C. lobatulus* is much more common along Transect 1 than Transect 2.

Cribrostomoides crassimargo (Norman)

Cribrostomoides crassimargo is not observed in waters shallower than 30 meters. It is more abundant along Transect 1, having peak abundance of 3.2 % at 59 meters water depth.

Discorbis squamata Phleger and Parker

Discorbis squamata is observed in only one sample along Transect 1 (29.6 meters, 5 % abundance). Along Transect 2 it occurs at 16.3 and 19.8 meters water depth, with a peak abundance of 6 % at 19.8 meters.

Eggerella advena (Cushman)

Eggerella advena is found at nearly all depths and sites, making it the most numerous species observed in this study. *E. advena* comprises 5 % to 20 % of the assemblage in most samples. It reaches highest abundances at 29.6 meters water depth (48.1 %) along Transect 1 and at 71.9 meters water depth along Transect 2 (25.3 %). The species exhibits trace abundances (i.e., <1 %) below 90 meters water depth.

Elphidium incertum (Williamson) var. *clavatum* Cushman

In this study *Elphidium incertum* var. *clavatum* is the fifth most abundant species. With the exception of sample T1-8 (82.4 meters) *E. clavatum* is absent from all samples that were acidic after thawing. This epifaunal species has greater abundances and a wider range of occurrences along Transect 1 than Transect 2. It is most abundant along Transect 1 in waters less than 20 meters. *Elphidium clavatum* was also found to be very common at the deepest site (site T1-10, 103 meters, >17 % abundance).

Elphidium subarcticum Cushman

Elphidium subarcticum is an epifaunal species that is very common in waters shallower than 30 meters, making it the third most numerous species observed in this study. *Elphidium subarcticum* and *E. clavatum* account for approximately 15 % of all tests observed in this study. Other species of this genus occur in only trace numbers. *Elphidium subarcticum* is somewhat more abundant along Transect 2 than along Transect 1. For both transects *E. subarcticum* is absent, or essentially so, below 59 meters water depth.

Epistominella vitrea Parker 1953

Epistominella vitrea is a species with a calcite test and it is observed in all samples that had alkaline pH values. It is more abundant in waters that are less than 30 meters deep and slightly more abundant along Transect 2 than Transect 1.

Fursenkoina fusiformis (Williamson)

Fursenkoina fusiformis is relatively rare along both transects and it is found in water depths ranging from 20 meters to 59 meters.

Globobulimina auriculata (Bailey)

Globobulimina auriculata is most abundant at the deepest site (T1-10, 103 meters) and is rarely observed along Transect 1. It is absent from Transect 2.

Globocassidulina algida (Cushman) and *Globocassidulina islandica* (Nørvang)

Both species are absent from samples that were acidic after thawing. The two species are seen in waters that are less than 59 meters deep and are more abundant along Transect 1. Along Transect 1 *Globocassidulina islandica* abundance peaks at its deepest occurrence (5 %, 59 meters, Site T1-6). *Globocassidulina algida* has its peak abundance at Site T1-5 (5 %, 50.6 meters). Both species are very rare along Transect 2 (with counts ranging from a single test to 1.3 %). No tests are observed below 50.6 meters.

Glomospira gordialis (Jones and Parker)

Glomospira gordialis is rare. It is more common along Transect 1 than Transect 2, although Transect 1 abundances never exceed 4 %. The species is absent from the shallowest and deepest sites.

Hippocrepina indivisa Parker

Hippocrepina indivisa is found only in water exceeding 50 meters depth. Peak abundances (9 to 10 %) occur at depths of approximately 72 meters to 82 meters in both transects.

Nonionellina labradorica (Dawson)

Nonionellina labradorica is absent along Transect 2. Along Transect 1 it has a 1 % abundance at 59.0 meters and 9 % at 103.0 meters. It is absent across the delta surface and in the acidic samples.

Quinqueloculina spp.

Quinqueloculina spp. is observed in shallow to intermediate water depths, but more commonly along Transect 2. For both transects abundances peak at approximately 30 meters while it is absent below 51 meters.

Reophax arcticus H.B. Brady

The species is very rare along Transect 1. Along Transect 2 it is limited to intermediate water depths, exhibiting peak abundance at 71.9 meters.

Reophax curtus Cushman

R. curtus is found in waters greater than 30 meters depth. It is much more prevalent along Transect 2 than Transect 1, with abundances that peak around 65 meters and decreasing with increasing depth (i.e., 0.5 % at 103 meters).

Reophax scottii Chaster

Reophax scottii was observed only along Transect 2, in water depths ranging from 10.0 meters to 71.9 meters. It is least abundant in the shallows, reaching a maximum at 50.6 meters (Site T2-15), and decreasing in deeper water.

Saccammina atlantica (Cushman)

Saccammina atlantica is much more abundant along Transect 2. Along Transect 1 *S. atlantica* is scattered in occurrence and appears only at trace levels (<1 %). For Transect 2 *S. atlantica* first appears below 20 meters water depth, reaches peak abundance around 42 meters depth (>30 %), and then declines to ~1 % abundance at 103 meters.

Saccammina difflugiformis (H. B. Brady)

Saccammina difflugiformis is rarely observed along Transect 1. It reaches a broad peak in intermediate water depths along Transect 2.

Spiroplectammina biformis (Parker and Jones)

Spiroplectammina biformis is common in intermediate to deep waters along both transects. Abundances of *S. biformis* increase with depth, peaking at approximately 70-80 meters before decreasing slightly in deeper waters.

Spiroplectammina typica Lacroix

Spiroplectammina typica first appears in waters of intermediate depth, reaching peak abundance at approximately 60 meters. Abundances of *S. typica* then decrease steadily with increasing water depth.

Textularia torquata Phleger and Parker

Textularia torquata is the fourth most common species observed in this study. It is found in intermediate and deep waters along both transects with abundances peaking around 72-82 meters water depth.

Trochammina lobata Cushman

Trochammina lobata is observed along both transects, near the delta break. The species was slightly more abundant along Transect 1, reaching a maximum abundance of 5 % at 59 meters water depth.

Trochammina squamata Parker and Jones

Trochammina squamata is observed only along Transect 2. It has a peak abundance at 20 meters water depth.

The distribution and relative abundances of 14 of benthic foraminiferal species are presented as biofacies maps (Figures 8 through 21). These 14 species were selected to coincide with biofacies maps produced by Phleger (1952) and Parker (1952). The 14 mapped species are:

Adercotryma glomeratum

Cibicides lobatulus

Cribrostomoides crassimargo

Elphidium incertum var. clavatum

Elphidium subarcticum

Eggerella advena

Globocassidulina algida

Nonionellina labradorica

Reophax curtus

Reophax scottii

Saccamina atlantica

Spiroplectammina biformis

Textularia torquata

Trochammina squamata

DISCUSSION

Sample Preservation and Dissolution

Benthic foraminiferal tests that are composed of calcium carbonate (calcite) are susceptible to dissolution when exposed to acidic conditions. It is very likely that several samples in this study were affected by dissolution. When first collected, each sample had a preservative added to it so that its pH was alkaline before freezing. After thawing it was discovered that six samples were acidic, i.e., two samples below 82 meters water depth along Transect 1 (T1-8 and T1-9) and four samples below 62 meters water depth along Transect 2 (T2-11, T2-12, T2-13, and T2-14). These samples tended to be muddier and more organic rich than shallower samples. It is likely that the decay of organic compounds in these samples produced acids that overwhelmed the buffering capacity of the preservative. The acidic conditions in these samples affected delicate and/or smaller calcite species; more so than larger and/or robust calcite species. The deepest sample (Transect 1, T1-10, 103 meters water depth) was alkaline after thawing and not affected by dissolution. Agglutinated species were unaffected by dissolution.

The following calcareous species are missing in acidic samples but are present in alkaline samples (Figure 6); thus their absence is likely due to dissolution:

Buliminella complanata;

Buccella frigida;

Elphidium incertum var. *clavatum*;

Elphidium subarcticum;

Epistominella vitrea;

Globobulimina auriculata;

Globocassidulina algida;

Nonionella auricula; and

Nonionellina labradorica.

The net affect of dissolution is that it alters the relative abundance of one species to another. The result is an increased percent abundance for the arenaceous species (i.e., agglutinated species) and the larger and/or more robust calcite species (if the dissolution is not complete) relative to more delicate calcite species. This is illustrated in Table 2 where the ten most common benthic foraminiferal species identified in this study are listed in column two. If the samples that were acidic after thawing were removed from the data, then the top ten most common species would be those listed in column three of Table 2.

Rank	Phleger (1952) & Parker (1952): 10 Most Common Species ¹ (9079 tests)	% of tests ¹	This Study: 10 Most Common Species (All samples; 5749 tests)	% of tests	This Study: 10 Most Common Species (Samples having >7 pH; 3912 tests)	% of tests
1	<i>Eggerella advena</i>	39	<i>Eggerella advena</i>	14	<i>Eggerella advena</i>	15.5
2	<i>Elphidium subarcticum</i> ²	7.2	<i>Adercotryma glomeratum</i> ³	13	<i>Elphidium subarcticum</i> ²	12.9
3	<i>Saccammina atlantica</i>	6.8	<i>Elphidium subarcticum</i> ²	9	<i>Elphidium incertum</i> var. <i>clavatum</i>	8.5
4	<i>Textularia torquata</i>	6.7	<i>Textularia torquata</i>	7.4	<i>Saccammina atlantica</i>	5.4
5	<i>Elphidium incertum</i> var. <i>clavatum</i>	5.5	<i>Elphidium incertum</i> var. <i>clavatum</i>	5.7	<i>Cibicides lobatulus</i>	4.8
6	<i>Reophax scottii</i>	4.6	<i>Spiroplectammina biformis</i> ⁴	5.2	<i>Adercotryma glomeratum</i>	4.2
7	<i>Trochammina squamata</i> ⁵	3.6	<i>Saccammina atlantica</i>	5.0	<i>Textularia torquata</i>	3.9
8	<i>Spiroplectammina typica</i>	3.6	<i>Spiroplectammina typica</i> ⁶	3.8	<i>Reophax scottii</i>	3.8
9	<i>Eponides frigidus</i> ⁷	3.6	<i>Reophax scottii</i>	3.6	<i>Buccella frigida</i> ⁸	3.5
10	<i>Cibicides lobatulus</i>	3.3	<i>Cibicides lobatulus</i>	3.2	<i>Quinqueloculina</i> spp. ⁹	2.8

Table 2 Ten most common benthic foraminifera for the Merrimack Embayment.

Notes: ¹The selection of these ten species is based on abundance data taken from a limited set of sample sites in Phleger (1952) and Parker (1952) that are geographically proximal to the sites used in this study; ²Species in **bold** have calcite tests, non-bold species are arenaceous; ³Ranked 17th (at 0.9 %) by Phleger (1952) & Parker (1952); ⁴Ranked 12th (at 3.0 %) by Phleger (1952) & Parker (1952), ranked 13th (at 2.2 %) by this study after acidic samples are removed; ⁵Ranked 16th (at 1.9 %) by this study after acidic samples are removed; ⁶Ranked 12th (at 2.6 %) by this study after acidic samples are removed; ⁷Not observed by this study; ⁸Ranked 12th (at 2.3 %) by this study prior to removing acidic samples; ⁹Ranked 15th (at 1.9 %) by this study prior to removing acidic samples.

Despite the effects of dissolution this discussion will demonstrate that the data presented here are robust. Several important trends are documented and many useful conclusions are drawn. Thus, the findings of this study were minimally impacted by sample preservation. Nonetheless, a conservative approach is taken and the discussion that follows considers only data from samples that were alkaline after thawing.

Species Abundance vs. Depth

As stated previously, benthic foraminifera become more abundant with increasing water depth (Table 1). This proximal to distal increase in foraminiferal density is observed along both

transects. Phleger (1952) and Parker (1952) also observed increasing foraminiferal density with depth, particularly in the southwest section of the Merrimack River embayment.

Foraminiferal Assemblage Analyses

Species diversity, dominance, equitability, and evenness are assemblage indices that provide information about the environment where a sediment sample was collected. These indices are used to complement geophysical and sedimentological analyses of the Merrimack River delta.

Species Diversity

Simple diversity is a count of all species present in a sample. As a general rule low sample diversity implies harsher environments, where one or a few species are better adapted for survival than other species. A sample with high diversity implies an environment that is less severe and where many species are able to coexist on a more equal basis. Simple diversity can also be affected by foraminiferal preservation, including the selective dissolution of calcareous species (discussed above), as well as seasonal changes in foraminiferal populations.

Along Transect 1 simple diversity is lowest near shore at 9.0 meters water depth (13 species), peaked from 50.6 to 59.0 meters (35 to 36 species, respectively), and then decreased to 22 species at the deepest site (103.0 meters; Figure 7). The peak in simple diversity along Transect 1 coincides with the delta break at approximately 50 meters and the change in seafloor sediments from sand to mud below 60 meters (Figure 6). Simple diversity along Transect 2 has two highpoints, one at 16.3 meters (30 species) and the other at 50.6 meters (30 species) before decreasing steadily to a low at 92.5 meters (14 species). Like Transect 1, the more distal peak in simple diversity along Transect 2 coincides with the delta break and roughly coincides with an increase in seafloor mud content below 60 meters water depth. The abrupt decrease in Transect 2 diversity for samples collected below 50.6 meters is very likely biased due to dissolution of the calcite species.

The sample collected from Transect 2, Site T2-20, is also biased; possibly by dilution (i.e., because of terrigenous particles far out-numbering foraminifer tests). Foraminifera were extremely scarce in this sample and only 75 tests were collected. To statistically represent foraminiferal abundances in a sample requires the collection of approximately 300 tests (Buzas,

per. comm.). Thus, in sample T2-20 the number of species observed and their relative abundances are not considered, in a strict sense, to be completely representative of the in situ assemblage. None-the-less, species diversity for the five remaining Transect 2 sites, spanning 16.3 to 50.6 meters water depth, implies a different environment when compared to similar sites along Transect 1. Grain size analyses support this observation. For example, the samples taken from 16.3 meters and 19.8 meters along Transect 2 are coarser and not as well sorted as sample T1-2 along Transect 1 (18.5 meters water depth).

The peak in simple diversity at roughly the delta break along both transects makes sense. Species that favor a sandy seafloor could have a geographic distribution that extends distally from the delta surface to the delta break, where the sediment composition is richer in mud and organic matter. Conversely, species that prefer the deeper, muddy environments may extend proximally to the delta break where the sediments are more enriched in sand. The diversity of species at the delta break is further increased by the likelihood that the delta break has its own unique assemblage of species. Thus, the sediments of the Merrimack Delta may consist of three broad environments: 1) shallow, less than approximately 50 to 60 meters water depth; 2) the delta edge, 50 to 60 meters water depth; and 3) deep, greater than 60 meters depth. Each environment has its own unique benthic foraminiferal assemblage that may or may not contribute to the simple diversity of adjacent environments. Simple diversity may be controlled by light penetration, sediment organic content, substrate, seasonality, sedimentation rate, benthic turbulence (by storm waves, tides, or currents) or by other parameters as well as combinations of these variables.

A historical comparison of diversity between this study and Phleger (1952) and Parker (1952) can only be accomplished qualitatively. This is due in part to the differences in the geographic area of the two studies and the already mentioned uncertainties between the “comparable” sites of Phleger (1952) and Parker (1952) and this study. Sixty-two species of benthic foraminifera were identified in this study, while Parker (1952) described 74 species, although across a much larger area. However, Phleger (1952) tabulated the abundances of approximately 58 species across the same region. The lower number of species tabulated by Phleger (1952) may be due to the combining of species concepts, such as his combining the counts of *S. difflugiformis* in with *S. atlantica*. It is not known if other species were treated the

same. The uncertainty of combined species concepts by Phleger (1952) makes it difficult to draw further comparisons to this study.

In comparison to the Merrimack Embayment, Thomas et al. (2000) found that species diversity in Long Island Sound has decreased since the 1960s. They suggested that environmental stress from seasonal hypoxia, pollution or other variables have caused the changes in species' relative abundance.

Species Evenness

Species evenness is a gauge of how evenly the total number of foraminifera identified in a sample is distributed amongst the species present. In general, a graph of species evenness follows that of species diversity when plotted against water depth (Figure 7). Evenness was determined by the relationship:

$$E = e^H/S \quad (\text{A rearrangement of the SHE index for } E)$$

Where: E , is the species evenness index; e , is the natural log; H , is the Shannon-Weiner diversity index; and S , is the number of species (Wakefield, 2003). The Shannon-Weiner diversity index in turn is:

$$H = - \sum_{i=1}^S (p_i(\ln p_i)) \quad (\text{Shannon-Weiner diversity index})$$

Where: S , is the number of species; and p_i , is the proportion of the i th species (Wakefield, 2003).

