ADFEX

Environmental Impact Statement (EIS)

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EXECUTIVE SUMMARY

Submarine slides are one of the major threats to the security of seafloor structures, man-made reservoirs and seafloor communication and transportation networks. It is presently not possible to predict with certainty the forces exerted by a submarine sediment "avalanche" on structures anchored onto the seafloor. Observations collected as a result of a successful ADFEX (Arctic Delta Failure Experiment) will prove useful for a number of applications, e.g. developing mitigation strategies to avoid erosion of buried structures such as transportation [pipelines] and communication [cables] networks, designing seafloor-anchored structures that can withstand submarine slide impact pressures, stabilizing slopes along inhabited coastal areas. ADFEX offers a rare opportunity to obtain real time field data on various parameters that are germane to offshore risk assessment. Results are also directly applicable to the calibration of numerical models. Funding sources for ADFEX include government, university and private sector organizations.

The ADFEX is an internationally-supported Geological Survey of Canada research project that is aimed at improving our understanding of the dynamics of submarine slides, and the geological and engineering implications of this mode of sediment transport. This document details the ADFEX proposal i.e., the triggering of a mesoscale submarine slide along the edge of the Kenamu delta (Lake Melville, Labrador) under controlled conditions and the probable environmental impact of this event on the adjacent prodelta marine environment. Work on this proposal was initiated in 1985 and is proceeding in five phases. The Environmental Assessment Review Process is included under phase 4 along with further field work on site characterization and field method development.

Kenamu delta was identified as a suitable setting for the ADFEX in 1988 following the interpretation of results of surveys from five deltas distributed throughout the western end of Lake Melville. One important characteristic of the Kenamu area was the extensive evidence of natural failures noted in geophysical records and in sediment core samples collected from the prodelta environment.

A pilot experiment was conducted in Norway in 1989 as part of the ADFEX proposal exercise. In this pilot study, 200 kg of explosives were used to trigger approximately 10,000 m^3 of sediment that "ran out" into the lake basin for a distance of about 3 km at an estimated velocity of 7 m/s. No adverse environmental impacts were predicted for this slide and this assumption was confirmed during the post-slide monitoring program. ADFEX will mobilize approximately 50,000 m^3 of sediment that will flow into an offshore submarine channel. The slide will be monitored by an array of instruments deployed on the channel floor, remotely by three research vessels, and aerially over the detonation site by a time-lapse camera. A short lived radioactive tracer will be used in conjunction with several micropaleontological transport indicators to obtain estimates of sediment sources and transport volumes. The explosive specified for the experiment is an environmentally-benign material; its pressure wave will be mitigated by burying the charges using water-jet drilling technology. Additional mitigation of detonation effect is achieved by spreading the explosive over three lines consisting of 12 to 15 charges per line and by sequentially firing the lines using microsecond delays.

Environmental impact monitoring activity is integrated with the ADFEX itself. For example, for scientific and engineering purposes, it is essential to know over what area the slide has been deposited and to ascertain its physiochemical characteristics relative to in situ sediment. Pre and post-monitoring activity includes underwater photographic data that can provide useful information on the density of local macrobenthic populations. Similarly, Kenamu basin water masses will be monitored before and after the experiment to assess changes in water characteristics and to determine advective transport levels of particles that are resuspended by the slide.

The Kenamu River delta has evolved as a result of the massive deposition of river-transported sediment to the prodelta basin. A conservative estimate of the annual discharge of bedload for the river is on the order of 150,000 m^3 and about 250,000 m^3 for the suspended load. ADFEX specifications call for the displacement of approximately 50,000 m^3 which should therefore be replaced within a one year period.

Reflection seismic data show that much of the sediment that has filled the basin adjacent to the Kenamu delta is derived from large submarine slides. Historically there have been a number of very large mass flows into this basin, some of these have volumes estimated at more than one billion m^3. By way of contrast, the proposed ADFEX sediment volume is less than 0.005 % of that involved in these larger naturally-triggered slides. Side scan sonar imagery of the margins of the Kenamu basin suggest that slides having volumes on the order of one million m^3 occur every few years. Evidence of the recent activity of this sediment transport process is also suggested for the Kenamu channel area by piston core samples. Thus ADFEX may be viewed as an effort to control the timing and exact location of a process that occurs naturally in the same area.

Studies of the population density of living foraminifera indicate that the Kenamu prodelta environment is one of significant natural variability (i.e., a system having a comparatively wide "envelope of variation"). The low species diversity is a typical feature of shallow water estuarine and marginal marine habitats and may be modulated, in part, by the local mass sediment transport processes. Photographic surveys of the Kenamu prodelta seafloor show a generally sandy substrate covered by epifaunal tracks, and a low number of relatively large infaunal burrows. The sandy sediments of the lower part of the delta foreslope are virtually devoid of megabenthos. In the offshore, fine sediment substrate environment of the Kenamu channel/basin, worm specimens are common; in this area small mollusc species of the burrowing or infaunal variety are rare to common.

Certain weather conditions (high winds and fog) could affect the exact timing of the experiment. Based on pre-experiment survey data, the direct effects of ADFEX on the environment are considered to be minor. An area of 10,000 m^2 of the seafloor could be covered by the slide. But this is a normal and naturally-occuring impact. This condition can be compared to the dredging of the Terrington Narrows navigation channel located at the western end of Lake Melville which would create about 18,000 m^2 of disturbed sediment substrate. In regard to the benthos of the Kenamu prodelta, the overall impact of the ADFEX can be defined as "minor" (Duinker and Beanlands, 1986) in the sense that it will only affect a localized benthic population over a short period of time (one generation or less) and would not effect other trophic levels or the Lake Melville benthic population itself. No significant impact on the local Kenamu traditional fishery is anticipated because the species involved are transient. The key elements of ADFEX (i.e., the detonation and the submarine slide) are mitigated by: (1) the burial, spatial distribution and detonation sequence of the explosive charges and (2) by the timing of the experiment with respect to seasonally-modulated biological production and migration activity.

This proposal was presented and circulated to the communities of Happy Valley-Goose Bay and North West River. The project provoked casual but positive response by the public.

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1. INTRODUCTION

The Geological Survey of Canada and the Norwegian Geotechnical Institute (NGI), in a collaboration with five Canadian universities, have designed a field experiment whereby a known volume of deltaic sand would be moved offshore by means of an artifically-triggered submarine slide. The Arctic Delta Failure Experiment (ADFEX) is supported under the Canada/Norway Research Agreement, and also includes participants and support from the French geotechnical community (CEMAGREF in Grenoble France) and the Institute of Hydroengineering in Gdansk (Poland). The study integrates: (a) the science and technology with respect to initiating a submarine slide using explosives, (b) monitoring the behaviour of the sediment mass during its movement into deep water, and (c) the geological and engineering implications of this mode of sediment transport, and of the resulting deposits. The knowledge needed for predicting the behaviour of natural underwater slides on communication cables, such as a transatlantic cable, for assessing recolonization of substrates disturbed by anthropogenic activities such as dredging, ocean dumping and offshore mining, or for risk assessment for offshore structures such as drilling rigs and pipelines, are examples of applied deliverables.

The first part of this EIS report describes the mechanics of ADFEX: research and planning phases, (including the Norwegian pilot study, completed in 1989), scientific justification, project design, funding, organization, scheduling and reporting. The second part of the report describes the environmental setting of the Kenamu delta ADFEX site, including river delta, basin morphology, oceanography, climate, Quaternary history, and benthic ecology in relation to several adjacent prodelta environments. The third part of the report details the perceived and real environmental impacts, including the effect of the environment on the experiment, the effect of the experiment on the environment, steps taken to mitigate environmental effects, the planned monitoring program, and public information sessions.

2. ADFEX- ARCTIC DELTA FAILURE EXPERIMENT

2.1. PROJECT DESCRIPTION

ADFEX functions as a subactivity of Geological Survey of Canada (DEMR) project number 420-8626 (SEDFLUX), that involves research on the transfer of sediment from the landmass to the continental shelf. ADFEX is a proposal for triggering a mesoscale submarine slide along the edge of the Kenamu delta under controlled conditions. ADFEX addresses the following two objectives within project SEDFLUX:

(1) Understanding sediment distribution processes within the deltaic environment; and

(2) Relating the mechanisms in (1) to delta morphology and to the architectural growth of sediment facies.

Specifically ADFEX will allow Canadian expertise to be developed in the fields of submarine slide initiation, monitoring of the ensuing sediment gravity flow, development of predictive numerical and physical models from data collected (so that future costly experiments may not be necessary), and applying this information to the fields of geology and geotechnical engineering. The project was launched in 1985. Ten formal planning meetings have been held in Canada, Norway, Poland, France, and the United States. ADFEX has five phases: (1) site selection, (2) site investigation, (3) pilot project, (4) environmental approval, and (5) full scale experiment, including post slide investigations and environmental monitoring.