Along Transect 1 foraminiferal assemblages tend to be most evenly distributed in samples that were recovered near the delta break, at approximately 50 to 60 meters water depth. This observation is difficult to substantiate for Transect 2 because samples collected below 50.6 meters water depth are biased by dissolution of the calcareous taxa. The high degree of evenness observed at the shallowest Transect 2 site (T2-20) is probably due to the statistically low number of tests collected from that sample. For Transect 1 the greatest degree of evenness coincides with the peak in species diversity. This result is expected because in a diverse community of organisms it is less likely that any one species will be significantly more abundant than the

remaining species. Further, the environmental conditions that affect the survival of each species (e.g., water temperature, food availability, seafloor sediments, etc.) are such that all species have a more equitable opportunity to survive and sustain their populations.

Species Dominance

Species dominance is a measure of how the abundance(s) of one or several species dominates the other species in a sample. Species dominance and species diversity usually have an inverse relationship to one another. A sample obtained in an environment with low diversity is more likely to have a strongly dominant species (or several species) than a sample recovered from a highly diverse environment. The Simpson dominance index is:

$$D = \sum_{i=1}^S [(n_i(n_i - 1))/(N(N - 1))] \quad (\text{Simpson dominance index})$$

Where: D is the Simpson dominance index; S, is the number of taxa; n_i , is the number of individuals in the i th species; and N, is the total number of individuals.

Transect 1 species dominance roughly follows the inverse of Transect 1 species diversity. The low point in species dominance matches the delta break (Figure 7). This is nearly the exact inverse to the high point in species diversity that coincided with the delta break. For Transect 2 the situation concerning diversity is more complex. Ignoring the biased samples (T2-11 through T2-14, and T2-20), the dominance curve for Transect 2 is generally low. This is in rough agreement with the unbiased samples that exhibit relatively high diversity along the shallow water segment. Yet the Transect 2 dominance curve is somewhat unchanged compared to the same interval for species diversity, an anomalous result that lacks explanation.

It is useful to remember that the observed assemblages and their characteristics as discussed here, i.e., diversity, evenness, and dominance, represent an annual average of a seasonal progression of changing assemblages. Knowing how the assemblages change seasonally would provide an added dimension to understanding the benthic foraminiferal communities and the benthic environment. This in turn will provide better delineation and characterization of offshore sand and gravel resources.

The geographic area covered by this study may exhibit greater evenness and less dominance than what was observed 60 years ago. Table 2 shows that the three most common species observed by Phleger (1952) and Parker (1952) account for 53 % of all tests in a comparable area. For this study the six most common species account for 51 % of all tests. This implies a greater evenness and correspondingly less dominance amongst the assemblages today than in the time of Phleger (1952) and Parker (1952) for the study area.

Statistical Analyses

The data in this study were analyzed using a statistical technique known as Q-mode cluster analysis. The purpose of cluster analysis is to provide an independent assessment of the data so to lessen any bias imparted by human interpretation. Cluster analysis also provides another method by which data can be studied and compared to measurements of species diversity, evenness, and dominance.

Q-mode cluster analysis uses percent foraminiferal abundance data from each sample to identify groups of samples that have a mathematical commonality to one another. The technique is useful because it can mathematically reveal statistical grouping of samples. These statistical groupings may illustrate actual groupings in the environment, i.e., biotopes such as the delta surface, delta break, and the delta front.

For the cluster analysis only species that accounted for >1 % of the population in at least one sample were used with the software PAST (PALaeontological STATistics, ver. 1.72; 2007). Several clustering measures such as Raup-Crick were employed and each measure produced very similar cluster dendrograms. Because the PAST program revealed consistent trends in the data and because these trends made sense with respect to the Merrimack River delta, it is assumed that the clusters are true representations of the data rather than artifacts of the clustering process.

Cluster analysis yielded several distinct foraminiferal assemblages: 1) a “shallow” assemblage, located at approximately 30 meters water depth but where Transect 1 and Transect 2 samples cluster separately; 2) a “deep” assemblage at 40 to 100 meters water depth, again, Transect 1 and Transect 2 samples cluster separately; and 3) a “delta edge” assemblage at approximately 50 meters water depth, where samples from both transects cluster together. The distinction between the shallow assemblages that occupy the delta surface and the deep assemblages of the delta front may be attributed to substrate characteristics. Fine to coarse sand

characterize the seafloor in water depths shallower than 40 meters, while mud becomes increasingly abundant at greater depths.

There is good agreement between the distinct groupings identified by cluster analysis and those revealed by measurements of species diversity, evenness and dominance. These analyses show that at a minimum, foraminiferal assemblages do differentiate the sandy delta surface from the muddy delta front, as well as identify the delta break. The analyses of the foraminiferal assemblages also show significant differences between the two transects although sediment character and water depth for both transects change parallel to the shore and are similar to one another. This biotic information complements the findings of the geophysical and sedimentological techniques that are used for mapping the extent and character of each part of the delta.

Foraminiferal Distributions

This section discusses the three overarching findings of this study: 1) foraminiferal assemblages change from proximal to distal across the delta; 2) foraminiferal assemblages change from one transect to another; and 3) foraminiferal assemblages can ground-truth geophysical and sedimentological techniques to assess offshore sand and gravel resources. Figure 6 summarizes these three findings by depicting ten of the 17 benthic foraminiferal species described below. All 17 species were not included in Figure 6 so to reduce overcrowding the pie diagrams.

Proximal to distal changes in foraminiferal assemblages

The species identified in this study tend to fall into three geographic distributions (i.e., biogeographic provinces): 1) species that primarily inhabit the delta surface (less than 50 meters water depth); 2) species that primarily inhabit the delta front (greater than roughly 60 meters water depth); and 3) species that inhabit the delta break and possibly overlap with the distribution of group 1) and/or group 2). Each of these three geographic distributions has a unique assemblage of species that has some overlap with an adjacent province. This allows each assemblage to delineate a specific area of the delta and provide information about its sediments (Table 3). Phleger (1952) and Parker (1952) considered there to be two principal biogeographic

provinces for the western Gulf of Maine, a sand facies and a mud-sand/mud facies. They also recognized that there may be one or more distinct subfacies and that overlap was likely.

Environment	Diagnostic Species
Delta surface (topsets; coarse to fine sand): <50 m – Transect 1,	<i>Cibicides lobatulus</i> , <i>Elphidium clavatum</i> , <i>Discorbis columbiensis</i>
Delta surface (topsets): <50 m – Transect 2	<i>Elphidium subarcticum</i> , <i>Saccammina atlantica</i> , <i>Trochammina squamata</i>
Delta break (fine sands): 50-60 m – Transect 1	<i>Buccella frigida</i> , <i>Globocassidulina islandica</i> , <i>Glomospira gordialis</i>
Delta break: 50-60 m – Transect 2	<i>Reophax scottii</i> , <i>Reophax curtus</i> , <i>Saccammina difflugiformis</i>
Delta front (foresets/bottomsets; muds): >60	<i>Adercotryma glomeratum</i> , <i>Spiroplectammina spp.</i> , <i>Textularia torquata</i> , <i>Globobulimina auriculata</i> , <i>Nonionella auricula</i> , <i>Nonionellina labradorica</i>

Table 3. Species diagnostic of deltaic environments. Note: calcite species are in **bold**.

Cibicides lobatulus is a calcareous species that exclusively inhabits the shallowest areas of the delta (Figures 6 and 8) and thus, it was unaffected by dissolution. It is much more common along Transect 1, having abundances of 32 % at Site T1-1 and 24 % at Site T1-2. Along Transect 2 *C. lobatulus* abundances peak at Site T2-20 (8 %). *C. lobatulus* is absent below 60 meters. At sites geographically comparable to this study, Phleger (1952) and Parker (1952) found *C. lobatulus* to have equal distributions along both transects, with peak abundances at approximately 20 meters water depth. They found *C. lobatulus* to be absent below 50 meters. Over a larger geographic area, Phleger (1952) and Parker (1952) observed *C. lobatulus* to have a peak abundance near shore and north of the Merrimack River. In comparison to Phleger (1952) and Parker (1952), this study found that *C. lobatulus* has retreated landward, becoming much more constrained along the shore and much more abundant near the mouth of the Merrimack River.

Globobulimina auriculata is a calcareous species that inhabits the delta front (Figure 6). It is most abundant at the deepest site (16.4 %, 103.0 meters, Site T1-10) and least abundant at site T1-6 (2 %, 59.0 meters). Its absence in samples T1-8 (82.4 meters) and T1-9 (92.3 meters) is a likely indicator of dissolution since both samples were acidic after thawing. Although

Phleger (1952) and Parker (1952) did not observe *Globobulimina auriculata* at sites comparable to this study, they did record the species at other locations in the region where water depths were greater than 40 meters.

Adercotryma glomeratum is an arenaceous species that becomes progressively more abundant along Transect 1 from the delta break (2 % at 50.6 meters, Site T1-5) to the delta front (20 % at 103.0 meters, Site T1-10; Figures 6 and 9). Transect 1 offers the clearest support for this trend because it had fewer acidic samples (T1-8 and T1-9). For Transect 2 the trend of increasing *A. glomeratum* abundance with increasing water depth is somewhat tenuous, but still supported. For example, it is unlikely that the observed abundance of *A. glomeratum* in the acidic sample T2-11 (52.4 % at 92.5 meters) would be lower than the abundance observed in the alkaline sample T2-15 (1.3 % at 50.6 meters) had dissolution not been an issue. Further, the alkaline sample T1-10 (103.0 meters) serves as a guide as to how abundant *A. glomeratum* might have been if the deeper Transect 2 samples were not acidic. At comparable locations to this study, Phleger (1952) and Parker (1952) reported *A. glomeratum* to be present in the muddy delta front, absent at the delta break, and absent on the delta surface; all the while having greater abundances along Transect 1. When considering the larger region covered by Phleger (1952) and Parker (1952), this study observed that *A. glomeratum* has now shifted significantly closer to the shore and it is more abundant (Transect 2 is indeterminate; Figure 9).

The distribution of *Textularia torquata* is similar to *A. glomeratum*, i.e., the range of both species extends from the delta break at 50.6 meters to the delta front. Along Transect 1 *T. torquata* (an arenaceous species) is most abundant at the base of the delta front (24 %, 71.5 meters, sample T1-7; Figures 6 and 10). This conclusion is not affected by the dissolution that occurred in samples T1-8 and T1-9. However, it is not possible to determine the peak abundance of *T. torquata* along Transect 2 due to dissolution in samples collected below 50.6 meters water depth. The distribution and abundances of *T. torquata* observed in this study are similar to those of Phleger (1952) and Parker (1952). They found *T. torquata* to be more common in the muddy delta front, absent on the delta surface and having greater abundances along Transect 1.

Globobulimina auriculata and *Cibicides lobatulus* are two calcareous species that have separate biogeographic provinces. When combined with the arenaceous species *Adercotryma glomeratum* and *Textularia torquata*, the four taxa characterize and delineate two broad biogeographic provinces. The area covered by *Adercotryma glomeratum*, *Globobulimina*

auriculata and *Textularia torquata* ranges from the fine sands of the delta break to the muds of the delta front. *Cibicides lobatulus* is observed on the delta surface in fine to medium sands. These provinces coincide with different seafloor sediments and demonstrate how the assemblages occupy different areas of the delta. This information in turn serves to ground-truth geophysical techniques.

Five additional species deserve mention as to how their distributions and abundances have or haven't changed over time. The first species is *Spiroplectammina biformis*, a species that Phleger (1952) and Parker (1952) found exclusively in the muddy delta front (Figure 11). This study found the distributions and abundances of *S. biformis* to be largely unchanged over 60 years. The second species is *Cibrostomoides crassimargo*, which Phleger (1952) and Parker (1952) also found to inhabit the more distal sections of the delta (Figure 12). However, this study found that *C. crassimargo* has nearly disappeared from the same geographic area. The third species is *Elphidium subarcticum* (Figures 6 and 13). Both this study and Phleger (1952) and Parker (1952) found *E. subarcticum* to range from the delta surface to the delta break, with roughly the same abundances. Phleger (1952) and Parker (1952) found the fourth species, *Eggerella advena*, to range from the delta surface to the delta front (Figures 6 and 14). However, over comparable study areas, abundances of *E. advena* today are considerably less abundant across the delta surface than the historical values observed by Phleger (1952) and Parker (1952) (14 % vs. 39 %, respectively; Table 2). In Long Island Sound, Thomas et al. (2000) also found a strong decrease in *E. advena* abundances since the 1960's. They speculate that *E. advena* abundances may have been influenced by changes in their food supply. Specifically, the increased eutrophication of Long Island Sound since the 1960's has resulted in an increase of more labile organic material and decreased the supply of degraded and refractory organic matter. The fifth and last species is *Reophax curtus* (Figure 15). This species is observed along a broad north-south band that is centered near the delta break, it is absent near the shoreline, and it rarely occurs in the deepwater. This distribution is a significant departure from Phleger (1952) and Parker (1952) who observed the species becoming more abundant with increasing depth and distance from the delta break.

What controls the observed proximal to distal changes in foraminiferal distributions across the Merrimack Embayment is not entirely resolved. We assert that foraminiferal distributions are independent of sediment type, per se. The data presented here suggests that

foraminiferal distributions are primarily controlled by food availability and/or the combination of other environmental variables. This conclusion is based on an examination of the fourteen biofacies maps that compare benthic foraminiferal distributions in this study to those of Phleger (1952) and Parker (1952) (Figures 8 through 21). These maps do not reveal any obvious correlation between foraminiferal distributions and the bedforms observed by Hein et al. (2007; Figure 3). This implies that the processes controlling the formation and distribution of the bedforms, and the character of the seafloor sediments, are independent of the environmental variables that control benthic foraminiferal distributions. Specifically, the action of the Merrimack River outflow, storm waves, tides, and bottom currents upon reshaping the seafloor and controlling sediment type at any one locality (e.g., Hein et al., 2007) may play less of a role in determining where benthic foraminifera live than other factors such as food availability, temperature, and salinity (e.g., Leckie and Olsen, 2003). Phleger (1952) and Parker (1952) came to the same conclusion by stating that foraminiferal distributions in the western Gulf of Maine are largely independent of sediment type. In Long Island Sound, Buzas (1965) suggested that the proximal to distal distribution of benthic foraminifera (i.e., their depth zonation) is related to the distribution of their food supply. If this reasoning can be applied to the Merrimack Embayment, then the observed depth zonation of some benthic foraminiferal species may be controlled primarily by the distribution of their food.

Although a benthic foraminiferal species may be regarded in the literature (and here) as typifying a particular sedimentary facies or section of the delta, this is more a statement of convenience than explicit fact. It should not be construed that there is an intrinsic association between the distribution of the species and sediment type. Instead, a species distribution is only indirectly associated with sediment type, the true association is between the distribution of the species and its food (and/or the preferred combination of other environmental variables). It is the preferred food of that species which may be closely associated with a particular sediment type.

Transect 1/Transect 2 foraminiferal assemblages

Five species highlight differences in the benthic foraminiferal assemblages between the northern and southern transects in this study. For several species the observed latitudinal differences between the two transects are accentuated when they are compared to the findings of Phleger (1952) and Parker (1952). The latitudinal differences illustrate that the observed

assemblages are not simply a function of water depth as it increases parallel to the shore. Nor are the latitudinal differences in the assemblages a consequence of the delta's sedimentary composition changing distally. The discussion that follows also demonstrates that the differences between Transects 1 and 2 are independent of the effects of dissolution.

Reophax scottii is an arenaceous species that was observed only along Transect 2 (Figures 6 and 16). It inhabits the deltaic sands from 10.0 meters water depth to 71.9 meters, where the mud content of the sediment reaches 52 %. Peak abundance of *Reophax scottii* (27 %) occurs at 50.6 meters water depth, coincident with the delta break. Finding *R. scottii* along only one transect and so close to the shore is a significant departure from the biogeographic distribution observed by Phleger (1952) and Parker (1952). At sites comparable to this study and over a wider region, they observed *R. scottii* along a broad north-south band that followed the coastline and centered on the most proximal sections of the delta front. Phleger (1952) and Parker (1952) found *R. scottii* in very high abundances across limited areas (49 % at 73 meters). They also observed *R. scottii* to be very scarce or absent across the broad delta surface.

The distribution of *Trochammina squamata* is similar to *R. scottii* in that this arenaceous species is found only along Transect 2 (Figures 6 and 17). However, its abundance peaks at 19.8 meters water depth (11 %) on the sandy delta surface and tapers off distally. Over the larger region, Phleger (1952) and Parker (1952) observed *T. squamata* along a north-south, shoreline following band, coincident to the band observed for *R. scottii*. The narrow band of *T. squamata* did not reach as far north as the band along which *R. scottii* was observed (Phleger, 1952; Parker, 1952). Within the narrow band, *T. squamata* had peak abundances that were comparable to the modern day (approximately 5 % to 15 %), but occurring in much deep water (approximately 80 meters water depth; Phleger, 1952; Parker, 1952). Phleger (1952) and Parker (1952) regarded *T. squamata* to be a species characteristic of mud-sand sediments.

Saccammina atlantica is an arenaceous species whose modern day distributions and abundances depart significantly from those observed by Phleger (1952) and Parker (1952) (Figure 18). At sites comparable to this study, Phleger (1952) and Parker (1952) found *S. atlantica* to be confined to a narrow, north-south band located on the sandy, delta surface and the delta break. Across the larger region they observed abundances to be relatively uniform. In this study *S. atlantica* was found only in trace levels along Transect 1. Along Transect 2 *S. atlantica* occurs in the fine to medium sands of the delta surface, but at water depths (30.2 meters to 50.6

meters) that were similar to what Phleger (1952) and Parker (1952) recorded. Further, modern abundances of *S. atlantica* peak between 26 % and 30 % as compared to 11 % and 18 % observed by Phleger (1952) and Parker (1952).

The distribution and abundances of *Saccammina difflugiformis* (an arenaceous species) follows *S. atlantica* (Figure 6). *Saccammina difflugiformis* is found almost exclusively along Transect 2 (only two tests were obtained from Transect 1). *Saccammina difflugiformis* was the 13th most common species in this study, with peak abundances ranging from 12 % (30.2 meters water depth) to 10 % (62.6 meters water depth). Parker (1952) found *S. difflugiformis* to be uncommon across the Merrimack Embayment, but stating nothing more about its distribution and abundance. This finding is an oversimplification because Phleger (1952) combined the species concept of *S. difflugiformis* with *S. atlantica* for tabulation purposes and consequently did not map its distribution and abundance.

Elphidium incertum variation *clavatum* (a.k.a., *E. clavatum*) is a calcareous species found in all samples that were not affected by dissolution (Figures 6 and 19). The species is most common in the shallowest areas of the delta surface along Transect 1 (35 % at 9.0 meters water depth), with abundances decreasing distally to the shelf break. *Elphidium clavatum* is much less abundant along Transect 2, with a peak of 9 % at 10.0 meters water depth. The alkaline sample T1-10 at 103.0 meters water depth had *E. clavatum* abundances of 17 %, an anomalous result that may be tied to sediment transport. Alternatively, *E. clavatum* may be responding to a seasonal flux of organic matter to the seafloor and thus its occurrence at this deep site may be a short-lived spike in abundance. Phleger (1952) and Parker (1952) found abundances of *E. clavatum* to be more constrained to the shoreline and more common along Transect 2 (peak abundance of 48 %). They did not observe *E. clavatum* in water depths exceeding 41 meters.

Thomas et al. (2000) found a related species, *Elphidium excavatum clavatum* to be the most common foraminifera in Long Island Sound. As was occasionally observed with *Elphidium incertum* variation *clavatum* in this study, Thomas et al. (2000) noted that *Elphidium excavatum clavatum* sequester chloroplasts that might actively photosynthesize within the foraminifera. If such chloroplasts are active it may provide information about the depth of the photic zone in relation to the distribution of *Elphidium*.

Two benthic foraminiferal species exemplify taxa that are rare and/or are found outside the area covered by this study. *Nonionellina labradorica* is absent in all delta surface samples

and all acidic samples. However, at Site T1-10 (103.0 meters, an alkaline sample) *N. labradorica* has an abundance of 9 % (Figure 20). This finding is in keeping with Phleger (1952) and Parker (1952). They observed the species in moderate abundances but in very small, isolated pockets across the western Gulf of Maine. *Globocassidulina algida* occurs in low percentages across Transect 1, has single occurrences along Transect 2, and it is absent from any acidic samples (Figure 21). This spotty distribution is similar to the pattern observed by Phleger (1952) and Parker (1952).

Why the distribution and abundances of *Reophax scottii*, *Trochammina squamata*, *Saccammina atlantica*, *Saccammina difflugiformis*, *Elphidium clavatum*, and even *Cibicides lobatulus* have changed so much from one transect to another over a 60 year period is open to speculation. Although sediment composition can change significantly over distances as short as tens of meters within the Merrimack Embayment (Hein, per. comm.); it is assumed that bathymetric contours and sediment composition change parallel to the shoreline as water depth increases along both transects. Thus, the differences observed between the two transects in the distribution and abundances of a particular foraminiferal species, when compared to Phleger (1952) and Parker (1952), may be due to other variable(s) than water depth and sediment composition. One possible cause may be changes in the water column brought about by the Merrimack River outflow.

The regional barrier islands demonstrate that local currents and long shore transport follow the coastline, moving in a north to south direction (e.g., Fitzgerald et al., 1994). Transect 1 is positioned just north of a line running due east from the mouth of the Merrimack River while Transect 2 is several kilometers to the south. Based on the position of the two transects and local oceanographic conditions, it seems reasonable to assume that Transect 2 is influenced more by the outflow of the Merrimack River than Transect 1 (Phleger, 1952 and Parker, 1952).

The river outflow would affect all aspects of the water column, in particular its chemical and physical properties. One notable affect is the delivery and southward transport of nutrients from the river. These nutrients can influence biological productivity in the water column and on the seafloor, especially the abundance and distribution of macro and microfaunal communities, of which benthic foraminifera are a part. The degree of biological productivity at a particular location also influences the quantity of organics in the sediments. Thus, sandy environments that have higher productivity are likely to be richer in organics and contain different foraminiferal

assemblages than sands having lower productivity. This may be one possible explanation for the biotic differences observed between Transect 1 and Transect 2, both today and six decades ago.

Productivity would also play a role in the quality of the offshore sand and gravel from a resource perspective. How far offshore the affects of productivity may reach is unknown, but it is likely to be highly variable and dependent upon the season, meteorological events, currents, and how readily fluvial and marine waters mix. Caution needs to be applied to this discussion because of the relatively limited geographic area of this study. Although Phleger (1952) and Parker (1952) provide a valuable historical perspective for changes within the Merrimack Embayment, the much smaller scale of this study makes it difficult to determine the exact cause of the observed changes and to extrapolate them to a regional context.

Foraminifera and geophysical/sedimentological techniques

Foraminiferal assemblages can serve to ground-truth geophysical and sedimentological techniques for the assessment of offshore sand and gravel resources. This theme has been supported by the data and interpretations provided in this study. This section provides an overview of these findings.

The 14 biofacies maps delineate specific areas of the delta inhabited by individual species of benthic foraminifera. These maps also present the distributions of modern foraminifera in side-by-side comparison to the literature. The indirect association between foraminiferal distributions and sediment type allows these biofacies maps to complement maps that depict geophysical and sedimentological data.

Benthic foraminiferal assemblages also provide information that complements geophysical and sedimentological data. Figure 6 illustrates that each site on the delta where a sediment sample was recovered yields a unique assemblage of benthic foraminifera as well as a unique grain size analysis. Taken together with the side scan sonar data and grain size analyses (Figure 4) it is clear that the changing foraminiferal assemblages can be used to delineate the delta surface, delta break, and the delta front.

Cluster analyses of foraminiferal abundances provides a mathematically independent method to confirm or refute the findings of the biofacies maps and the observed assemblages. These analyses consistently show sample sites grouping as “shallow”, “deep”, and “delta edge”, in keeping with the geophysical locations for the delta surface, delta break, and the delta front,

respectively. The findings of species diversity, evenness, and dominance go hand-in-hand with the cluster analyses, i.e., presenting the delta as three distinct regions.

Benthic foraminifera are sensitive to environmental changes and a number of studies have examined foraminiferal responses to anthropogenic pollution, habitat disturbance, and global warming (e.g., Scott et al., 1995, 2003; Yanko et al., 1999). By monitoring proxies such as test deformities and anomalous changes in species populations, benthic foraminifera can provide insight into changing depositional conditions in the Merrimack Embayment. In this study test deformities were very rare with respect to the number of tests observed. The benthic species *Spiroplectamina biformis* exhibited the largest number of atypical tests but the observed deformities in test shape were minor. Occurrences of abnormal tests were also observed, although very rarely, for *Cibicides lobatulus*, *Cibicides lobatulus*, *Cibicides lobatulus*, *Cribrostomoides crassimargo*, *Elphidium subarcticum*, *Saccammina difflugiformis*, *Spiroplectamina typica*, and *Trochammina lobata*. The abnormal tests were found along both transects and at most water depths, but were slightly more common near the delta break. These observations of test deformities will provide a valuable baseline for future work given the current scarcity of data for the Merrimack Embayment. This baseline data will help with monitoring the biotic recovery of the seafloor following sand mining and the effects of pollution and global warming.

CONCLUSIONS

Benthic foraminiferal analyses were carried out on sediment samples collected in the Merrimack Embayment. The data produced were coupled with grain size analyses and to a lesser degree geophysical techniques, to delimit modern depositional environments. The observed findings for the area investigated by this study were:

1) Individual species tend to exhibit depth zonation by inhabiting distinct biogeographic areas of the delta. Fourteen biofacies maps depict and compare modern biogeographic areas to their spatial distributions observed nearly sixty years ago. In general, more species have exhibited a landward shift in their distributions (e.g., *Adercotryma glomeratum*, *Cibicides lobatulus*, *Reophax curtus*, *Trochammina squamata*) while fewer exhibited the reverse (e.g., *Elphidium clavatum* and *Elphidium subarcticum*);

2) Significant differences in the distribution of various benthic foraminiferal species exist between the two transects sampled in this study (e.g., *Reophax scottii*). These differences may point to the asymmetric influence of the Merrimack River outflow upon the two transects. The southern transect may experience higher productivity that in turn, affects the flux and nature of food availability at the seafloor. This may explain the striking asymmetry in foraminiferal assemblages observed between the northern and southern transects;

3) Unique assemblages of benthic foraminifera characterize each area of the Merrimack River delta that was sampled (see Figure 6). These assemblages are as distinct as the grain size distributions obtained from the same samples and they can serve to delineate specific areas of the delta;

4) Benthic foraminiferal distributions are independent of local bedforms and sediment type. Local foraminiferal distributions may be driven more by the distribution of food supply, which in turn is associated with sediment type;

5) Benthic foraminifera do serve as a tool for assessing offshore sand and gravel resources. The raw data collected on foraminiferal species distributions and populations, as well as processed data such as cluster analyses and indices of species diversity, evenness, dominance, all serve to delineate the delta in a manner that complements geophysical and sedimentological data. Independent of geophysical techniques, benthic foraminiferal might also serve as a proxy for substrate conditions pre- and post-sediment disruption. For example, they could gauge biotic recovery from offshore mining of sand and gravel resources by analyzing recolonization trends

and rates. This is a key determination to make with respect to assessing any impact to local fisheries and environmental permitting;

6) This study did not demonstrate environmental changes using test mutations. This is likely due to the limited scope of the project. However, the collected data will serve as a useful baseline to the larger study that would be needed to assess anthropogenic pollution and habitat disturbance; and

7) This study demonstrates the need to reexamine the Merrimack Embayment and the western Gulf of Maine on the scale undertaken by Phleger (1952) and Parker (1952). Increasing regional anthropogenic pressures that range from watershed development, coastal environmental impact (e.g., rising sea level and pollution), and marine development (e.g., increased fishing and mining of subaqueous sand and gravel deposits), all demand a more comprehensive understanding of the region prior to the implementation of any measure to utilize these resources or to mitigate human impact.

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TAXONOMIC NOTES

We closely followed the species concepts of Parker (1952), Todd and Low (1981), and Cushman (1944). These notes address the 62 species observed at all sites and/or provide commentary regarding how we differentiated these taxa from other similar species. For the benefit of the reader a brief synonymy is provided after the name of the species (where appropriate).

Adercotryma glomeratum (H. B. Brady) 1878 (ser. 5, v. 1, p. 433, pl. 20, figs. 1a-c)

The test of *Adercotryma glomeratum* is small to intermediate in size, subglobular in form, often orange in color, with a low and inconspicuous aperture, involute coiling, and having four chambers in the final whorl.

Ammodiscus catinus Höglund 1947 (bd. 26, p. 122, pl. 8, figs. 1,7; pl. 28, figs. 19-23; text figs. 82-84, 105-107, 109)

The test of *Ammodiscus catinus* is typically larger than *Ammodiscus minutissimus*, orange in color, planispiral, having narrow inner whorls that broaden rapidly, finely arenaceous, and occasionally observed attached to sand grains.

Ammodiscus minutissimus Cushman and McCulloch 1939 (v. 6, pl. 5, figs. 3,4)

Ammodiscus minutissimus is small in size, planispiral, white in color, finely arenaceous, and having narrow whorls that increase slowly in size. Abundances of *Ammodiscus minutissimus* never exceed 3%. It is sparsely and sporadically distributed along both transects.

Angulogerina angulosa (Williamson) 1858 (p. 67, pl. 5, fig. 140)

Astrononion stellatum Cushman and Edwards 1937 (v. 13, pt. 1, pl. 3, figs. 9-11)

Bolivina pseudoplicata Heron-Allen and Earland 1930 (v. 50, p. 81, pl. 3, figs. 36-40)

Buccella frigida (Cushman) 1922 (1921: 135-147)

This species is generally small in size, round in form and biconvex in edge view, and having a low trochospire. Most notable is the star-like pattern of pustules centered over the umbilicus and radiating outward along the ventral sutures. Many tests were glassy in appearance.

Bulimina aculeate d'Orbigny 1826 (v. 7, p. 269, n.7)

Buliminella complanata (Egger) 1893 (Cl. 2, bd. 18, p. 292, pl. 8, figs. 91, 92)

Buliminella elegantissima (d'Orbigny) 1839 (v. 5, pt. 5, p. 51, pl. 7, figs. 13, 14)

The test of this species is very small in size and delicate, often glassy in appearance. Its form is typical.

Buliminella sp.

Bulimina marginata d'Orbigny 1826 (v. 7, p. 269, n. 4, pl. 12, figs. 10-12)

The test of *Bulimina marginata* is small in size. Its chambers overlap those of the previous whorl and are rimmed by spines that are short and sharp. Only a single test of *Bulimina marginata* was observed in this study. Phleger (1952) and Parker (1952) did not observe the species at localities near our two transects.

Cibicides lobatulus (Walker and Jacob) 1798 (p. 642, pl. 14, fig. 36)

The test of this species can be very large in size. *Cibicides lobatulus* is characterized by a plano-convex shape, a coarsely perforate spiral side, and an arched, rimmed aperture.

Cribrostomoides crassimargo (Norman) 1892 (pt. 8, p. 17)

Test of *Cribrostomoides crassimargo* can be very large in size, orange in color, coarsely arenaceous, coarsely finished, with a small, narrow, rimmed aperture that is typical in form. The species was very rare.

Cribrostomoides jeffreysii (Williamson) 1858 (p. 34, pl. 3, figs. 72, 73)

Discorbis columbiensis Cushman 1925 (v. 1, pt. 2, p. 43, pl. 6, figs. 13a-c)

Discorbis squamata Phleger and Parker 1952 (pl. 6, figs. 10a-b, 11)

Eggerella advena (Cushman) 1921 (1922) (n. 9, p. 141)

The test of this species is small in size, triserial, composed of fine sand grains, has a smooth surface, and is typically orange in color. Chambers of the test rapidly inflate to produce a compact cone-like form. Some tests exhibit a gradual chamber inflation that produces a more elongated form of the species.

Elphidium advenum (Cushman) var. *margaritaceum* Cushman 1930 (Bull. 104, pt. 7, p. 25, pl. 10, fig. 3)

The test of *Elphidium advenum* var. *margaritaceum* is large, planispiral, round in outline, lacks a plug, has a granulated surface, and a compressed, imperforate margin. The retral sutures (i.e., septal bridges) are the most distinguishing characteristic of *E. margaritaceum*.

E. margaritaceum is very rare (<1 %) and occurs in waters <17 meters deep. *E. margaritaceum* was not observed by Phleger (1952) and Parker (1952). Phleger (1952) and Parker (1952) treated *E. margaritaceum* as a variety of *E. advenum* while Todd and Low (1981) considered it a separate species.