2.1.1. Phase 1

In phase 1, the initial site selected was Itirbilung Fiord, NE Baffin Island, where previous investigations had revealed extensive natural slide activity (i.e. 9 turbidity currents in 5 weeks) and a marine setting offering negligible environmental impact. Participants were, however, concerned with the logistics of working within a costly, remote and hostile environment. When pervasive subtidal permafrost was discovered during a reconnaissance survey in 1987, the site was deemed to be unsuitable for initializing a slope failure as the sediment was ice bonded. In 1988, SEDFLUX surveys of 5 Lake Melville deltas revealed one promising experimental site -- the Kenamu delta. It was found to have virtually all of the requisite features for ADFEX:

(1) sandy and steep foresets (bathymetric slopes near the river mouth) that presently prograde onto underconsolidated bottomset muds,

(2) one suitably sized submarine channel that would act to focus any delta front slide along its floor and towards a specific part of an offshore basin,

(3) no permafrost within the active part of the delta,

(4) no significant environmental risk,

(5) proximity to civilization and comparatively inexpensive logistics, and
(6) an environment in which natural sediment failures, with volumes over 100 to 1000 times larger than the planned ADFEX slide volume.

The Kenamu delta was selected as a suitable location to initiate a marine slide. Results of this experiment are considered fundamental to predicting actual slide runout distances, velocities and impact pressures of natural (e.g. earth-quake triggered) slides in Canadian offshore environments.

2.1.2. Phase 2

The second phase of the project focussed on marine surveys of the Kenamu basin based on cruises in 1988 and 1989 (Choquette et al., 1989; Long & Paradis, 1989). Data from cruise activities include a dense grid (> 600 line km) of high resolution seismic and sidescan sonar profiles, more than 100 grab samples tied both to UMEL bottom photography and sidescan sonar transects, ambient water characteristics measured using the AGC floc camera system, 20 Lehigh and piston cores, intertidal samples, cores and refraction seismics, and aerial photography. Results indicate a benthic environment with very low biomass that we attribute to sediment loading and fouling processes (for details see sections **3.7 & 4**)-- and can be considered a site of low economic and environmental impact risk. A final site investigation to collect necessary information to confirm the design of the explosive methodology is planned for the summer of 1990. Dynamic loading tests on collected samples will be used to help model the liquefaction front; Cemagraf will build a physical model of the Kenamu delta site to help optimize the location of the monitoring network and instrument moorings.

2.1.3. Phase 3

The third phase of the project involved the planning and execution of an ADFEX pilot study, to see: (1) if a submarine slide could be triggered with explosives, and (2) if the slide generated could be monitored. The first objective was considered crucial since explosives can also be used to compact sediment, rather than liquefy sediment. The pilot experiment was executed on a freshwater delta in the Storglomvatnet reservoir in northern Norway. Coordinates are 66° 45' 00"N, 14° 13' 10"E. Storglomvatnet is regulated for the production of wintertime hydroelectric power. The lake that forms the reservoir is presently 500 m above sea level, and the lake level is lowered during the winter period some 30 m through a sublacustrine tunnel to be discharged through a power plant into nearby Nordfjorden. Norsk Hydro is interested to ascertain the slope stability of the shoreline deposits during the annual lake lowering, and the possibility of tunnel blockage as a result of slide activity.

Two hundred kg of explosives (dynamite), placed on the lake bed (not buried as will be the case for the Kenamu Site), were used to generate the initial slide (for details see By et al., 1990). [At the Kenamu site the effect of the buried explosives on the water column is expected to be negligible: see section 4.] Approximately 10,000 m^3 of sediment was triggered to form a sediment mass that slid into the reservoir basin. Sediment traps were deployed before the experiment. Monitoring devices included geophones, acoustic sensors (a high frequency acoustic detection system), echo sounders, and accelerometers. The slide height (delta to lake basin) was about 150 m. The runout distance was about 3 km. The mass flow was observed to move at a velocity of about 7 m/s. No adverse environmental impacts were predicted and this was confirmed in subsequent observations. No surface waves were generated and no dead fish were observed. The geophones were moved by the mass flow some 80 to 90 m from their original positions.

The Norwegian Geotechnical Institute (NGI) looked into the generation of surface waves from submarine failures and slides. Their interest was in explaining why no surface waves were generated in the ADFEX pilot study. They examined the literature and concluded "Experience thus indicates that a submarine slide that generates substantial wave heights [> 1 m] must have a volume of more than one million cubic meters of sediment." As we plan to move only 5 % of this stated volume, the slide-generated wave in Lake Melville is expected to be insignificant.

NGI was also asked to provide some indication of the effect of explosives due to distance from the detonation. They found that the effect of explosives is reduced rapidly with distance from the detonation site. They provide the following general relationship between sediment disturbance or particle velocity, Vp (measured in mm/s), and distance, L (m), such that

(2.1.3.1) $$Vp = k\,(L/D)^{-0.5}$$

where k is a constant of proportionality ≈ 100 and D is the amount of explosives (kg). This relationship shows that the disturbance from an explosion drops off very fast, and thus the effect of explosives is concentrated in a small area.

2.1.4. Phase 4

With a site chosen that meets the established experimental design criteria, and having demonstrated the project's feasibility through the completion of a successful pilot project, phase 4 - the environmental assessment of the Kenamu site began. The EARP activity is scheduled to be completed by the fall of 1990. Information sessions with local groups and representatives will began in the spring of 1990 (see section 5.0), and will be followed through until the completion of the experiment when final results will be provided/presented to interested community groups. It is the intention of the project participants to keep all interested parties in the Lake Melville region informed and to share our results with them.

2.1.5. Phase 5

The final phase (5), the full scale experiment, is planned for the late summer (August) of 1991 given a successful conclusion to phase 4.

2.2 ADFEX JUSTIFICATION

Submarine landslides are among the major threats to the security of seafloor structures, man-made reservoirs and seafloor networks, and are also a very important mechanism for transporting sediment from deltaic to offshore prodelta environment. We presently know very little about the behaviour of the soil mass during its transport downslope. Numerical models presently employed to simulate such sediment transport, such as the turbulent flow model and the viscous debris flow model, could not be farther apart in their predictions. Consequently, we cannot presently predict with certainty the forces exerted by a submarine "sediment avalanche" on structures anchored onto the sea floor. ADFEX-collected data may be used for:

(1) developing mitigation strategies to avoid the erosion of buried structures such as transportation (road tunnels, pipelines) and communication networks (communication cables, defense listening posts and cable);

(2) designing structures anchored on the seafloor (petroleum industry well-heads) to resist landslide impact pressures;

(3) understanding relationships between submarine slides and wave generation in large

man-made reservoirs;

(4) stabilizing slopes in inhabited coastal areas;

(5) evaluating the recovery of marine benthos on a sterile substrate and on the impact of re-colonization of benthic productivity.

ADFEX will thus provide a rare opportunity to obtain real time field data on various parameters so important in offshore risk assessment, e.g. impact pressures on structures, information on the dynamic changes within a sliding mass, correlation of acoustic properties with mechanical & rheological properties. The project will also provide actualistic data useful in the interpretation of ancient mass flow deposits, observed in the rock record. A numerical model is one of the end-products of the project. In regard to modelling, we are presently are at the same stage, with respect to submarine slides, that we were regarding snow avalanches during the 1970's.

2.3 ADFEX PROJECT DESIGN

The full-scale experiment is planned for the summer of 1991. The selected site -- the Kenamu River delta -- already experiences natural submarine slides of substantially greater magnitude than that planned for the experiment. The experiment essentially schedules a sediment transport event around a carefully designed monitoring program. During the 1991 experiment, the plan calls for the use of dynamite to liquify, approximately 50,000 m^3 of shoreline sand that should flow along the floor of a submarine channel and onto a section of an offshore basin. A mothership (the CSS HUDSON), two launches, two boston whalers, a ship-based helicopter, and a host of moored instruments will be used to support the experiment and to monitor the flow dynamics of the slide and its environmental impact.

Project responsibilities are subdivided into four categories: (1) slide initiation, (2) flow dynamics, (3) pre and post slide surveys, and (4) numerical and physical modelling.

2.3.1. Slide Initiation

The liquefaction front of marine sediment is a key element in understanding how a sediment failure develops. This experiment also provides an opportunity to investigate how slide volume may be correlated with triggering energy so that inferences may be made about gravitational accelerations caused by earthquakes.

Parameters to be measured include:

(1) properties of the initial slide (slide volume and geometry, sediment properties, friction angle)

(2) pore pressure gradients (piezometer)

(3) density of sand (gamma logging)

(4) porosity, relative density (electrical resistivity)

(5) surface phenomena (high speed camera suspended from a balloon over the detonation site)

(6) ground accelerations, compressive & shear waves (seismographs)

Explosives used will be environmentally benign and either a pre-mixed dynamite or a two-component nitroglycerine explosive that can be safely pumped into the drilled holes. At least one licensed blaster will be on site. Between 40 to 100 m^3 of sediment can be liquified per kilo of explosives. Between 500 and 1000 kilos of explosives are to be used. Therefore, we anticipate that 50,000 m^3 of sediment will be liquified, in an elongate slide displacement. PVC water pipes will be emplaced by jet drilling to hold the explosives. The pipes will be 'jetted' into the sediment to depths of 10 m, the bottom 5 m will be filled with explosives. Approximately 10 to 20 kg of nitro will be emplaced per hole. Explosives are to be placed along three lines of holes oriented parallel to the present shoreline, with between 10 and 15 holes per line. The first line will be positioned some 15 m back from the delta lip, the second line 15 m back of the first line, the third and final line 5m back of the second line. The explosive placement and configuration is outlined in Figure 2.3.1.