Elphidium incertum (Williamson) var. *clavatum* Cushman 1930 (Bull. 104, pt. 7, p. 20, pl. 7, figs. 10a-b)

Tests of *Elphidium incertum* var. *clavatum* are generally large, planispiral, round to slightly ovate in form, lenticular shaped in edge view, and have up to eleven chambers in the final whorl. It has a ventral plug or plugs that distinguish it from *Elphidium subarcticum*.

Elphidium subarcticum Cushman 1944 (S.p. 12, p. 27, pl. 3, figs. 34, 35)

This species is typically large and planispiral, with a round to oval outline. Larger forms of *Elphidium subarcticum* have eight to nine chambers while the smallest tests have 4-5 chambers. Tests are opaque but some were found to be green in color, presumably due to the internal sequestering of photosynthetic organisms. It was not unusual to find tests

strongly attached to sand grains. To differentiate *Elphidium subarcticum* from other members of this genus the lack of a ventral plug and the fine granular surface texture was noted. This last characteristic is especially diagnostic along the sutures of the test.

Eoepionidella pulchella (Phleger and Parker) 1952 (pl. 6, figs. 18a-b, 19, 20)
Epistominella vitrea Parker 1953

Fursenkoina fusiformis (Williamson) 1858 (p. 63, pl. 5, figs. 129, 130)

The test of *Fursenkoina fusiformis* is small, very delicate and glassy. Its comma-shaped aperture may extend slightly and appear neck-like. *Fursenkoina fusiformis* has rapidly inflating chambers while its spire can vary from low to high.

Globobulimina auriculata (Bailey) 1851 (v. 2, p. 12, pl. 1, figs. 25-27)

In this study tests of *Globobulimina auriculata* are large, typical in form, often glassy, and delicate. *Globobulimina auriculata* is most abundant at the deepest station and is rarely observed along transect one (it is absent along transect two). Phleger (1952) and Parker (1952) recorded similar abundances and depth distribution but not at localities analogous to those in this study.

Globocassidulina algida (Cushman) 1944 (S.p. 12, p. 35, pl. 4, fig. 24) and
Globocassidulina islandica (Nørvang) 1945 (v. 2, pt. 2, p. 43, text figs. 8a-c)

Globocassidulina algida occurs in a wide range of forms with some being gradational with *Globocassidulina islandica*. One end member of *G. algida* is distinct in having greatly inflated chambers, resembling a closely packed cluster of grapes. These tests are often glassy in appearance and large in size compared to *G. islandica*. The opposite end member of *G. algida* is smaller in size, often opaque and having minimal chamber inflation. To differentiate this latter form of *G. algida* from *G. islandica*, we evaluated the position of the aperture with respect to the umbilicus. Tests having an aperture opening towards the margin were identified as *G. algida* while tests having an aperture opening towards the umbilicus were identified as *G. islandica*. Tests of *G. islandica* are typically opaque and smaller in size than those of *G. algida*. The observed form of *G. islandica* ranges from smooth to having slightly inflated chambers. Aperture orientation was used to differentiate *G. islandica* from *G. algida*.

Globulina gibba d'Orbigny 1826 (v. 7, p. 266, n. 10)

Globulina glacialis Cushman and Ozawa 1930 (v. 77, n. 2829, art. 6, p. 71)

Glomospira gordialis (Jones and Parker) 1860 (v. 16, p. 304)

The coiling of *Glomospira gordialis* is highly variable, ranging from almost planispiral to globular. The test is orange in color and finely arenaceous.

Guttulina lactea (Walker and Jacob) 1798

Hippocrepina indivisa Parker 1870 (v. 5, p. 176, fig. 2)

The complete test of *Hippocrepina indivisa* is moderate in size but extremely rare. Typically, only the conical terminus is preserved. The single chambered test is finely

arenaceous, delicate, orange in color, and has fine creases that are transverse to the long axis.

Lagena clavata (d'Orbigny) 1846

The test of *Lagena clavata* is elongate, smooth, delicate, and having a distinct neck and apical spine. A single test was observed in 16.3 meters water depth at site T2-19. Phleger (1952) and Parker (1952) did not observe the species.

Lagena mollis Cushman 1944

Lagena mollis is similar to *Lagena clavata*. However, *L. mollis* is less swollen and has a finely striate surface. Only two *L. mollis* tests were observed (at ~50 meters water depth in Transect 1). Phleger (1952) and Parker (1952) did not report the presence of *L. mollis*.

Lenticulina sp.

Miliammina frigida (Phleger and Parker) 1952 (pl. 3, figs. 20a-b)

Miliammina fusca (H. B. Brady) 1870 (ser. 4, v. 6, p. 47 (286), pl. 11, figs. 2a-c, 3)

Nonionella auricula Heron-Allen and Earland 1930 (v. 50, p. 192, pl. 5, figs. 68-70)

Nonionellina labradorica (Dawson) 1860 (v. 5, p. 191, fig. 4)

Psammosphaera fusca Schulze 1875 (p. 113)

Psammosphaera fusca is generally large to very large. It is composed of coarse sand grains of varying mineralogy that are widely separated by cement; this gives the test a coarse finish. Typically the test has a single aperture. Abundances are low and it is observed at intermittent water depths (approximately 20 to 75 meters).

Pseudopolymorphina novangliae (Cushman) 1923 (Bull. 104, pt. 4, p. 146, pl. 39, figs. 6-8)

Pyrgo sp.

Quinqueloculina spp.

We use a broad species concept for *Quinqueloculina* spp., grouping together species such as *Q. seminula* and *Q. subrotunda*. The tests of species comprising this genus can be very large, oval in form, have a porcelainous finish, and exhibit four chambers on one side of the test and three on the other side. Specimens are typically white and opaque, but some are nearly transparent. Tests are often complete but some are broken, where the latter are perhaps not recent in age and having been reworked.

Quinqueloculina lata Terquem 1876 (p. 82)

Quinqueloculina seminula typical (Linné) 1758 (ed. 10, p. 786)

Reophax arcticus H.B. Brady 1881 (ser. 5, v. 8, p. 405, pl. 21, fig. 2)

Reophax arcticus is typical in form for the region. The test is small in size, uniserial, and with chambers that are wider than long.

Reophax curtus Cushman 1920 (Bull. 104, pt. 2, p. 8, pl. 2, figs. 2, 3)

This species is highly variable in form. *Reophax curtus* is large, coarsely arenaceous, coarsely finished, and composed of grains having variable mineralogy. Chambers generally increase slowly in size, although this can vary. It was rare to observe more than three chambers in a test. A delicate, neck-like final chamber composed of finer grains was occasionally seen. Fragments of *R. curtus* tests comprised of a single chamber were differentiated from *Saccammina atlantica* by observing an opening on the broader end of the fragment.

Reophax scottii Chaster 1890-91 (1892) (p. 57, pl. 1, fig. 1)

Incomplete tests of *Reophax scottii* (having ~4 to 8 chambers) were counted as a whole organism. In general, *R. scottii* was distinguished from *R. gracilis* by having more than 10 chambers. Some tests of *R. scottii* had greater than 15 chambers. Chambers of *R. scottii* tend to be nearly as wide as long. By contrast, *R. gracilis* tends to have chambers that are longer than wide. Given this criteria, no tests of *R. gracilis* were considered to be present in this study.

Saccammina sp.

Saccammina atlantica (Cushman) 1944 (S.p. 12, p. 5, pl. 1, fig. 4)

Saccammina atlantica is large, coarsely arenaceous, sometimes smoothly finished, and composed of grains having variable mineralogy. The test is teardrop shaped but lacks a distinct neck. The rounded base of the teardrop is closed, permitting *S. atlantica* to be differentiated from broken tests of *R. curtus*.

Saccammina difflugiformis (H. B. Brady) 1879 (v. 19, p. 51, pl. 4, figs. 3a-b)

Saccammina difflugiformis is small in size, has a teardrop shape that often tapers to a distinct neck, somewhat finely arenaceous, and having a smoothly finished surface. Occasionally the test contains large grains that are cemented flush with the surface. Some small tests of *S. difflugiformis* might be considered as gradational with *S. atlantica*.

Spiroplectammina biformis (Parker and Jones) 1865 (v. 155, p. 370, pl. 15, figs. 23, 24)

Spiroplectammina biformis is generally small in size, but having a variable number of chambers present after the initial whorl. The test is finely arenaceous and sometimes bent or twisted after the initial whorl.

Spiroplectammina typica Lacroix 1931 (n. 582, p. 14, fig. 9; n. 591, p. 6, text figs. 2, 3)

This species is widely variable in form. Some tests are comprised of a single, uniserial, planispiral whorl. Other tests have a limited number of biserial chambers extending from the initial whorl. The largest tests are compressed and broad in form, having many chambers after the initial whorl. Tests of *S. typica* tend to be white, have a salt and pepper appearance, and are somewhat coarsely arenaceous for their size.

Textularia earlandi Parker 1952 (Phleger, 1952 3: 80-89)

Textularia torquata Phleger and Parker 1952 (pl. 3, figs. 9-11)

The test of *Textularia torquata* is small, coarsely arenaceous for its size, compressed and often slightly twisted. *Textularia torquata* is biserial, having a slightly lobulate periphery, with rapidly enlarging chambers that make the apertural end the broadest.

Trochammina sp.

Trochammina advena Cushman 1922 (p. 20, pl. 1, figs. 2-4)

Trochammina inflata (Montagu) 1808 (p. 81, pl. 18, fig. 3)

Trochammina lobata Cushman 1944 (S.p. 12, p. 18, pl. 2, fig. 10)

Trochammina inflata is generally large in size, round to ovate in form, constructed of fine to coarse grains, having a smooth finish, and is typically orange in color.

Trochammina cf. *macrescens* (H. B. Brady) 1870 (ser. 4, v. 6, p. 51, pl. 11, figs. 5a-c)

Trochammina quadriloba Höglund 1948 (v. 24, pt. 2, p. 46)

Trochammina squamata Parker and Jones 1865 (v. 155, p. 407, pl. 15, figs. 30, 31a-c)

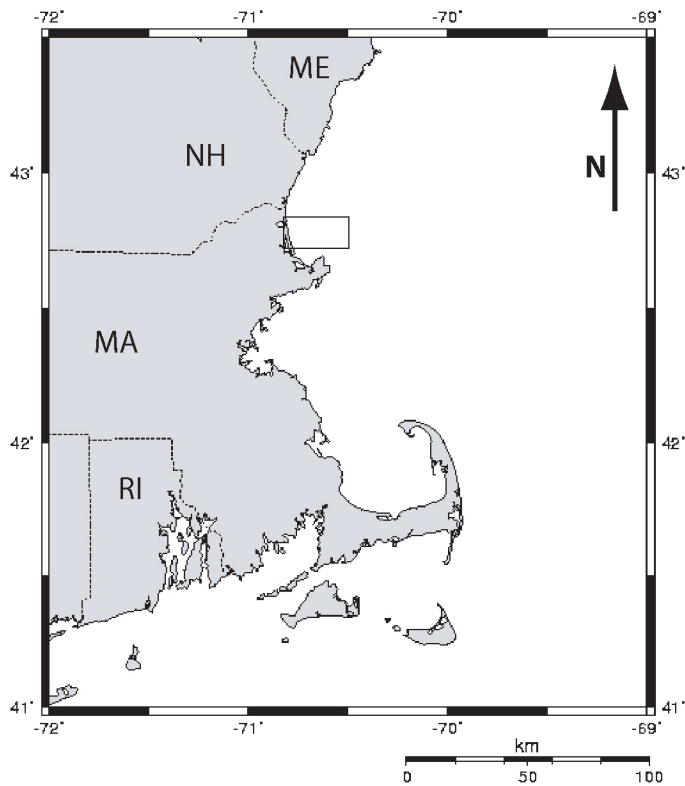


Figure 1. Merrimack Embayment, study area (box)
http://www.aquarius.geomar.de/omc/make_map.html

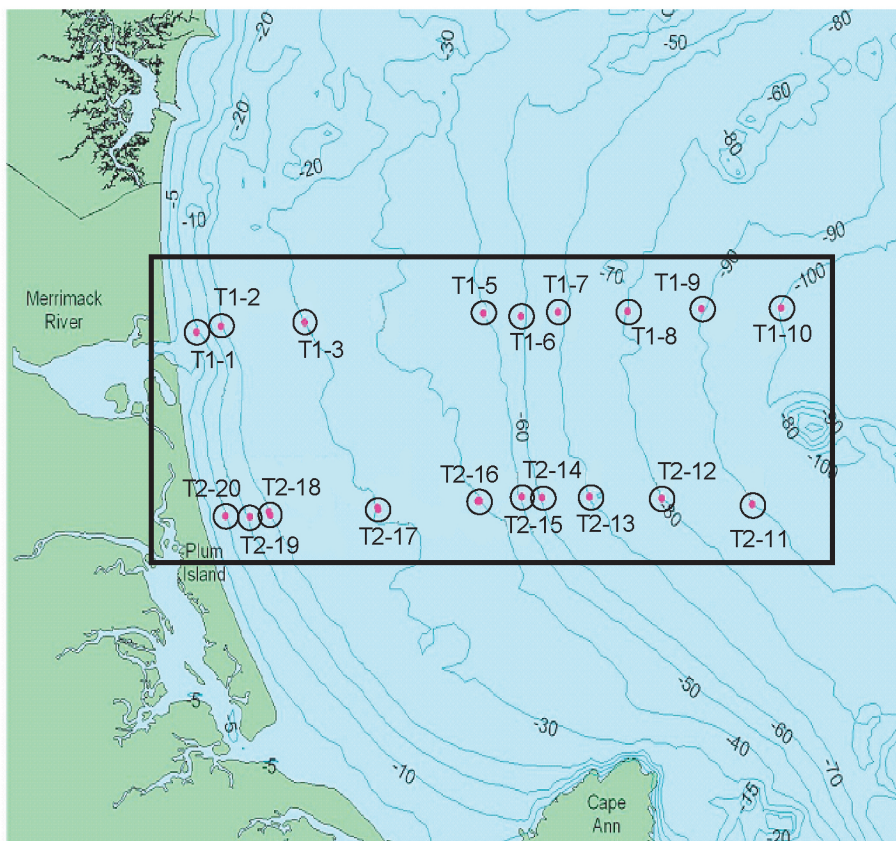


Figure 2. Merrimack Embayment, station locations

-  Bedrock / Lag Deposit
-  Sandsheet
-  North Oriented
-  Northwest Oriented
-  West Oriented