A transect of peizometers (pore pressure sensors) will be installed to record pore pressure, both on shore (3 across x 3 deep) up to 50 m from the detonation site, and offshore (3 across x 2 deep) up to 400 m from the detonation site. A coastal survey will be undertaken at the detonation site, before and after the experiment, to allow calculation of the exact dimensions and volume of sediment liquified by the blasting sequence. In ADFEX, sediment is liquefied through blasting; in nature a variety of mechanisms can liquefy sediment, including earthquakes. Sediment is liquefied when the pore pressure suddenly increases and the sediment looses all internal strength, i.e. it has the properties of a liquid rather than a solid with internal strength. An electrical resistance net will be emplaced within the detonation site to monitor the speed of slide initiation. Sediment tracers (short-lived radioisotopes, see section 4) will be placed within the detonation area using jet drilling. Tracers will arrive at the ADFEX site through normal air transport in medical packages. Tracer sensors are to be placed at 200 m, 400 m, & 800 m from the detonation site. Wave height sensors are to be placed at a distance of 800 m to measure the propogation of surface waves.

2.3.2. Flow Dynamics

A major thrust of ADFEX is to measure and understand the flow dynamics of a submarine slide. The experiment will allow real-time data to be collected on the slide phenomenon and enable, for the first time, the runout distance of a slide to be measured along with velocity distributions in both the debris flow portion and the subsequent slide-related turbidity current. Due to the nature of the delta sediment, a cohesionless flow is expected to develop. Based on a rapid change in seafloor slope, fronting the Kenamu delta from greater than 10° to less than 1.5°, the transition from debris flow to turbidity current may occur between 1 and 3 km from the river mouth. The average thickness of the debris flow is estimated to be less than 2 m for the dense flow.

Figure 2.3.2 provides information on the geometry of instrument arrays within the Kenamu prodelta basin. Parameters to be measured will permit the calculation of the potential impact pressures on structures (for example a well-head) in the path of a submarine avalanche/slide. The eroding effect of the avalanche, i.e. the basal shear stress, will be obtained: important in designing and placement of pipelines and communication cables. A launch will be employed as the main acoustic station within 500 m of the detonation site at 45 m water depth. It will use an anchoring system to occupy stations 100 m apart across the Kenamu Channel. A network of geophones will be installed on the seafloor to monitor the arrival and duration of the gravity-driven mass flow that will be generated.

Measurements on the nature of the particle dynamics within the gravity flow (turbidity current), and the time needed for the water column to recover from the suspension of fine-grained bottom sediment that is associated with submarine avalanches, will be collected. The AGC Floc camera will be moored at about 6.5 km from the river mouth, to measure the settling velocity of particles after the passing of the turbidity current (Fig. 2.3.2). A grid of sediment traps will be placed along the predicted transport pathway. RALPH, a seabed-moored, multi-instrument package, will be placed ≈ 4.5 km from the river mouth. Likewise, the distribution and dissipation of internal motions set up by the slide and its associated sediment gravity flow is to be measured through current meter and thermistor chain moorings (Fig. 2.3.2). The mothership, the CSS Hudson, will conduct CTD-water sampling for water quality, and will deploy a bedload water sampler. The following parameters are expected to be obtained from this aspect of the experiment:

(1) initial slide volume (surveyed)
(2) flow width and thickness (time dependent) (traps, acoustics)
(3) impact pressures (loading plates)
(4) 3-dim. sediment transport (tracer, current meters, acoustics)
(5) flow velocities (current meters, geophones, acoustics)
(6) sediment loads (traps, water sampling, attenuance meter)
(7) flow density (acoustics)
(8) internal waves (thermistor chains, CTD-salinity-temperature-depth profiler)
(9) water column recovery (floc camera)
(10) surface waves (pressure sensor)
(11) basal shear stress (profiling current meter, RALPH)

2.3.3. Pre/post Slide Studies

It is essential to know precisely the morphology and the nature of the sediment involved in the slide and where it has been deposited (i.e. to distinguish the ADFEX gravity flow deposit from natural slide deposits that may have formed earlier in the year, associated with the spring river discharge flood). Such measurements will make it possible to correlate depositional history with geotechnical properties. Post slide surveys will provide data on variations in the physico-chemical properties of the slide sediment, once it has been deposited. The slide deposit will be described in terms of morphology, litho-stratigraphy, seismo-stratigraphy, and biostratigraphy. A grid of grab samples will be collected along transects 1 week before, then several hours to days after the experiment. Before and after transects will also include underwater photography using a ROV -- a remotely operated vehicle. The Kenamu basin water masses will be sampled before and after the experiment to assess changes in water quality. Coring will include vibrocores, box cores, and Lehigh cores. Analog and digital sidescan mosaics will be compared with those previously collected. The seafloor will be mapped in terms of reflectivity values before and after the slide. Parameters to be measured include:

(1) bottom morphology (swath sonar, sidescan sonar, high-freq. sounder)
(2) change in sediment type (sequential coring)
(3) sediment structures (core peels, x-radiography)
(4) change in geotechnical properties (of both loaded preslide sediments and remolded slide mass)
(5) seafloor reflectivity changes (Huntec ARM)
(6) seismic velocities (core measured)
(7) slide extent (radioactive tracers, bio and lithotracers).
(8) recolonization rates (sequential field work)
(9) a marker horizon will be defined for future sedimentation rate and monitoring measurements.

2.3.4. Model Development

A principle outcome of ADFEX involves the validation and elaboration of numerical models that are presently used to predict the fate and consequence of submarine slides (e.g. frictional, viscous & hydrodynamic models). Actual models are quite limited, although somewhat sufficient for the little data available for use in their computation. ADFEX will provide a unique set of real time data that will make possible the development and validation of a new model that will link the dense flow and the suspension flow. The new unified model could then be used to predict the behaviour of future slide motions for engineering risk assessment and for the transport of sediment by submarine landslides.

Physical modelling activities will be carried out in France by CEMAGREF. This group is building a scaled model of the Kenamu delta ready for use in early spring, 1991. Apart from scientific purposes related to numerical models and field evaluations, the physical model will be necessary to simulate various instrumentation deployment strategies. After the experiment, physical model testing will be carried out to evaluate the precision and accuracy of physical models in predicting mass sediment transport phenomena. CEMAGREF has proven, over the last 15 years, that it could simulate the morphology of submarine slides and turbulent flows and also the dynamics of snow avalanches (which are quite analogous to submarine slides).

2.4. ADFEX FUNDING

Canadian universiy participants are funded principally from an NSERC strategic grant. The Geological Survey of Canada will contribute through general operating funds and ship-based support. The Norwegian Geotechnical Institute has raised funds principally through contracts from the petroleum industry (Saga Petroleum, Petrobras) and Norsk Hydro. The French and Polish geotechnical labs (CEMAGREF, Inst. Hydroengineering, respectively) are raising funds principally from national government sources.

2.5. PROJECT ORGANIZATION CHART

ADFEX Project Officer: Syvitski (GSC/BIO)

Slide Initiation	Flow Dynamics	Pre-Post Slide Survey	Phys. & Num. Models
Norem/By (NGI)	Hay (Mem. U.)	Schafer (AGC)	Locat (UL)
Sawicki (E. Ang)	Heffler (AGC)	Forsberg (NGI)	Brugnot (Cemagref)
By (NGI)	Leblond (UBC)	Syvitski (AGC)	Béghin (Cemagref)
Locat (UL)	Long (INRS)	Locat (UL)	Norem (NGI)
Leroueil? (UL)	Norem (NGI)	Moran (AGC)	Schieldrop (NGI)
Konrad? (UL)	Syvitski (AGC)	Long (INRS)	
Kurfurst (TS)		Hein (UC)	
		Sharp (TS)	

2.6. PROJECT ACTIVITY LIST

2.6.1. Pre-experiment

-TFFS (field support) arrangements
-shipment of field equipment
-video recording of activities
-local hotel arrangements
-local arrangements with the coast guard

-local arrangements with military
-local arrangements with Kenamu and Goose Bay fishermen (transport and/or monitoring)

2.6.2. The Experiment

-Kenamu delta base setup
-navigation transponder setup
-laser ranging system setup
-assembly of drilling raft
-drilling holes for explosives array
-CSS HUDSON arrives
-deployment of moorings
-SPM survey (attenuance profiling, water sampling, floc camera profiles)
-setup hydrophone net
-setup sediment traps
-setup master launch stations
-setup sidescan sonar (fixed system)
-setup seismograph
-load explosives
-setup explosives triggering network
-check local fishing nets
-deploy tracers
-deploy balloon camera
-connect detonation system
-detonation
-monitor recording instrumentation
-fish monitoring (visual)
-aerial camera monitoring
-hydrophone array monitoring
-high frequency sounder (SPM) monitoring
-video recording of activities

2.6.3. Post Experiment

-archiving of records and observations at central data facility on HUDSON
-SPM monitoring
-tabulation of data items and disposition
-dismantling and cleanup of shore-based facilities
-equipment loading on CSS HUDSON
-ROV survey and bottom sediment sampling of tracers
-collection of sediment traps and other moorings
-box core and grab sampling survey
-Lehigh core survey
-geophysical surveys (CSS HUDSON and Launch)
-recovery of navigation transponders
-fish net check
-final demobilization
-public relations presentations (local) and media interviews

2.7. REPORTING

2.7.1. Internal Reports -- useful for communication between the scientists, engineers and technical staff actively working on the project. These reports are to be considered miscellaneous, non-published reports and will be made available to sponsors and management, released occasionally to fulfill reporting obligations. Authorship will be depend on the individual report.

2.7.2. Data and Technical Reports -- useful for communication between ADFEX scientists and the scientific community at large. These reports are to be considered published (limited review) and will be made available at cost. They will be self-contained, and shall include scientific objectives, detailed methodology, and a listing of pertinent data. Authorship will be depend on the individual report. All of these reports will be published on open file by the Geological Survey of Canada and as a Canadian Technical Report of Hydrography and Ocean Sciences. Examples include ADFEX: Kenamu site investigation; ADFEX: Slide initiation; ADFEX: Flow Dynamics; ADFEX: Pre and Post slide studies; and ADFEX: Numerical and Physical Modelling.

2.7.3. Scientific Manuscripts -- will consist of externally-reviewed papers that will appear as a special issue of an appropriate international journal. Such a volume will contain between 10 and 20 manuscripts.

ADFEX KENAMU SITE - ENVIRONMENTAL SETTING

3.1. KENAMU RIVER AND DELTA SYSTEM

The Kenamu River delta evolved as a result of the rapid deposition of sediment carried from the Kenamu River that drains a hinterland basin area of 4,403 km^2 (Fig. 3.1.1). The drainage basin is covered in a dense growth of spruce (76 %) and birch (21 %) trees (Anderson, 1985), and has a maximum relief of 305 m. Bedrock is composed principally of granite and granitic gneiss. The Kenamu is the third largest river entering Lake Melville (after the North West River and Churchill River (Fig. 3.1.2). Its total length, including tributaries is 613 km. Most of the river is between 50 and 75 m wide; at its mouth the river is 450 m wide. River bed sediment texture ranges from gravel to large boulders through much of its course, except for the last 10 km nearest the river mouth where the decrease in water velocity associated with the widening of the channel promotes the deposition of sand.

Since the Kenamu River itself is not gauged, its discharge characteristics must be estimated. Except for one station (the Naskaupi River), all of the Lake Melville hydrometric stations fall within the Churchill River system. The Minipi River drainage basin borders the Kenamu basin. Like the Kenamu River it is unregulated, and is therefore considered to be a good proxy indicator of the Kenamu River discharge conditions. The Minipi River basin is smaller (55 % the size of the Kenamu River basin) at 2,330 km^2. It is assumed that the precipitation falling on these neighbouring basins is the same and that a linear relationship based on relative drainage basin size can be used to estimate the rate of discharge for the Kenamu River (Table 3.1.1).

Almost 60 % of the annual discharge of the Kenamu River occurs during May, June and July (Fig. 3.1.3). Although the fluvial discharge is relatively low in August, a heavy rain storm can increase flow rates substantially for at least one or two days.

Table 3.1.1. Streamflow of the Kenamu River as predicted from seasonal flows measured in the neighbouring Minipi River.

Month	Mean Discharge (m^3/s)	(%)	Range (m^3/s)	Year	Mean Annual Discharge (m^3/s)	Maximum Daily (m^3/s)
		(1979-1986)				
JAN	37	2.7	30 - 45	1979	118	448
FEB	29	2.2	22 - 42	1980	128	479
MAR	23	1.7	16 - 29	1981	134	712
APR	31	2.3	15 - 48	1982	113	621
MAY	252	18.9	93 -389	1983	105	475
JUN	356	26.7	156 - 535	1984	??	??
JUL	171	12.8	96 - 254	1985	110	574
AUG	**108**	**8.1**	**77 - 163**	1986	86	279
SEP	**88**	**6.6**	**60 - 119**			
OCT	98	7.3	53 - 127			
NOV	88	6.6	44 - 134			
DEC	52	3.9	36 - 74			

A stream power approach is used to estimate the bedload carried by the Kenamu River to its river mouth, i.e.

(3.1.1) $P = \rho g Q S = (10^3) (10) (Q) (3.2 \times 10^{-4}) = 3.2 Q$

where P is stream power, ρ is the fluid density, g is the acceleration due to gravity, Q is the discharge, and S is the slope of the river bed (i.e. 31 km inland equals a rise of 10 m),

(3.1.2) $\tau \ddot{u} = P/B = 3.2 (Q/B)$

where τ is basal shear stress, $\ddot{u}$ is the mean flow velocity, and B is the hydraulic radius of the river, (3.1.3) $j_B = (\rho_s/(\rho_s - \rho))(3.2Q/B)(e_B/(g \tan(f))) = (1.61)(3.2Q/B)(0.1/6.3) = 0.082Q/B$

where j_B is the linear rate of bedload, ρ_s is particle density, f is the friction angle, e_B is the entrainment factor,

(3.1.4) $J_B = j_B B = 0.082 Q$ in kg/s

where J_B is the cross-sectional rate of bedload. If a critical threshold discharge for bedload initiation of 50 m^3/s is assumed, given the very low slope for the lower portion of the Kenamu River, then the annual discharge of bedload for the Kenamu River is 150,000 m^3 (Table 3.1.2). The suspended sediment load for the Kenamu River Basin can be estimated using sediment yield estimates for the coast of Labrador (Binda, Day & Syvitski, 1986) of approximately 39 $T/km^2/year$, giving us an annual estimate of 100,000 m^3 of sediment. Thus the total sediment volume (suspended plus bedload) discharged by the Kenamu River is ≈ 250,000 $m^3/year$.

The total width of the Kenamu delta is 2.2 km of which only 800 m is active at any one time. Delta foreset beds prograde into water depths of between 10 and 15 m. Based on annual bedload estimates, the rate of delta progradation is approximately is 10 to 30 m/year. ADFEX plans call for removing approximately 50,000 m^3 (10 m deep x 40 m inland from the delta lip x 125 m in length across the delta). Thus the volume of sediment planned to be removed will be replaced naturally within a one year period.

Table 3.1.2. Sediment load estimated for the Kenamu River

Month	Mean Discharge (m^3/s)	Bedload (kg/s)	Bedload (m^3)
JAN	37	0	0
FEB	29	0	0
MAR	23	0	0
APR	31	0	0
MAY	252	21	32120

Month	Mean Discharge (m^3/s)	Bedload (kg/s)	Bedload (m^3)
JUN	356	29	44370
JUL	171	14	21410
AUG	**108**	**9**	**13760**
SEP	**88**	**7**	**10700**
OCT	98	8	12230
NOV	88	7	10700
DEC	52	4	6120
TOTAL			**151,410**

A summary of survey gillnetting catch data (Riche, 1965; Anderson, 1985) suggest that over 90 % of the fish caught are the white sucker (*Catostomus commersoni*) and the longnose sucker (*Catostomus catostomus*), although the Atlantic salmon (*Salmo salar*), eastern brook trout (*Salvelinus fontinalis*), threespine stickleback (*Gasterosteus aculeatus*), lake whitefish (*Coregonus clupeaformis*), round whitefish (*Prosopium cylindraceum*), and rainbow smelt (*Osmerus mordax*) have also been caught using this technique. According to Blair (1943), the salmon migration on the Kenamu River extends from about June 25 to the end of July. During this period, a potential (i.e. estimate) 15,000 salmon may traverse the Kenamu system (Riche, 1965). Angling activity is almost non-existent in the lower river due to the slow water velocity that creates poor angling conditions (Anderson, 1985). During both the August 1988 and July 1989 field operations, "traditional" gill netting activity (B. Slade, pers. comm., Dept. Fisheries and Oceans, St. John's, Nfld.) involving up to five nets were observed along the edge of the river delta.

3.2. BASIN MORPHOLOGY

A delta consists of topsets (sediment layers that are relatively flat lying and reflect fluvial processes), underlain by foresets (steeply dipping sandy layers that reflect rapid deposition of bedload under the action of gravity and form just offshore of the edge of the delta lip). Both topset and foreset sediment build out (prograde) onto soft bottomset muds. The Kenamu foresets have slopes between 13° and 25°, across a water depth interval of between 10 and 20 m. There exists a large submarine channel, informally called the Kenamu Channel, that has its head about 200 m offshore from the edge of the Kenamu delta, in 25 m of water, and therefore lies directly seaward of the modern Kenamu delta foresets. The channel is ≈ 700 m wide and maintains this form for 6 km, until a water depth of 85 m. Thereafter the channel flares out and disappears into what is informally called the Kenamu Basin. The basin is between 5 and 9 km wide with depths of between 150 and 160 m. Figure 3.2.1 provides a simplified bathymetry of the Kenamu Channel and the Kenamu Basin. In addition to the detailed hydrographic surveys completed for Lake Melville in 1954-55, the Canadian Hydrographic Survey resurveyed the the Kenamu Channel at a scale of 1:20,000 and the Kenamu delta front at a scale of 1:10,000. The major change in offshore bathymetry between these two survey periods is related to the addition of sediment to the seafloor, which is manifested by a general shallowing (in places over 1 metre), and in places a deepening (up to 5 m) of the seafloor due to natural slide activity.