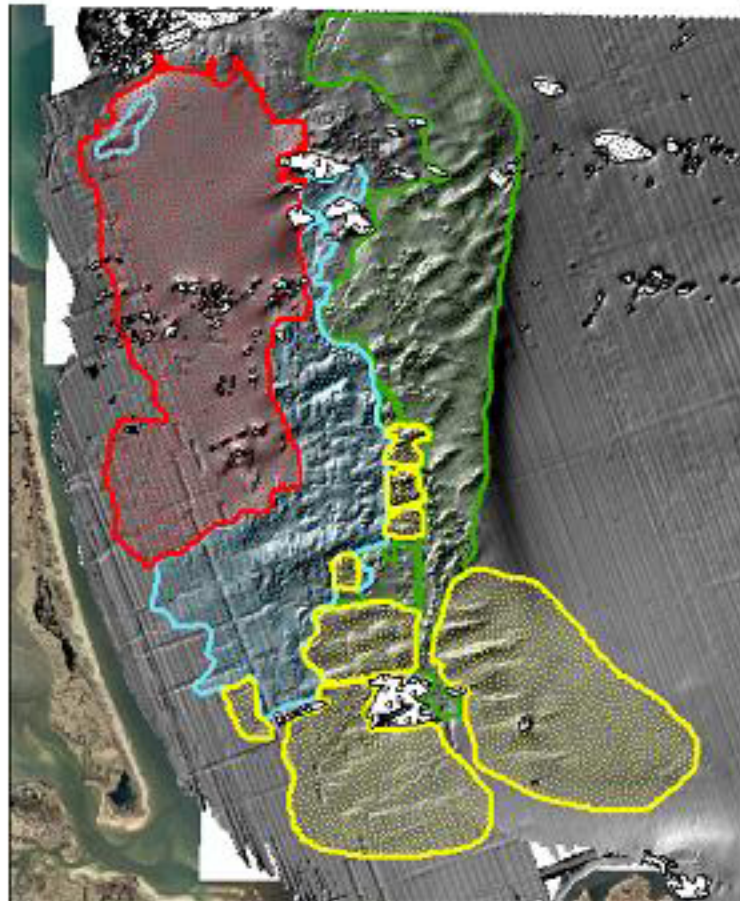
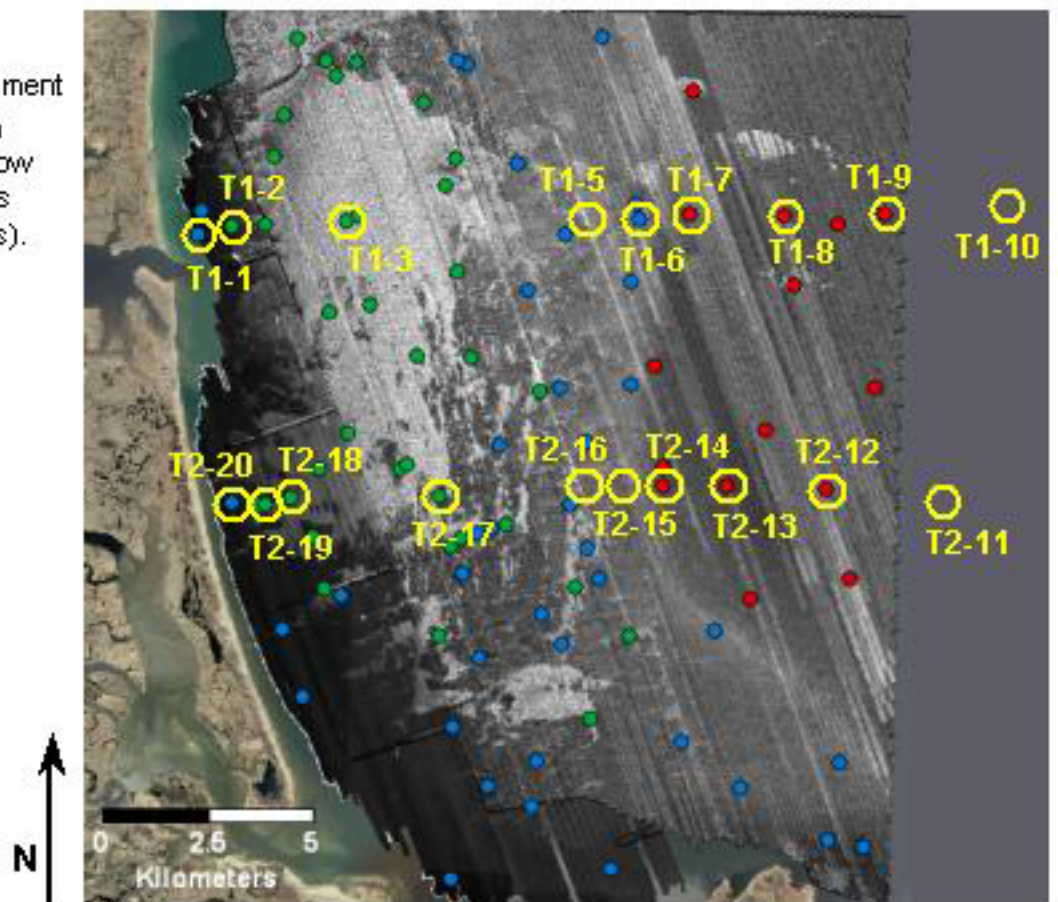


Figure 3. Merrimack Embayment Bedform types and locations (Image provided by C. Hein)

Figure 4. Merrimack Embayment Side scan sonar and station locations for this study (yellow circles; red, green, blue dots represent Boston Univ. sites). (Image provided by C. Hein)



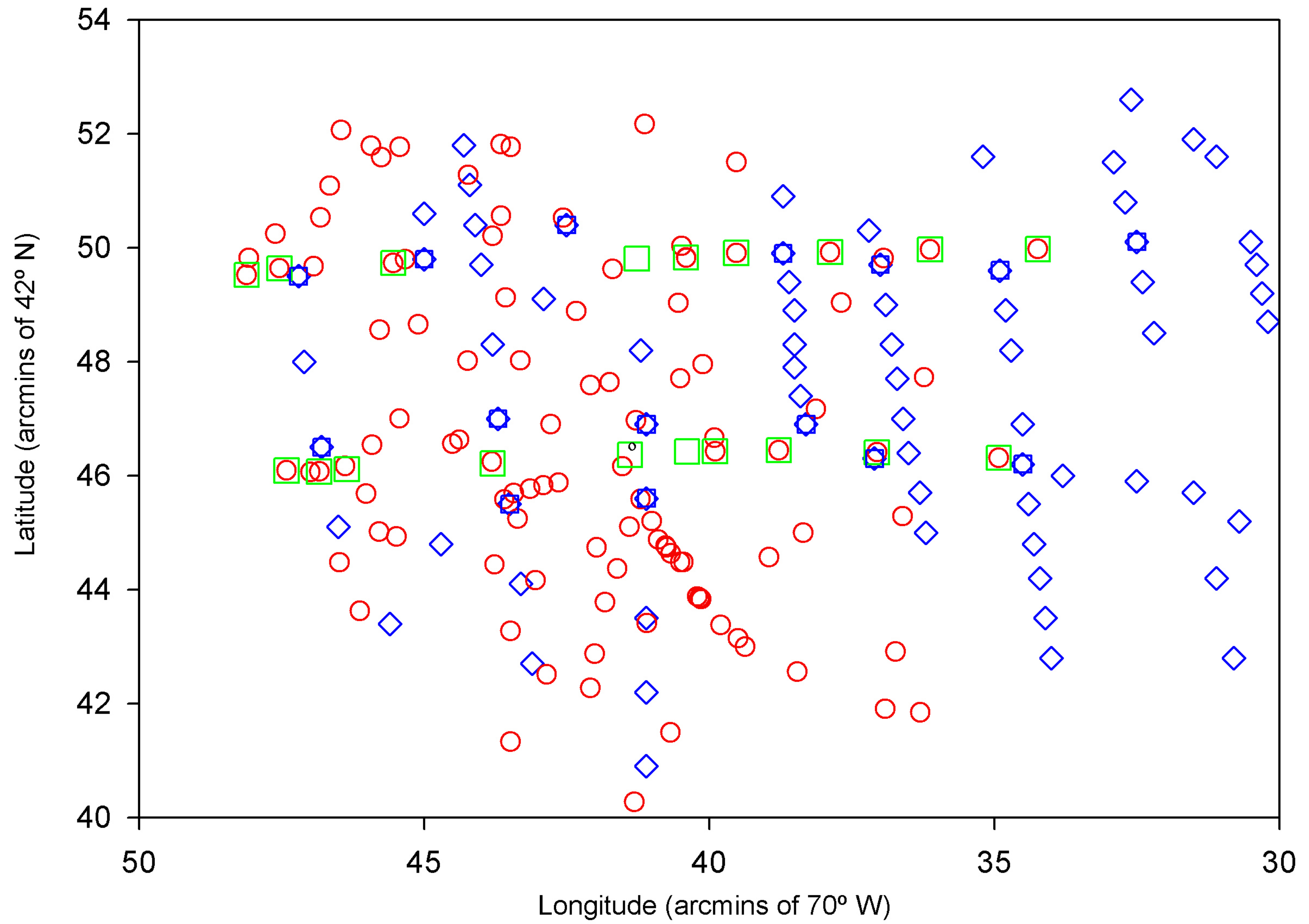


Figure 5. Sample sites for the Merrimack Embayment

- ◇ Phleger (1952) and Parker (1952) sites
- Boston University sites
- MMS (this study)
- Phleger (1952) and Parker (1952) "comparable sites" to this study

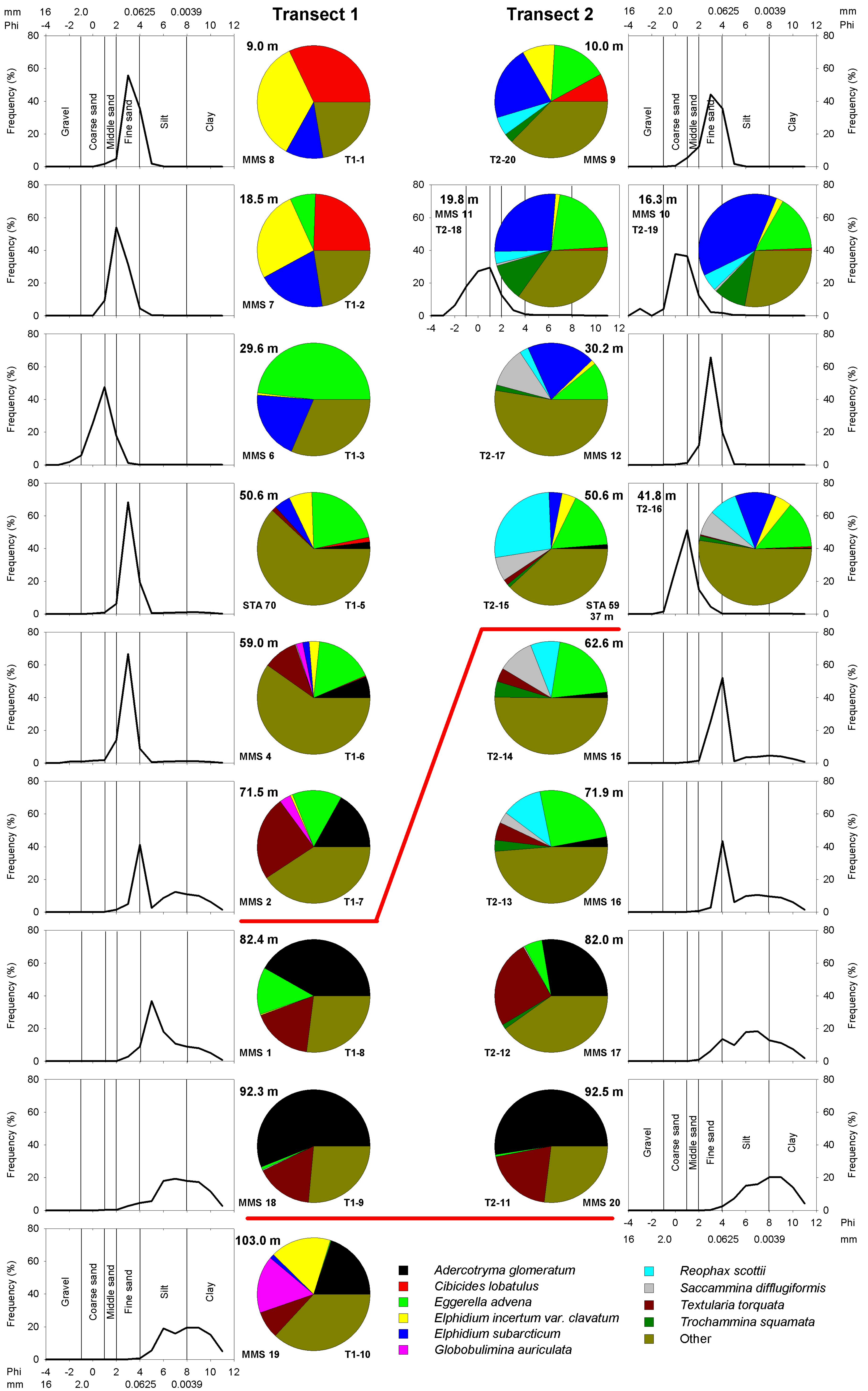


Figure 6. Foraminiferal assemblages of the Merrimack Embayment. For each sample the abundances of up to ten species are presented; all other species are grouped and depicted as "Other". Red lines enclose the six samples that were subject to dissolution. Grain size data provided by C. Hein.

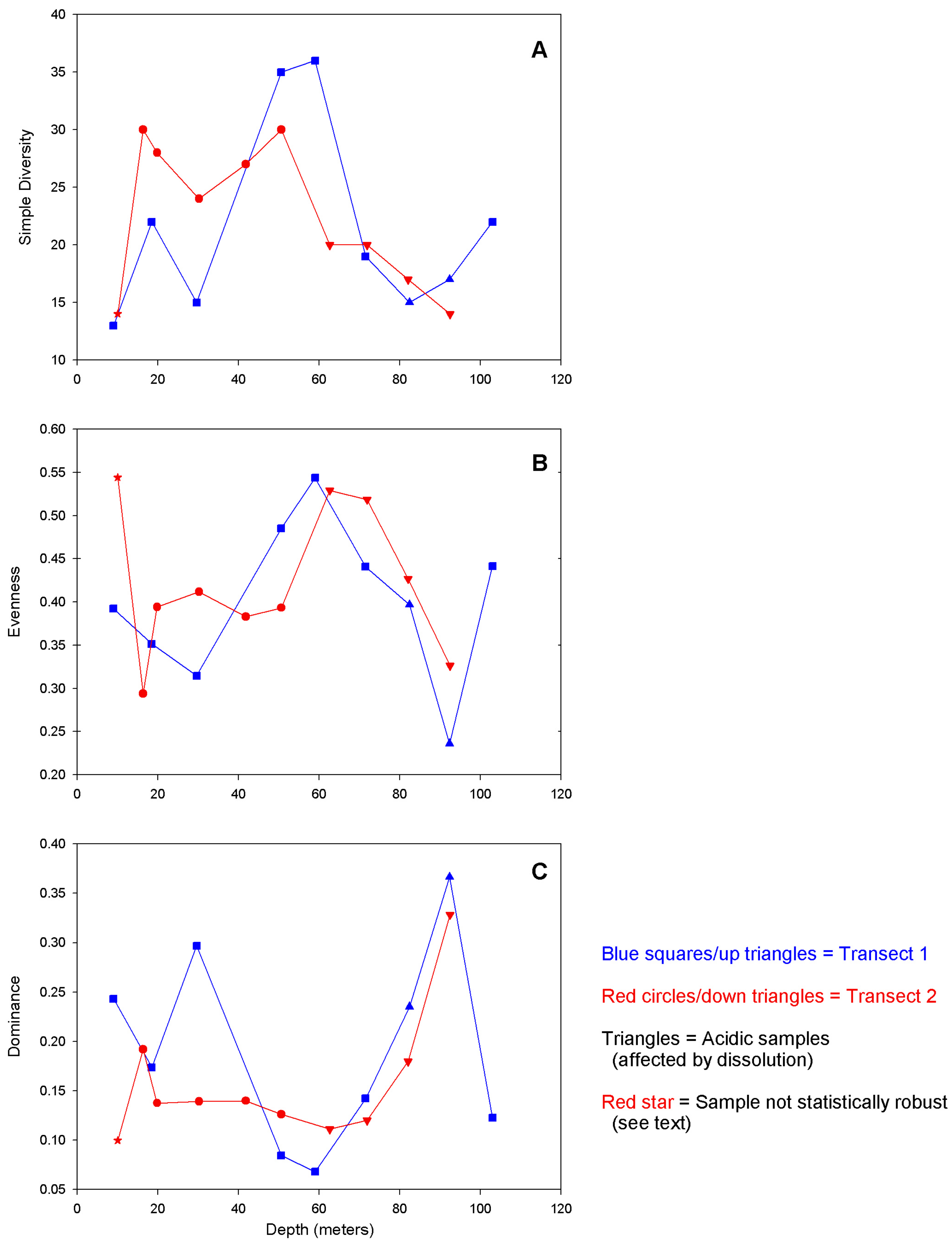


Figure 7. Benthic foraminiferal simple diversity (A), species evenness (B), and species dominance (C) for the Merrimack Embayment