3.3. OCEANOGRAPHY

The oceanography of Lake Melville has been addressed by Bobbitt & Akenhead (1982) and Vilks et al. (1984). Lake Melville is a large fjord, over 200 km in length, exceeding 30 km in width. The main part of the fjord (called Lake Melville) is separated from the coastal waters of Labrador, that comprise Groswater Bay, by a long and shallow sill called The Narrows (12 km long, 30 m deep). The water in Lake Melville consists of an upper layer, a mixture of fresh river water and underlying sea water that has been mixed upwards by entrainment and turbulence, a middle layer (also known as a compensating current) that is controlled by the amount of sea water transferred to the upper layer by the entrainment process, and a deep layer that lies below the depth of the sill (30 m) and is periodically exchanged seasonally by deep water renewal associated with the fall storm season that lifts more saline shelf waters over the sill.

Due to the high discharge rates, the top layer has practically the same salinities throughout the fjord (0 to 7 ppt). This indicates minimal vertical exchange between this brackish layer and the deeper sea water due to entrainment. The thickness (up to 10 m) of the homogeneous section of the surface layer is strongly influenced by wind conditions. The halocline occurs between 5 and 20 m, where the salinity reaches a value of ≈ 25 parts per thousand. The salinity of the surface waters remains low throughout the year, as the Churchill River is regulated to allow discharge rates of 1,500 m^3/s during the winter period. In the absence of strong down-inlet winds, short-term variations in river flow have negligible effect on the salinity within the system.

The temperature of the surface of the fjord ranges from freezing conditions (< -0.5^{o}C) during the winter season, to greater than 15^{o}C during August. The salinity and temperature of the deep water occupying the Kenamu Basin, range from winter conditions of < 0.0^{o}C and 28 ppt., to summer conditions of 0^{o}C and 27 ppt.

Bobbitt & Akenhead (1982) note that internal tide motion may play a major role in the circulation of Lake Melville because the sill extends up to the stratified layer, so that a shear flow of appreciable magnitude is produced. Depending on the natural variation in freshwater discharge to Lake Melville, the freshwater layer has a residence time of between 4 and 6 months. The tidal amplitude at the Kenamu delta ranges between 0.5 m (average tide) to 0.7 m (large tides). Because of tidal choking at The Narrows, the tide inside Lake Melville is a factor of 5 smaller than waters on the seaward side of the sill. The tides are not symmetrical in Lake Melville, having an ebb tide 1.4 times longer in duration than flood tide (Nutt, 1963).

The circulation fronting the Kenamu Delta, i.e. within 2 km of the river mouth, is controlled by discharge of freshwater from the Kenamu River through the months of May to November. Sediment carried by the Kenamu River is deposited directly in front of the delta. The Kenamu River apparently carries little suspended sediment, at least relative to the plume from the Churchill River, which invariably appears more turbid on satellite and air photographs. During the month of August, the Kenamu River has flow speeds of between 0.1 to 0.3 m/s. At 2 km from the delta front, due to flow expansion, the surface velocities have been reduced to a few cm/s. The circulation further out from the Kenamu Delta, i.e. more than 2 km off the river mouth, is controlled by the discharge from the Churchill River that flows over a 10 m deep channel that separates Goose Bay from the Kenamu Basin, called the Goose Bay Narrows. Because the Goose Bay Narrows is only 800 m wide, and the summer discharge from the Churchill River is ≈ 3500 m^3/s, the surface water velocity through the channel is ≈ 1 m/s on flood tide and up to 5 m/s on the ebb tide (always in the seaward direction). These velocities decrease exponentially out from the The Narrows, so that as the surface plume cuts across the Kenamu prodelta, the flow velocity is reduced to between 20 and 100 cm/s. Wind drift can enhance or decrease these current speeds. The influence of the Churchill River plume out from the Kenamu River can be seen on satellite and air photographs (Fig. 3.3.1).

The suspended sediment regime of the Kenamu Basin has only been ascertained for the low discharge periods (August, 1979, October, 1983: Vilks et al., 1984; July, 1989: Long & Paradis, 1989) of both the Kenamu and Churchill Rivers. Surface concentrations are usually less than 10 mg/L, and deeper waters are always less than 1 mg/L. The Churchill River plume contains a great proportion of humic substances (typical of rivers draining marshy environments) which make the water very murky and turbid. Therefore light attenuation is very high in this river plume and this light reduction must contribute to a decreased level of primary production in Goose Bay (e.g. Cloern, 1987). The low salinity of Goose Bay may also contribute to low primary production (Farrow et al., 1983). The suspended particles are flocculated and settle in the form of very large (500 μm) and stable aggregates.

3.4. CLIMATIC CONDITIONS DURING SUMMER SEASON

The ADFEX experiment is scheduled for August, 1991. Climatic conditions at this time can be estimated using weather record averages (Table 3.4.1). On an annual basis, August has the second highest mean monthly temperature and rainfall and the highest mean monthly days with measurable rainfall and greatest rainfall in a 24 hour period. Wind blows hardest from the west and southwest with a total percent frequency [% F] of about 20 % in relation to a total of 16 measured directions (i.e., sectors). Westerly and northwesterly winds would have the greatest impact on nearshore delta operations and hardware (e.g., jet drilling from an anchored barge, instrument cable networks). Launches and larger vessels operating in the offshore would experience some difficulty maintaining course on survey lines but, based on previous field experience in 1988 and 1989, should be able to effectively occupy anchor stations for monitoring purposes.

TABLE 3.4.1 Climate normals based on 1955-1980 data

Monthly Means	July	August	September
Sea level pressure (kPa)	100.93	100.98	101.14
Standard deviation	0.17	0.21	0.22
Air temperature (^{o}C)	13.1	12.0	7.3

Monthly Means	July	August	September
Mean daily radiation (relative)	7.93	5.83	3.18
Rainfall (mm)	105.1	103.2	84.5
Days with measurable rainfall	17	17	15
Greatest rainfall in 24 hours(mm)	56.9	79.2	44.2

Wind characteristics

Mean wind speed in km/hr [% F]

Sector	July	August	September
N	13.9 [4.9]	14.2 [4.4]	16.0 [4.6]
NE	15.3 [10.5]	15.4 [7.5]	16.9 [5.3]
E	9.5 [2.7]	10.1 [3.1]	10.5 [2.0]
SE	9.7 [1.8]	9.9 [1.8]	10.0 [1.2]
S	14.3 [8.8]	14.2 [8.0]	14.4 [7.5]
SW	15.7 [7.5]	16.5 [8.3]	17.6 [9.2]
W	17.4 [10.7]	16.4 [11.9]	18.4 [15.3]
NW	15.3 [3.9]	15.3 [4.8]	17.4 [5.3]
CALM	[9.2]	[7.9]	[5.9]
Gust speed	101	101	122
Sector	S	SSE	WNW

There are no recorded data on the wave climate of Lake Melville. Published theoretical relationships between wind speed, duration and fetch have been used to estimate wave heights and periods for August winds blowing from the NW, W and SW sectors at mean speed for periods of one and six hours (Table 3.4.2). The calculations suggest that the most serious wave conditions, with respect to launch and small craft operations, are developed during southwesterly wind events that persist for at least six hours. In the past, winds in this category have occurred less than 10 % of the time during August.

TABLE 3.4.2. Maximum wave height (H) and period (P) predictions: Kenamu prodelta area.

Sector	Fetch (km)	Duration one hour H(m)	Duration one hour P(s)	Duration six hours H(m)	Duration six hours P(s)	Wind speed (km/h)[m/s]
NW	15	<.5	<2.0	<.5	<2.0	15 [4.0]
W	9	<.5	<2.0	<.5	<2.0	16 [4.5]
SW	20	<.5	<2.0	<.5	2.0	17 [5.0]

3.5. QUATERNARY HISTORY

Lake Melville contains thick sequences of ponded (basin-fill) and conformable (basin-drape) stratified sediments overlain by hemipelagic muds (Vilks et al., 1984). The former were deposited in a glacial setting, the later in the existing fluvial mode of sediment transport. In the Kenamu Basin, much of the fill comes from large slides, slumps and sediment gravity flows that have transported both coarse grain sediment from the North West River delta and the Kenamu delta as they have prograded (i.e. through accumulation of sediment, the river mouth has progressively moved seaward) and finer grained sediment from along the margins of the basin. Historically there have been some very large mass failure of marine sediments into Kenamu Basin, some greater than 10^9 m^3 of sediment (Fig. 3.5.1). This value can be compared to the planned ADFEX displacement of 5 x 10^4 m^3 which is less than 0.005 % of this naturally displaced sediment. Recent sidescan sonar imagery of the margins of the Kenamu Basin provides indications that slide volumes on the order of 10^6 m^3 occur every few years (i.e. shown by sharp images of slide scar features, intermixed with older more subdued slide features). Thus ADFEX is only controlling the timing and exact location of what occurs naturally and often in the same area.

3.6. BASIN SEDIMENTOLOGY

Sediment samples collected from the seabed less than one kilometre from the delta front consist of fine sand and/or coarse silt. Those further away quickly attain clay values of between 60 to 80 % of the sample weight, of which between 20 to 30 % of the sample weight consists of particles whose grain diameter is less than 0.5 μm (Figs. 3.6.1 & 3.6.2). The distribution of sand in seabed sediment follows the geometry of the Kenamu delta perimeter with values > 40 % sand being typical of areas nearest the river mouth (topset and forset beds) (Fig. 3.6.3). There is a well defined boundary at the 10 % sand isocline, that has a pronounced north-south orientation which appears to be independent of depth. This pattern is similar to aerial photographs and Landsat images of the surface water SPM patterns (described in section 3.3) and is therefore probably related to the interplay of fluvial sand particle transport from the Kenamu river delta and fluvial transport of silt (Fig. 3.6.8) and clay size particles derived from riverine sources in Goose Bay (e.g., Churchill River). A Goose Bay source for the very fine mud fraction is also suggested by the gradient in sand percentages between 10 to 40 % observed along the southwestern section of the Kenamu delta perimeter. This pattern is similarly observed in the percent clay, mean grain size (Fig. 3.6.4), and colloidal clay (< 0.5 μm diameter) isoclines. Aerial photographs indicate that Kenamu River water contains significantly lower concentrations of suspended matter compared to offshore surface waters (Fig. 3.3.1).

Throughout the Kenamu Basin, organic carbon concentrations (OC) in seabed sediment are < 1.0 %. The > 0.8 % field is restricted to the river mouth area and to a small elongate area lying along the base of the delta foreslope (Fig. 3.6.5). The 0.60 to 0.79 % field occurs near the head of the ADFEX channel over a depth range of 10 to 60 m. Offshore sediments are characterized by OC concentrations of < 0.6 % that may reflect a possible sediment dilution effect involving fine particle (hemipelagic) deposition from the inferred Goose Bay source. Reflection seismic records indicate gas pockets in sediment (subbottom depths of 1 to 5 m) in water depths of < 20 m, suggesting that the depositional pattern of organic matter has probably been stable over the past several hundred years.

Carbon/nitrogen ratios show a wide range of variation in the Kenamu prodelta area (Fig. 3.6.6). Ratios > 20, which are generally considered as indicative of terrestrial OC, occur at two locations. One of these is situated along the base of the delta usually at depths greater than 30 m. The other occurrence encompasses a broad area that lies within and to the north of the distal part of the Kenamu channel. Typically marine C/N ratios (< 10) are confined to the southern side of the Kenamu channel, and to deeper offshore environments throughout Lake Melville.

Kenamu channel and basin sediment is composed of between 20 to 38 % plagioclase (feldspar), 13 to 34 % potassium feldspar, 9 to 34 % quartz, 12 to 38 % mica, 2 to 5 % chlorite, and less than 2 % kaolinite, and less than 1 % smectite. This mineralogy is typical of what is known as glacial flour, i.e. rock that has been ground up by glaciers during the last ice age.

A piston core collected in the ADFEX channel (CSS Dawson 88-030-006) displays evidence of naturally-triggered submarine slides that have occurred in the recent past in this prodelta environment. The upper 400 cm of the core consists of alternating layers of sand, silty sand and clayey silt. These layers are separated by sharp, generally horizontal boundaries that often show deformation features suggestive of mass flow transport and/or sediment loading (Fig. 3.6.7). Individual slump events appear to be separated by comparatively coarse organic detritus layers that may represent early spring deposition of organic material that accumulated in the Kenamu river channel during the previous fall season. Slumped deposits lying between major organic layers have thickness of 25 to 50 cm. At the 400 cm level, there is a pronounced transtion accross a deformed boundary from relatively sandy sediment to bioturbated(?) muddy material containing relatively fine but visible organic particles. This organic-enriched fine sediment may represent in situ channel floor material that reflects ambient offshore hemipelagic depositional processes and which, in this instance, has been covered by sucessive mass flows derived from the Kenamu delta.

Evaluation of the microfossil and organic matter (OM) content at several levels in core 006 reflects the probable source of sediment comprising distinctive textural/structural layer types. The fine, silty, bioturbated mud found below the 400 cm level appears to be associated with offshore hemipelagic depositional processes. It contains large numbers of nearshore foraminiferal species (**Spiroplectammina biformis** and **Elphidium excavatum**) distinctive fibrous masses of OM and very few thecamoebian specimens. Mass flow-related layers are distinct in regard to their increased numbers of thecamoebian specimens, relatively low numbers of foraminifera specimens, and by the discrete nature of OM particles compared to the matted, fibrous masses of in situ channel sediment OM. In vertually all of the different textural layers ascribed to mass flow processes, the lower number of foraminifera specimens (i.e., a dilution effect) is one characteristic that clearly distinguishes these deposits from in situ channel material.

3.7. BENTHOS-ECOLOGICAL SETTING

3.7.1. Benthonic Foraminifera Assemblage Variations

Benthonic foraminifera populations were sampled in 1988 and 1989 in order to assess the ecological setting of the Kenamu prodelta environment in relation to several other similar local environments that occur in the western part of Lake Melville. Foraminifera, members of the subphylum Sarcodina, are marine-estuarine organisms having a single-celled protoplasmic body. There are two major subgroups recognized on the basis of their skeletal structure (calcareous and arenaceous). Arenaceous types are associated with both estuarine and deep sea habitats while calcareous species are prominent in continental shelf and nearshore marine environments. The skeletal remains of foraminifera have wide application as stratigraphic markers and as sediment tracers. Thecamoebians are a group of amoeboid protozoa present in a wide variety of freshwater habitats (e.g., Patterson et al., 1985). In ADFEX, thecamoebians are utilized as sediment source tracers for that fraction of the total SPM load derived from local riverine sources.

Living foraminifera distributions have been utilized world-wide in ecological and pollution studies. In this report, 1988 collected-data on living foraminifera occurences (as opposed to fossil occurences) are used as an index of local prodelta environmental variation in the Lake Melville system. Total population data (living plus dead specimens) from the 1989 grab sample suite are used to characterize larger basin-wide spatial variation of the benthic marine environment adjacent to the Kenamu delta (Fig. 3.7.1.1).

The Kenamu prodelta environment is inhabited by 10 living species of foraminifera having an average population density of 0.9 specimens per cc of wet surficial sediment. These values are intermediate in magnitude compared to those observed in Northwest River and Mulligan River prodelta environments (Table 3.7.1). The Kenamu prodelta living foraminifera populations are unique in terms of their high percentages of calcareous species (Fig. 3.7.1.2 & 3.7.1.3). The Kenamu calcareous assemblage is represented almost entirely by *Haynesina germainica* which often represents 100 % of the living population (Fig. 3.7.1.4). In the other two prodelta environments, *H. germanica* ranges from 7.4 to 40 % of the living population.

Living foraminiferal species number (i.e., species diversity) has enjoyed widespread use as a general indicator of environmental stability. Estuarine and shallow marine environments are characteristically reflected by relatively low numbers of species (e.g. Schafer & Cole, 1978, 1986; Scott et al., 1980). As such, the Kenamu prodelta can be viewed as a relatively variable benthic environment, probably a reflection of the Kenamu prodelta lying within the seasonal watermass layer of Lake Melville which extends to a depth of at least 10 to 15 m (see Bobbitt & Akenhead, 1982). Compared to the N.W. River and Mulligan prodelta settings, the Kenamu prodelta environment is unique in terms of *H. germanica* percentages. This species is common to arctic nearshore environments with water depths less than 15 m (Schafer & Cole, in prep.).

TABLE 3.7.1. Comparison of living benthonic foraminifera populations in three Lake Melville prodelta environments.

	Total No. of living species (N)	Population Density (NL/cm^3)	Water Depth (m)	(range)
Kenamu prodelta	10	0.9	17	5.0-25.0
N.W. River delta	14	1.8	12	4.5-26.0
Mulligan R. delta	8	0.3	13	1.5-24.3

3.7.2. Benthonic Foraminifera and Thecamoebian Spatial Distributions

In the Kenamu delta area of Lake Melville, the number of living foraminifera specimens per cm^3 of wet sediment (NL/cm^3) shows a distinctive north to south oriented band of relatively high concentrations (> 10) that is essentially orthogonal to the axis of Kenamu channel (Fig. 3.7.2.1). Distal channel areas are characterized by NL/cm^3 of < 10. In the distal channel environment, the ≤ 10 field covers a relatively wide depth range and appears to have boundaries comparable to spatial SPM patterns observed on aerial photographs. Because of sediment dilution and resuspension effects, shallow water prodelta environments along the peripery of the Kenamu delta are also characterized by NL/cc levels of < 10. Living calcareous foraminifera occur in relatively high percentages in the narrow water depth interval of 30 to 80 m. Most of the delta platform is barren of living calcareous specimens.