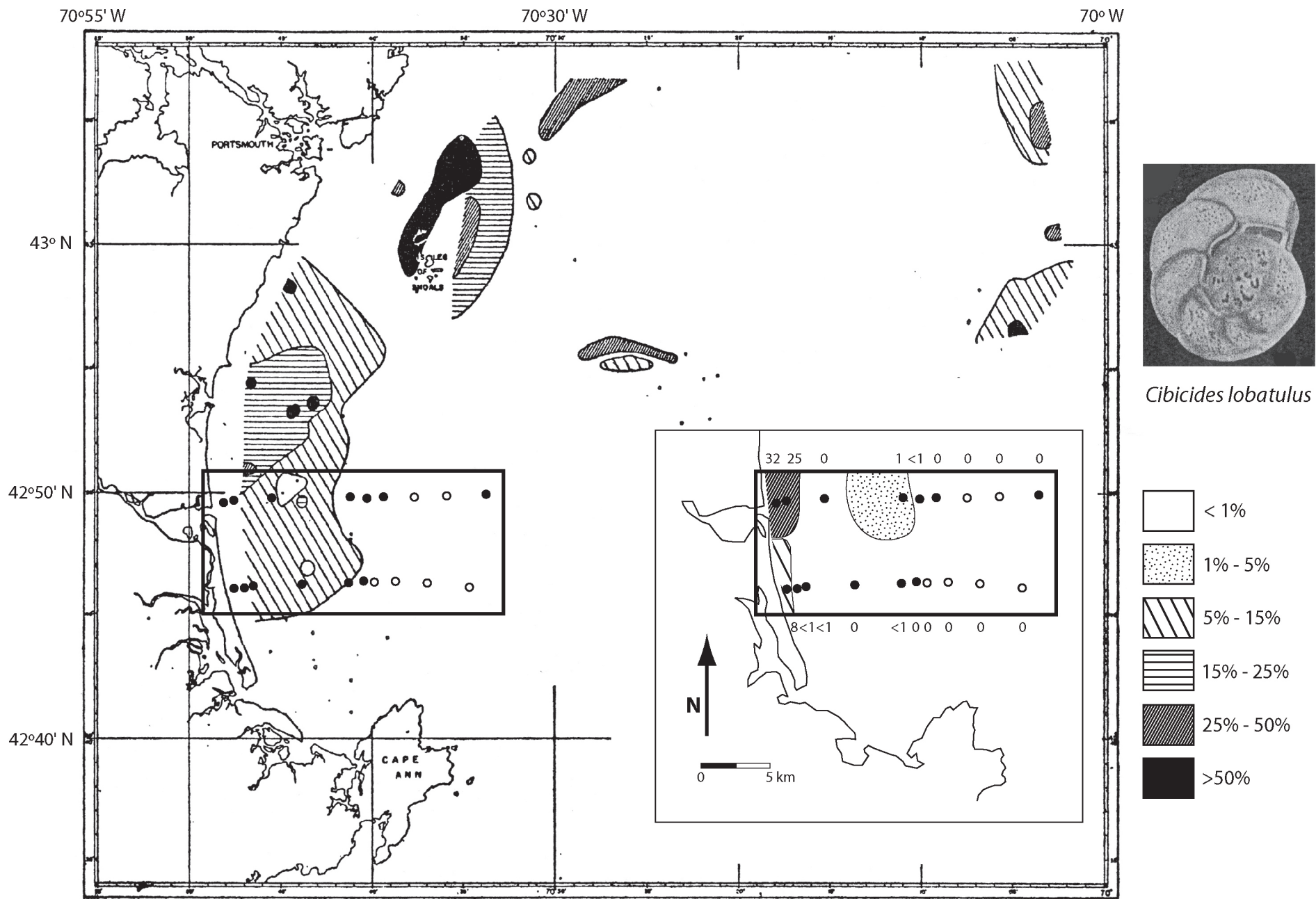


Figure 8. Distribution of *Cibicides lobatulus* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.



Figure 9. Distribution of *Adercotryma glomeratum* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

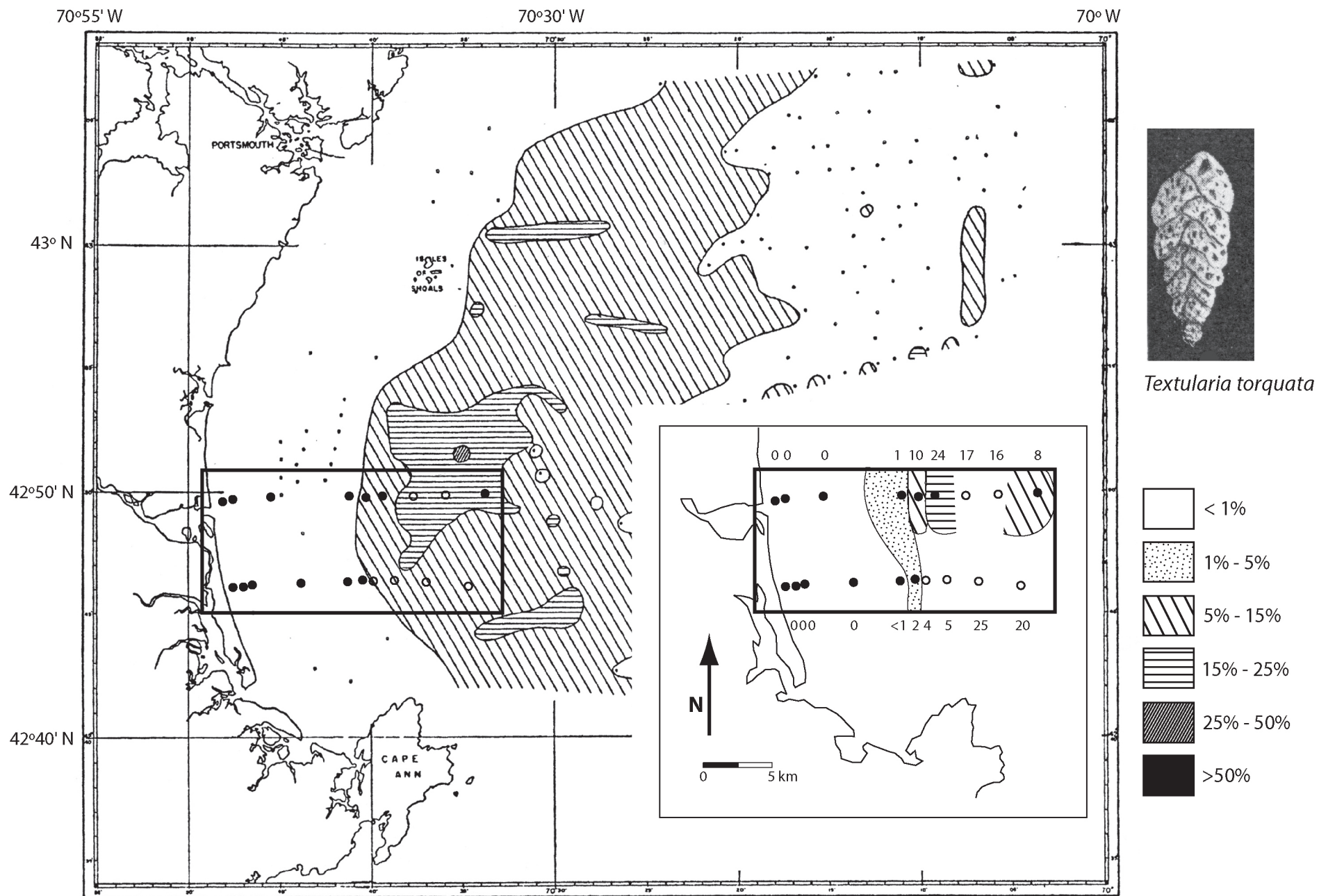


Figure 10. Distribution of *Textularia torquata* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

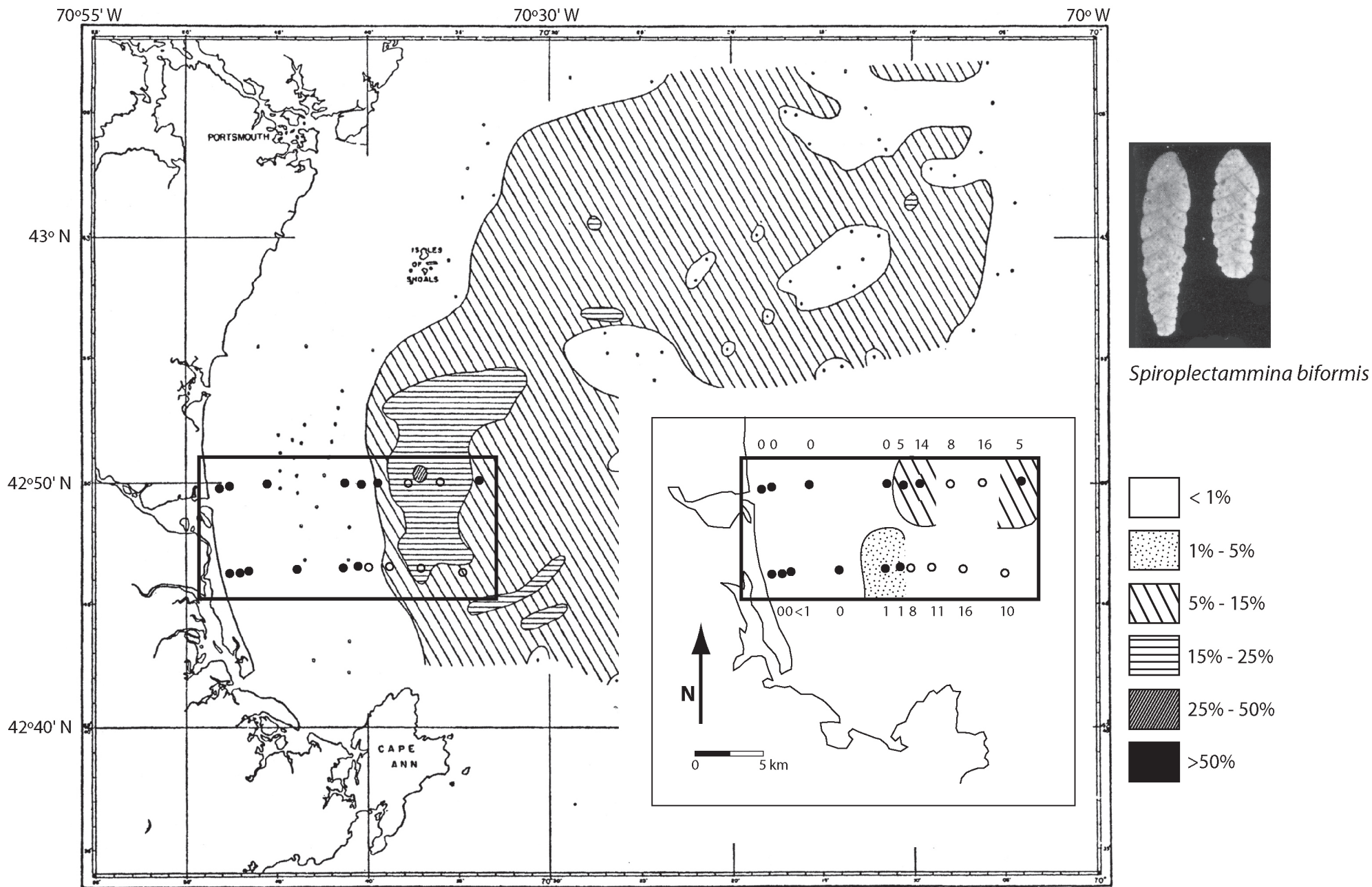


Figure 11. Distribution of *Spiroplectammina biformis* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

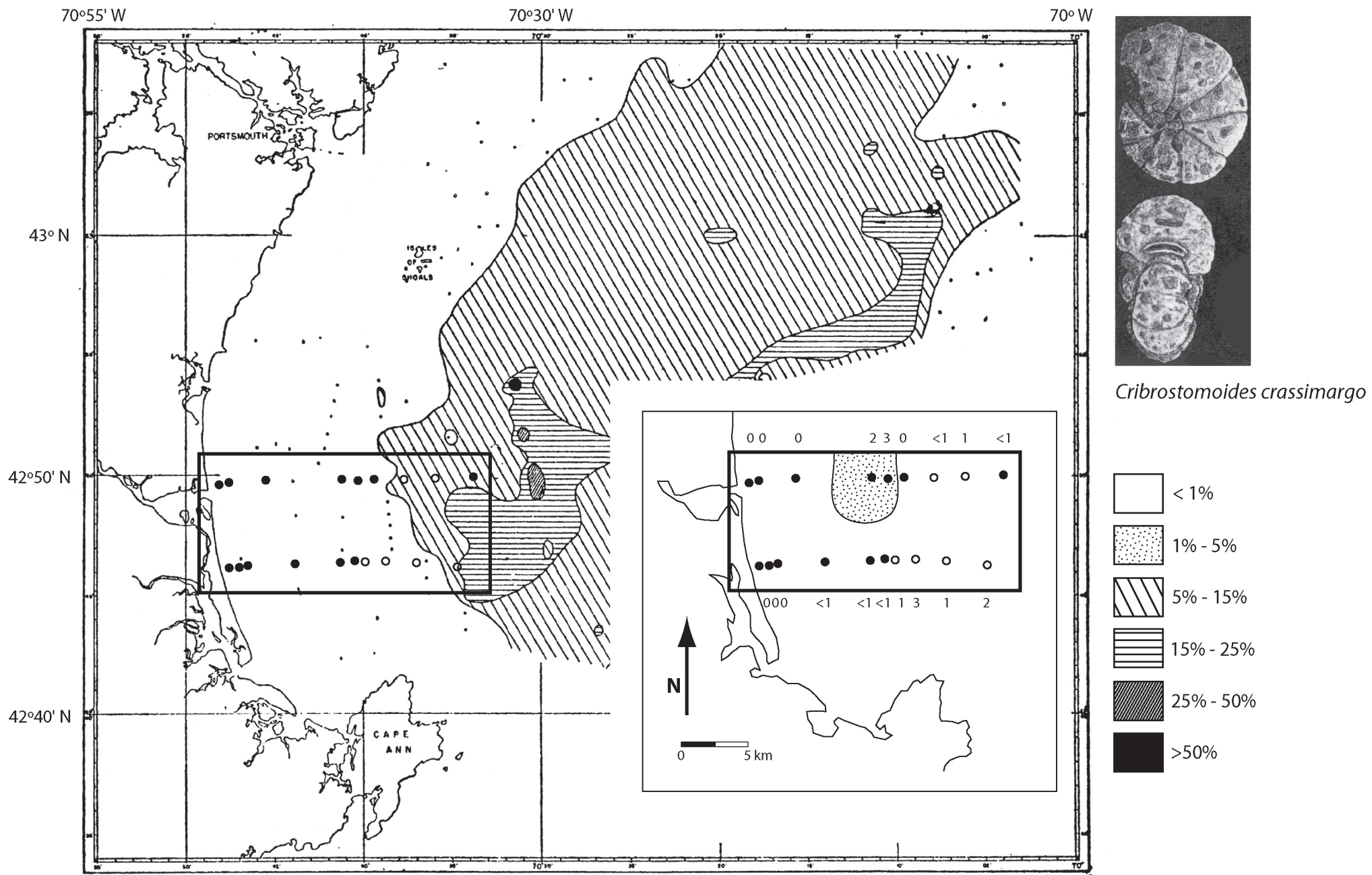


Figure 12. Distribution of *Cribrostomoides crassimargo* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

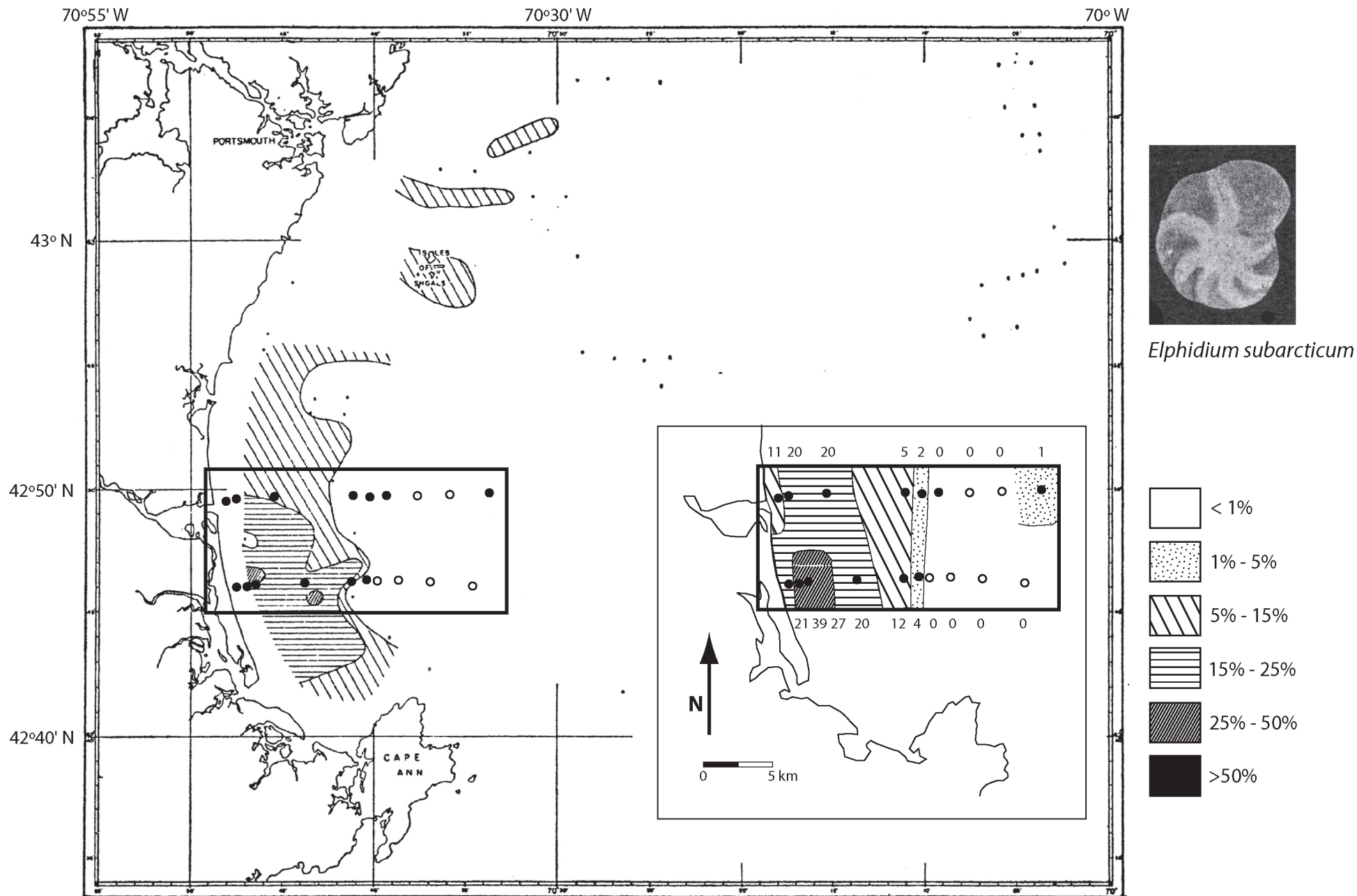


Figure 13. Distribution of *Elphidium subarcticum* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

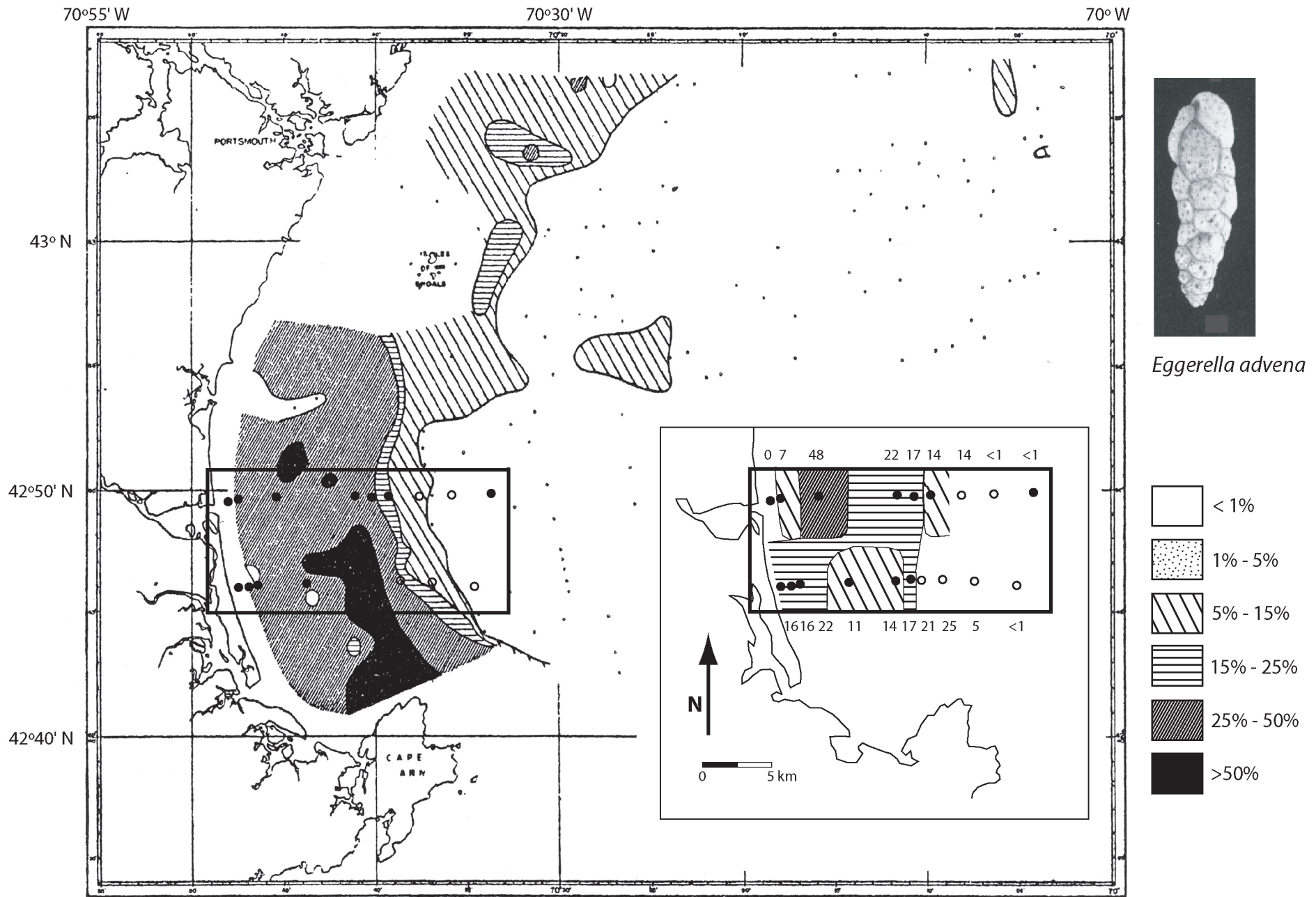


Figure 14. Distribution of *Eggerella advena* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

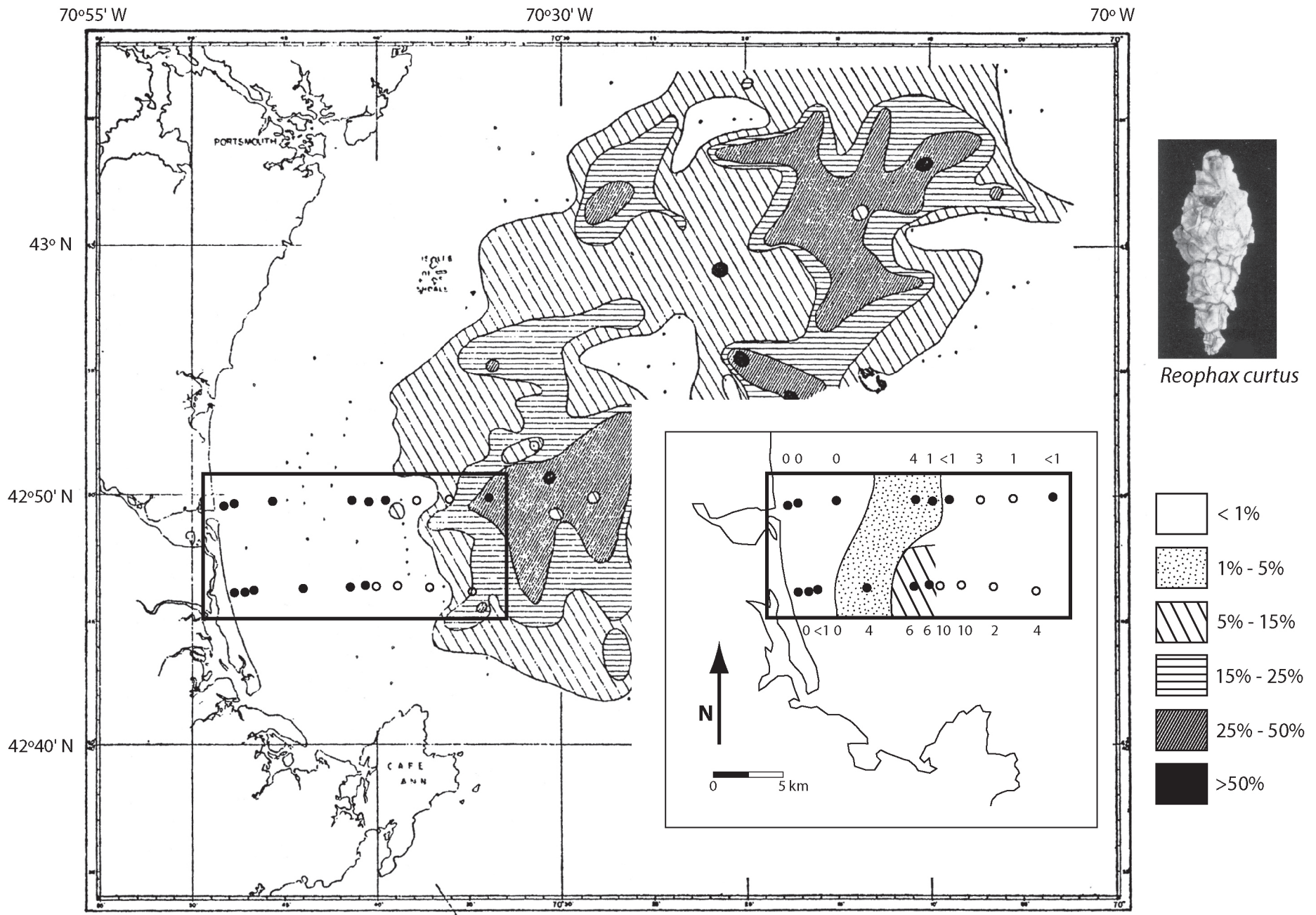


Figure 15. Distribution of *Reophax curtus* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

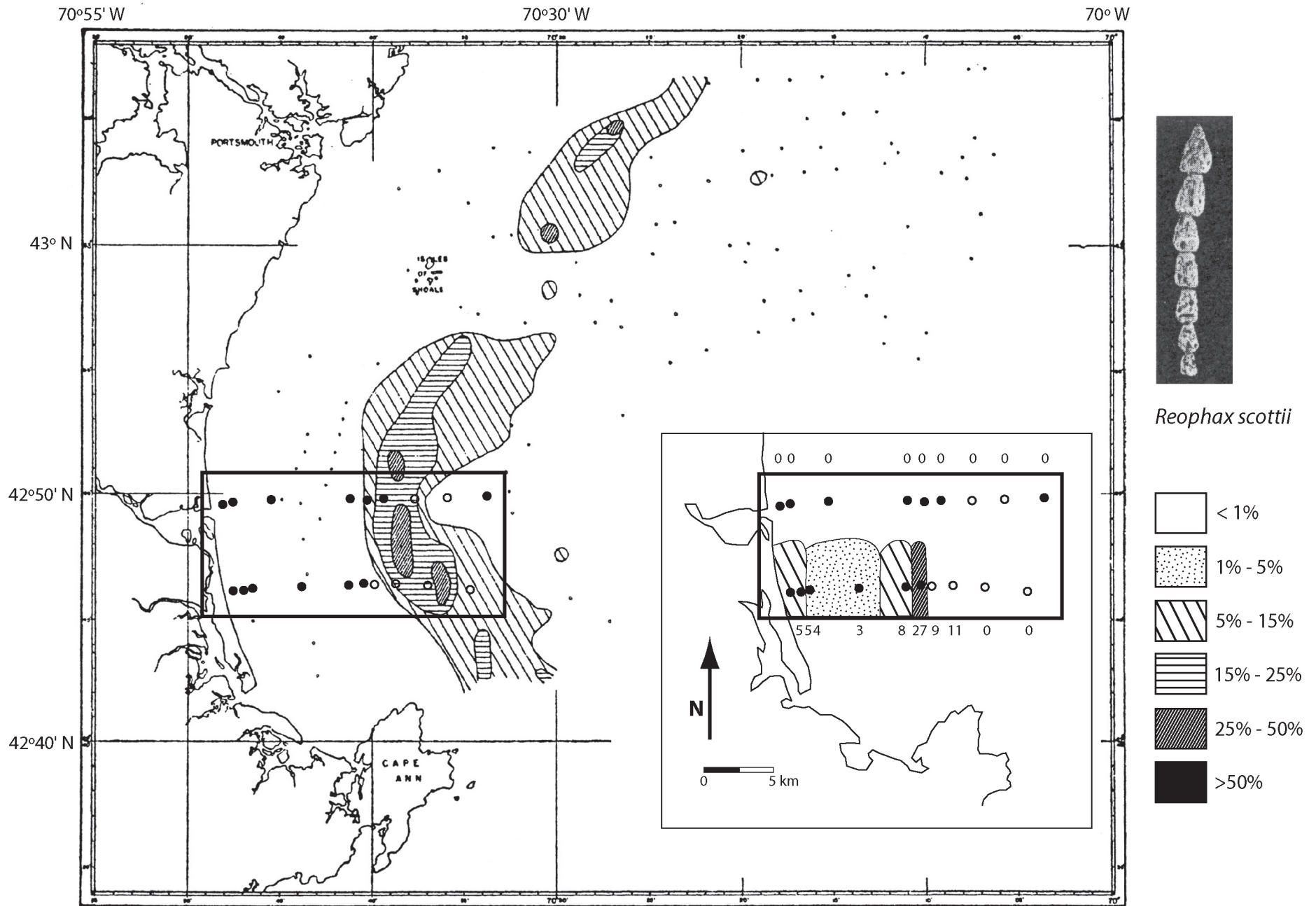


Figure 16. Distribution of *Reophax scottii* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

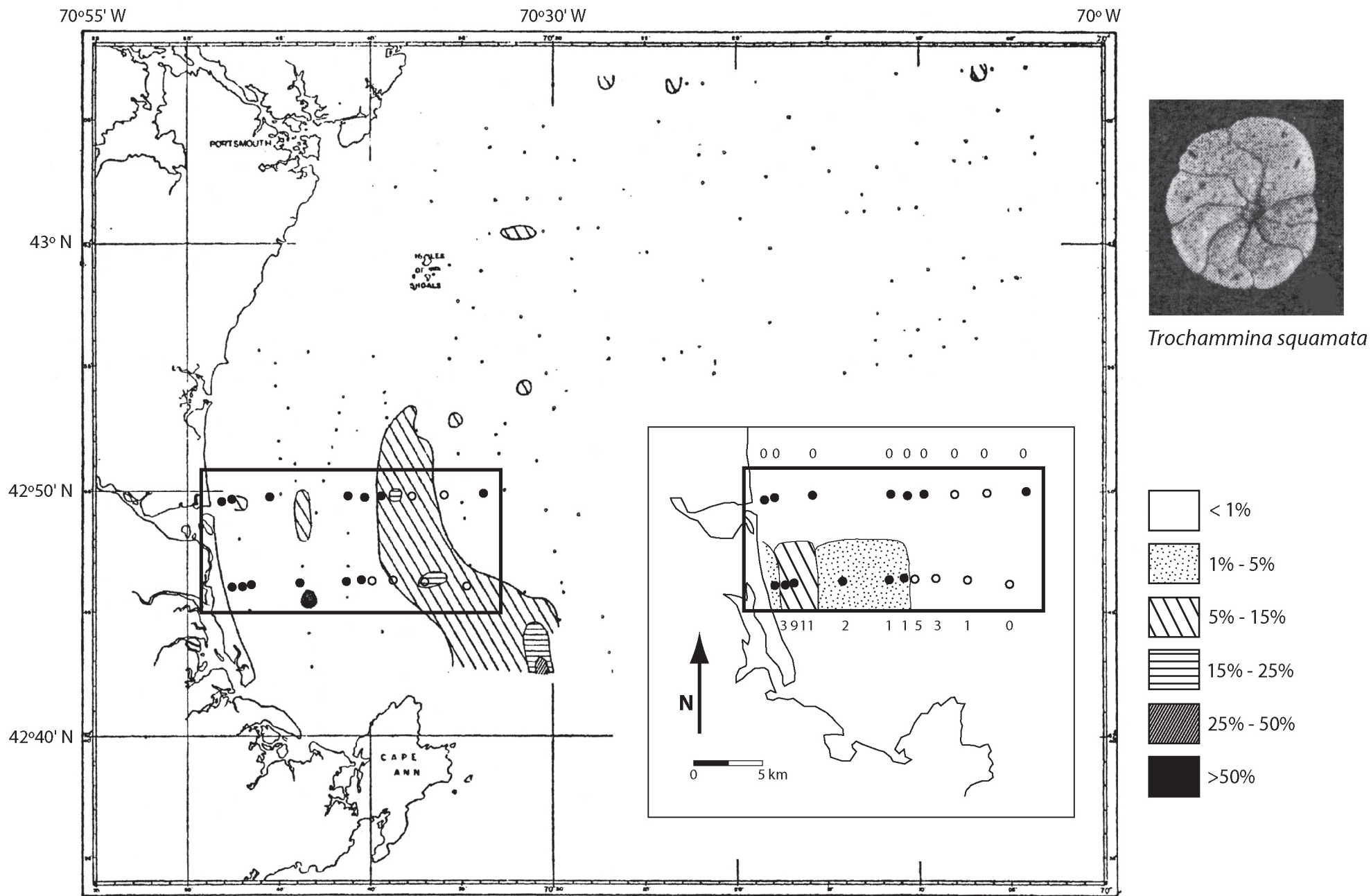


Figure 17. Distribution of *Trochammina squamata* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