The species *Spiroplectammina biformis* is an arenaceous foraminifera that is found in many east coast Canadian estuarine to marginal marine habitats. It occurs throughout the Kenamu prodelta area where it dominates the total foraminifera population. In the relatively deep distal parts of the Kenamu channel, its relative abundance drops to < 25% (Fig. 3.7.2.2). It highest total population percentages are confined to the 30-50 m depth interval. *Haynesina spp. (H. orbiculare + H. germanicum)* is a calcareous species group that occurs at water depths > 20 m, where it marks the transition from upper estuarine to marginal marine watermass conditions.

In the Kenamu prodelta area, the total number of thecamoebian tests per cubic centimetre of wet sediment (TN/cm^3) pattern shows a decrease in concentration from south to north (Fig. 3.7.2.3). Specimen concentrations are generally high in water depths of < 50 m and particularly at < 30 m adjacent to the edge of the Kenamu delta. In the distal part of the Kenamu Channel, thecamoebian TN/cm^3 are typically < 50. *Difflugia bacillariarium* is the dominant species in offshore thecamoebian assemblages (Fig.3.7.2.4). Its distribution pattern is clearly orthogonal to the Kenamu channel axis and its proportion of the total thecamoebian population is < 10 % along the periphery of the delta. This pattern compares favourably to surface water SPM patterns observed on aerial photographs suggesting either (1) a possible source area to the west (Churchill River), or (2) selective transport of this species to distal deep water environments because of its relatively small size (< 100 μm).

3.7.3. Bottom Photographic Surveys

Bottom photography was used in both the 1988 and 1989 survey cruises to obtain visual data on the nature and density of the benthic community. The surveys were completed using 35 mm UMEL cameras set at F5.6 and focused at 135 cm. The compass-tail fin trigger weight shown in the photos is 40 cm long. In 1988, photographs were taken along a drift transect (AA-BB) that is oriented parallel to the peripery of the Kenamu delta over a depth range of 20 to 25 m (Fig.1 & Plate 1). The photographs from this area reveal a relatively sandy substrate covered by epifaunal tracks (Plate 1); no positive indication as to what benthic species might be responsible for these tracks was found. The apparent absence of burrows in this area is probably an indication of sediment instability and comparatively high sedimentation rates; an interpretation consistent with the distribution pattern of sand size particles.

During the 1989 survey, eight camera transects (1 to 2 km in length) were occupied: near the Kenamu delta, within the Kenamu channel, and at several control locations within Kenamu basin (Plate 2). On average, about 30 exposures were made along each transect. Results confirm the 1988 data. Near the delta foreslope, sediments appear virtually devoid of dense megafaunal populations (Plate 2). In the softer and finer offshore bottom sediment environments, starfish are occasionally observed along with some evidence of small worm (?) burrows (Plate 3). These results agree with visual data from of screened (1.0 mm) grab sample material collected during the 1989 survey.

3.7.4. Macrobenthos and Organic Detritus in Bottom Sediments

One to two litre volumes of each grab sample was washed through a one mm sieve to obtain information on macrobenthic species. In general, there are two main groups of macrobenthic species and a category of plant fragments. Polycheate type worms are ubiquitous throughout the Kenamu prodelta area. The worms are either free standing tube types or free swimming types. The second group consists of molluscan species which are all active burrowing or infaunal types (Table 3.7.4.). Of the eleven mollusc species identified in the samples, virtually all are indicative of shallow, cold water, esuarine environments with relatively high sedimentation rates. The bulk of the plant material found in the grab samples is terrestrial in origin and includes moss, grass, twigs, deciduous leaves, conifer needles, and cone scales that are washed into the prodelta basin as part of the fluvial suspended load.

TABLE 3.7.4. Mollusc species contained in grab samples

SPECIES	DEPTH RANGE	ECOLOGY
Astarte elliptica (Brown)	2-440 m	arctic to New England, clay or/& sand substrate.
Axinopsida orbiculata (Sars)	2-940 m	arctic to New England, clay or/& sand substrate.
Cylichna alba (Brown)	1-500 m	arctic to North Carolina, cold water.
C. gouldii	1-60 m	arctic to New England, cold water.

SPECIES	DEPTH RANGE	ECOLOGY
Lyonsia arenosa (Moller)	1-100 m	arctic to Maine, any bottom type.
Macoma balthica (Linne)	0-30 m	arctic to Georgia, hyposaline environments, suspension & deposit feeder.
Oenopota incisula (Verrill)	6-900 m	arctic to New England, any bottom type, feeds on other molluscs.
Portlandia arctica (Grey)	2-2500 m	arctic to Gulf of St. Lawrence, muddy or clayey substrates, river mouth and ice front settings.
P. frigida (Torell)	5-2500 m	arctic to New England, tolerates low salinities.
Thyasira equalis (Verrill and Bush)	10-2800 m	Greenland to Maryland. The genus is deeply infaunal in fine sediments.
T. gouldii (Philippi)	2-800 m	arctic to Cape Hatteras, clay substrate preferred.

4. IMPACTS- PERCEIVED AND REAL

4.1. EFFECT OF ENVIRONMENT ON THE EXPERIMENT

Effects of the evironment on the experiment consist primarily of weather effects. High river flows resulting from intense rainfall events might occur over several days and could: (1) delay the installation of instruments, (2) hinder ship movements by flooding the ships radar signal, or (3) delay the triggering of the slide. Fog would reduce visibility which could effect aerial photography. Wind can generate a storm surge that could interfere with tidal flat operations. Fine sediment may also be resuspended by waves and could "contaminate" moored sediment traps. Northerly and Westerly winds would have the greatest effect by generating waves that would limit launch activities. In a positive context, the orthogonal spatial distribution of several faunal and textural indices, with respect to the Kenamu channel, should facilitate documentation of sediment transport processes since slide sediment will be carried directly across these ambient "baseline" patterns.

4.2. EFFECT OF THE EXPERIMENT ON THE ENVIRONMENT AND ON THE LOCAL SOCIOECONOMIC SETTING

There are several direct and indirect effects that the experiment will have on the environment and community, although all are considered to be minor. One direct effect involves the number of instrument moorings and survey vessels that will be in place for approximately a two week period in August. However, with proper lead time and through "notices to mariners", and adequate communication with local residents as to the exact location of these moorings, this effect can be fully mitigated.

Burial of the benthic community along the submarine channel in which the slide material will flow, is another direct environmental effect. An area of 10,000 m^2 could be covered by slide sediment with the thickest sediments occuring over the deepest part of the channel floor producing an elongate deposit that would thin toward the sides of the channel and towards the Kenamu basin. Areas periperal to the channel would be expected to receive a "dusting" of comparatively fine particles, but this should not significantly affect epifaunal or infaunal populations. The overall disturbance can be defined as a "minor impact" (Duinker & Beanlands, 1986) in the sense that it will affect a localized benthic population over a short period of time (one generation or less) but should not affect other trophic levels or the Lake Melville benthic population itself. An analogy of the impact of slide sediment burial of local benthos might be the on going dredging of the Terrington Narrows navigation channel. This activity may create an 18,000 m^2 sterile surface area. Studies of dredge spoil dumping at other ocean disposal sites (e.g. Schafer, 1976, 1982) indicate that foraminifera recolonize these sterile substrates in less than one year. The proposed slide represents a case of localized deposition in an isolated channel. By comparison, sand deposition and burial of benthos during the Kenamu River annual freshet can be expected to affect an area of as much as 3.4×10^6 m^2. Also by contrasts, natural slides that occur within this environment are 10 to 1000 times larger than the proposed ADFEX-generated slide (see section 3.5).

Dr. Bernard Long will be supervising the radioactivity component of the ADFEX experiment. Dr. Long has previously conducted similar experiments in the Bay of Fundy, Sable Island offshore, and in the Gulf of St. Lawrence. Four (4) Curies (or 148 GBq) of Neodynium-147 will be used, mixed in 2 kg of sand (4 samples of 500 g each). Neodynium (γ: 91 Kev (27.9 %) to 531 Kev (13.1 %)) has a half-life of 11.2 days. The tracer will be deposited in the form of sand sized glass beads. They will initially be injected to a depth of between 3 to 5 m using jet drilling techniques. This will ensure, in case no slide is generated, that the radioisotopes will be buried. Thus, as the radioactive material is bound to sand sized beads, and these will be immobile unless a slide is generated, no radioactive material will leak into the marine environment during the six weeks needed for complete decay of these isotopes. If a slide is generated, as is the intention, the radioactive material will be mixed into the liquified sand mass that might reach 100,000 m^3 in volume. Thus, the concentration of radioactive material will fall below accepted background levels within the first few minutes after detonation. The gamma counters used to measure the concentrations of these particles are capable of detecting 1 grain in 1,000,000,000 grains. Thus the method is considered environmentally benign. Finally, there is no recognized biological environmental pathway that would lead to human exposure as uptake of tracer coated glass beads in organisms is extremely inefficient (Dr. J.N. Smith, radioisotope lab PCS/BIO, DFO).