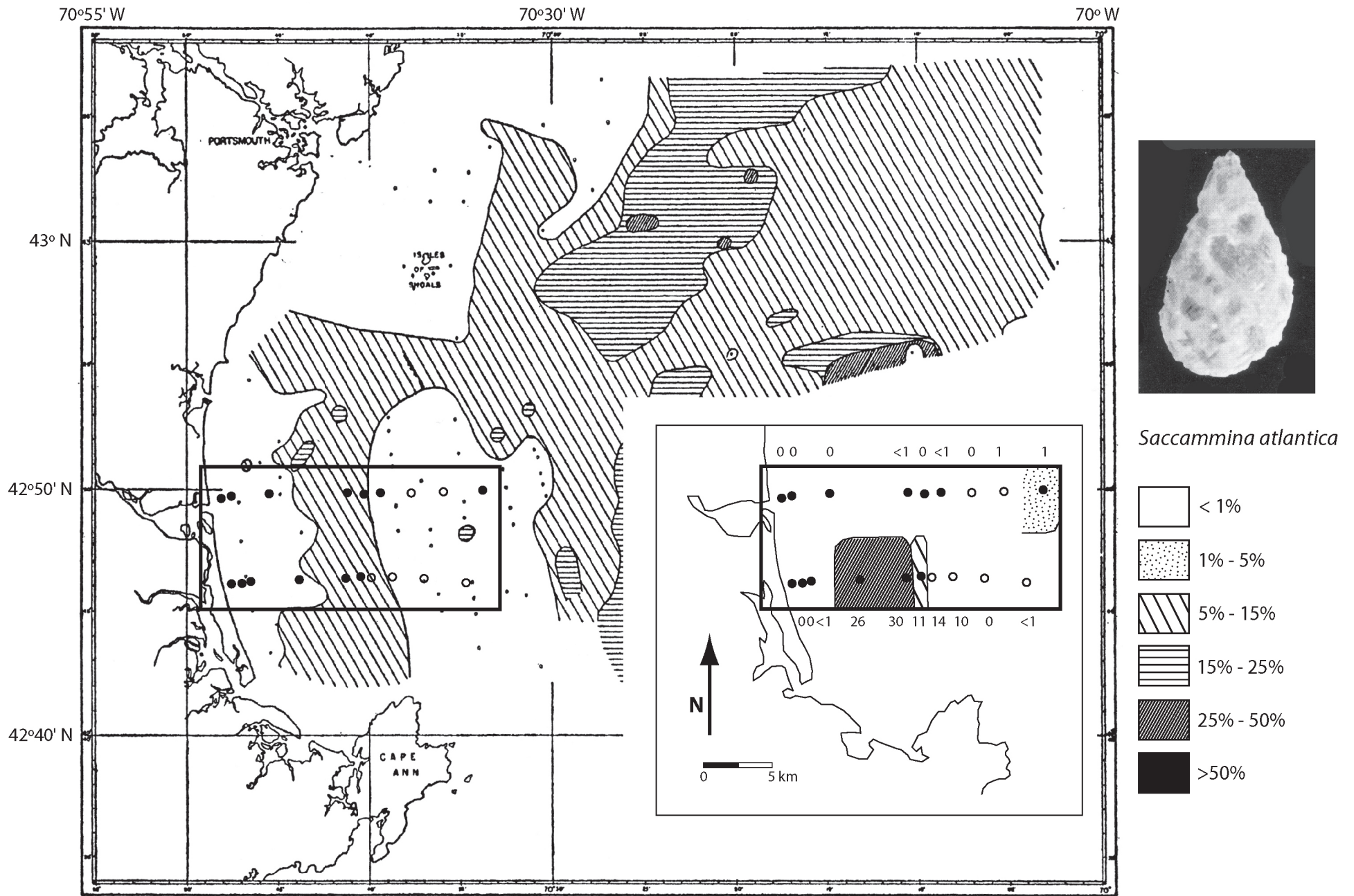


Figure 18. Distribution of *Saccamina atlantica* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

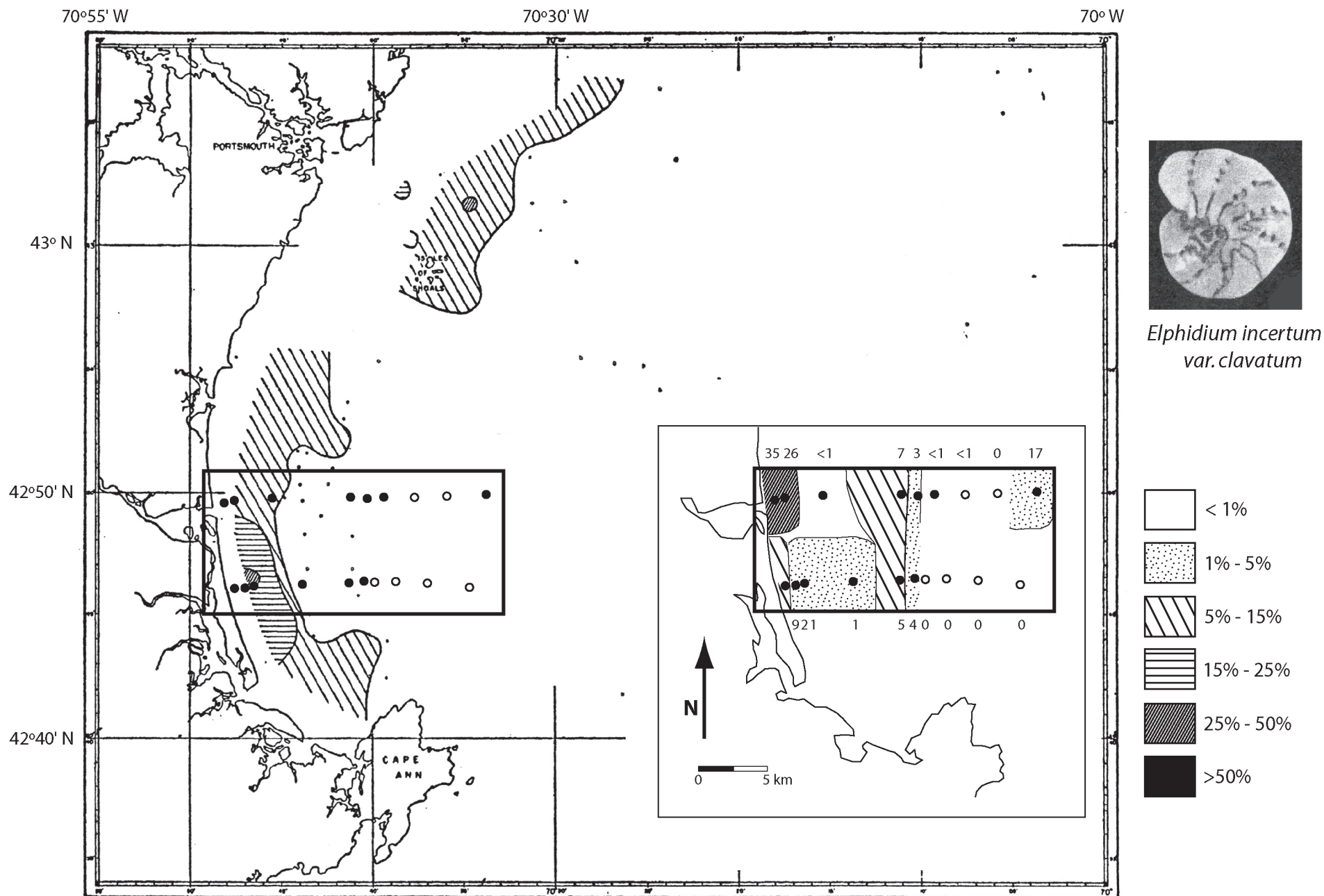


Figure 19. Distribution of *Elphidium incertum* var. *clavatum* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

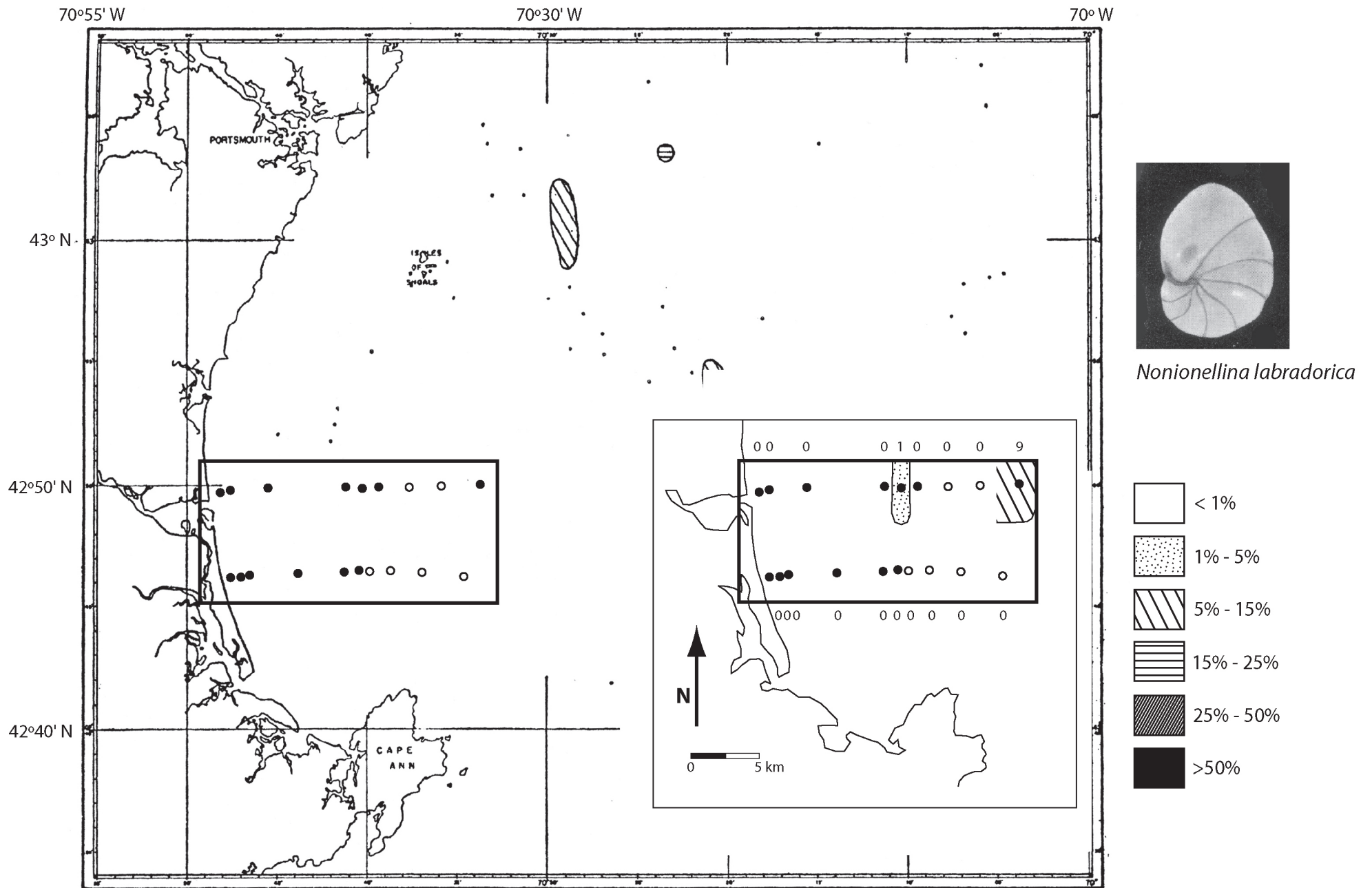


Figure 20. Distribution of *Nonionellina labradorica* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.

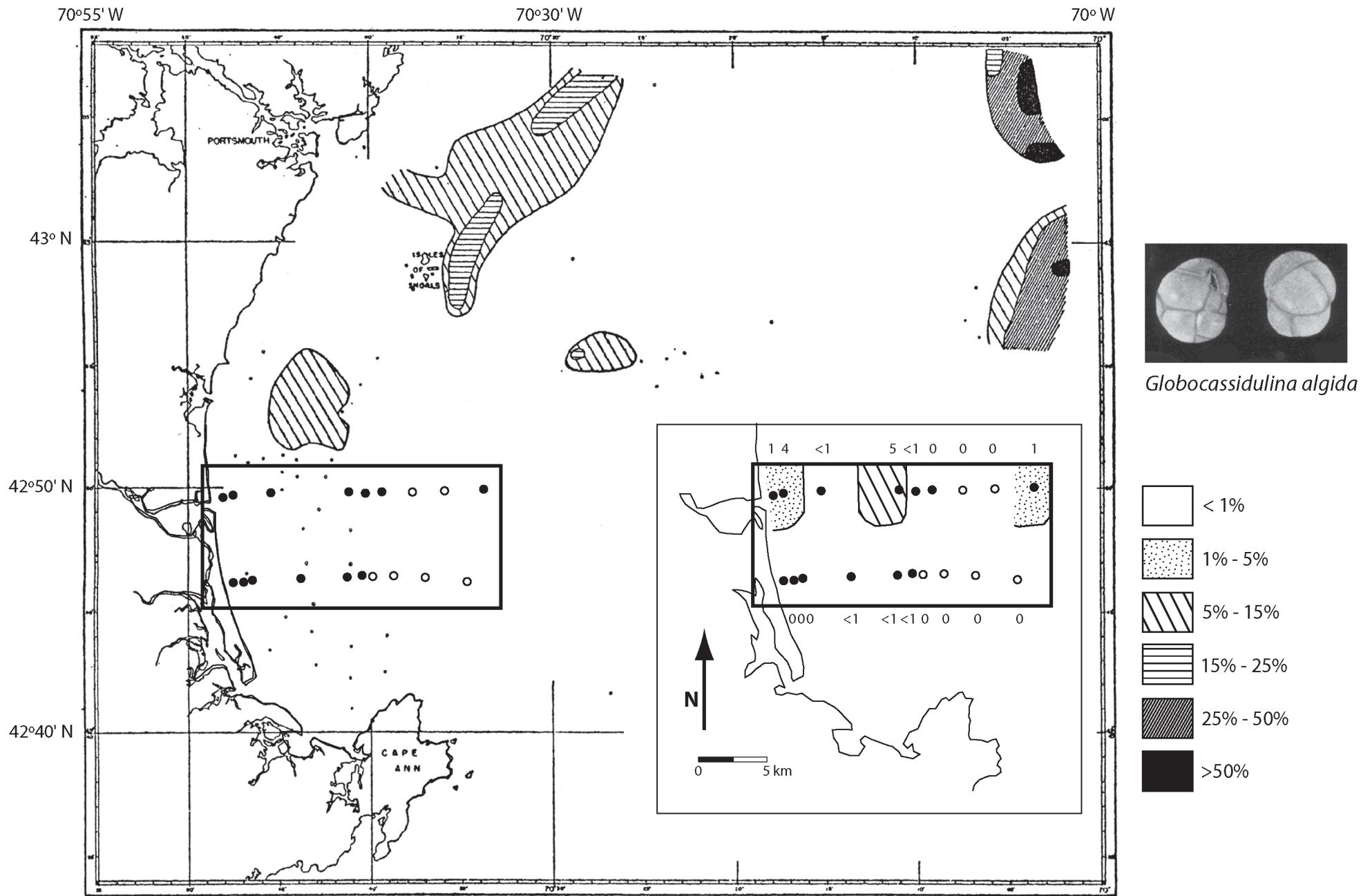


Figure 21. Distribution of *Globocassidulina algida* in percent of total population of benthic foraminifera; large map depicts 1946 data from Phleger (1952) and Parker (1952), inset map depicts this study (2005 data). Inset map: the 2005 study area (rectangle), closed circles depict sites where sample data was contoured and open circles depict sites where data was not contoured due to sample dissolution; percent abundances at each site are shown above and below the study area. Overlain on the large map is the 2005 sampling area and sites.