The detonation will generate two low frequency pulses of sound that will persist for several microseconds each. Its local acoustic effect may be analogous to distant thunder, except that the detonation will be of much shorter duration.

Suspended sediment plumes in bottom waters generated by the slide are predicted to persist above ambient levels for at least five hours. The Lake itself is exposed to similar or higher SPM loadings during the spring freshet period and the area of the Lake to the north of the Kenamu delta appears to be influenced over longer periods throughout the year by the suspended sediment flux of the Churchill River which reaches the study area by way of the Goose Bay Narrows.

No affect on the fisheries is expected. The planned buial of dynamite is such that no pressure wave should be generated within the water column (the usual cause of fish kill by explosives: Munday et al., 1986). Rather than ADFEX being a case of detonation of a 1000 kilo explosive package buried to a depth of ten metres within delta sediment, the planned experiment is actually a large number of synchronous 10 to 20 kilo detonations separated from the water and each other by some 20 to 50 m of sand (see Table 4.2.1) Also, if the fish nets typically placed around the river mouth of the Kenamu are positioned so as to be safely away (> 300 m) from the detonation site, then they should not even have to be removed during the experiment. Local survey vessel noise may provide an advantageous "noise attractant", temporarily increasing fish yields in these nets during the two weeks of the experiment.

Table 4.2.1. The particle motion, Vp (see equation 2.1.3.1) in mm/s, at various distances from a point of detonation, and using three examples of explosive mass.

EXPLOSIVE MASS (kg)	DISTANCE (m)			
	1	10	50	100
10	316	100	45	22
20	447	141	63	45
30	548	173	77	55

Happy valley hotels/restaurants/stores/airport/sea-transport are all necessary elements of the project logistics and will be utilized at one time or another by up to 30 scientists and technicians. In addition to some small outboard craft, it is anticipated that a local fishing boat may be needed to transport heavy equipment and personnel to and from the delta site especially during windy intervals.

4.3. STEPS TO MITIGATE ENVIRONMENTAL EFFECTS

Burial of explosives Charges will be buried to a depth of between 5 and 10 m using jet drilling technology (see section **2.3.1.**). This design would minimize direct effects of the detonation and will enable greater control of the forces applied to the sediment and therefore to the amount of sediment movement generated by the detonation.

Spatial distribution of explosives Charges will be set out in several lines that will be detonated at closely spaced intervals of time to minimize shock wave amplitudes and to properly liquefy the deltaic sand. The configuration of the explosive charge "lines" is designed to disturb less than 5 percent of the total delta peripery, and 0.2 % of the delta surface. Sediment removed will be replinished within 1 to 2 years naturally by sediment carried by the Kenamu River. Spacing of individual small charges along each line will serve to further diminish shock wave amplitudes and impact area.

Depth distribution of explosives All charges will be buried in the sediment in less than 1 m of water in keeping with recommendations of various studies on the direct effect of underwater explosions on marine species (e.g. Yelverton et al., 1975).

Timing of the experiment The slide will be triggered in the late summer after the annual freshet so as to minimize the potential for interference with adronomous fish species migrations, i.e the salmon run is largely over by the end of July (see section 3.1).

4.4. MONITORING PROGRAM

The ADFEX monitoring program overlaps substantially with activities pertinent to the EIS. The program is subdivided into three elements that provide a temporal and spatial framework for assessing the impact of the experiment on the local marine environment adjacent to the edge of the Kenamu River delta.

4.4.1. Presurvey Activities

Marine faunal survey Living and total foraminifera populations have been mapped as part of 1988 and 1989 survey activities. 1988 samples are from the Kenamu and, as well, from two control sites (Mulligan and N.W. River deltas). The characteristics of this trophic level of marine organism is deemed satisfactory for comparing the "steady state" benthic ecology of these three systems. These organisms are more easily sampled than larger and more sparsely-distributed soft-bodied megabenthos (see section 3.7.1).

Bottom photography survey A transect was completed made in 1988 along the peripery of the Kenamu delta to evaluate megabenthic and infaunal populations. This transect was supplimented by eight additional transects in 1989 giving a total of about 250 exposures (see section 3.7.3).

Suspended particulate matter Eight floc camera stations were occupied in and around the Kenamu delta during the 1989 cruise. Each station consisted of an XBT (Temperature-depth) profile followed by a floc camera profile with Knudsen one-litre water samples taken at bottom, intermediate and surface levels (see section 3.3).

Land-based seismics surveys Stratigraphic sections of the emerged peripery of Kenamu River, Northwest River and Mulligan River deltas were completed in 1988 using portable seismic reflection equipment. No permafrost was observed in the upper 50 m of the sediment section.

Offshore seismic and sidescan surveys In 1988, a Huntec DTS 500 Joule reflection seismic system was used to collect 500 km of high resolution profiles within and adjacent to the Kenamu prodelta area, and in areas periperal to four other river deltas in Lake Melville and Goose Bay. The nearshore areas of all five deltas were surveyed by a launch fitted with 3.5 kHz seismic and 200 kHz sounding systems. In 1989, a further 500 km of shallow reflection seismic data were collected in and adjacent to the Kenamu prodelta area using 12 kHz and 3.5 kHz systems. Settings were adjusted to accomodate both shallow water (< 25 m) and deep water (> 190 m) operations. Side scan sonar surveys were conducted adjacent to five deltas by launch in 1988 using a portable Klein system. A major offshore side scan sonar survey was completed as part of 1989 field operations using a Klein 100 kHz model 402A. About 400 km^2 area was covered by this survey (see section **3.5**.).

Offshore bathymetry The Canadian Hydrographic Service resurveyed the Kenamu offshore in 1989. 538 line km of soundings were collected using microwave navigation (Miniranger) control, ELAC LAZ 72 sounders, and a line spacing of 100 m (see section **3.2**.).

Sediment stratigraphy In 1988, a total of 52 m of sediment core was collected by piston coring at 11 stations positioned on Huntec seismic lines (see section **3.6**). 9.4 m of Lehigh gravity core were collected at stations near the edge of four river deltas in the Goose bay-Lake Melville area. In 1989, a push core was collected on a Kenamu River mouth bar levee; a second core was collected from the wave effected part of a river mouth bar.

Texture of surficial sediments In 1988, 40 grab samples were collected by launch along the peripery of the Kenamu delta to ground truth the 3.5 kHz reflectivity data. During the 1989 field operation, additional grab samples were collected in the Kenamu River channel using a small outboard boat. Concurrently, a grid of 222 Van Veen grab samples was completed over the predicted path of the slide.

4.4.2. The Experiment

High frequency acoustic profiling HF (high frequency) profiling provides data on suspended load characteristics of the water column. Profiling will be carried out within the submarine channel area in which the slide will occur. Sensors are designed to measure the growth and decay of the gravity flow generated by the slide (see section 2.3.2).

Attenuance profiling A monochromatic light beam (λ=660 nm) will be used in conjunction with water sample data to collect data on temporal changes on water turbidity (i.e. suspended particle concentration) at various water levels at a given location (i.e. the Hudson master station), and at selected stations after the slide has been initiated to monitor the water column recovery (see section 2.3.2).

Hydrophone monitoring of the slide propagation A hard-wired hydrophone array will be deployed to monitor slide dynamic characteristics, including slide velocity and duration at different points along the submarine channel axis (see section 2.3.2).

Seismometer This instrument will be deployed to measure ground accelerations associated with the slide-triggering detonation.

Time-lapse aerial photography Photographs will be collected over the detonation site at 1 second intervals using a balloon-deployed camera system. The photographs should provide a measure of surface phenomena at the detonation site, thus providing information on the time and extent of soil liquefaction (see section 2.3.2).

Sidescan sonar monitoring Side scan sonar imagery of the slide's flow through a section of the submarine channel will be obtained by placing a transducer on one side of the submarine channel. The transducer will be positioned to cover a section of the channel floor downstream from the detonation site. These records should provide real time information on slide duration, thickness of the slide, and any occurence of post-detonation sliding of additional material from the delta face (see section 2.3.2).

Sediment traps Standard cylindrical traps will be affixed to moorings located along and parallel to the axis of the submarine channel. These traps will provide information on the vertical flux of suspended sediment following the passing of the slide-generated sediment gravity flow (see section

2.3.2).

Tracer particles Very-short lived radiated tracer particles will be emplaced in the slide mass using a jet drilling technique. The tracers can be used to measure particle sorting effects in the slide mass. The tracers will also be used to estimate the thickness of the slide sediment (see section 2.3.3).

Pore pressure monitoring Several pore pressure sensors will be emplaced in and around the detonation site to monitor the release of excess pore pressure in the system and the liquefaction front (see section 2.3.1).

4.4.3. Post Experiment Surveys

Fish impact monitoring Although no impact on fish is expected from this experiment, the Kenamu delta shoreline will be monitored for dead fish for a period of 6 hours following the detonation. Floating fish will be sampled and examined with the help of DFO biologists. All observations will be tabulated and reported.

Grab sampling and coring network Sampling stations comprising the preslide network will be reoccupied to measure spatial and internal sediment characteristics of the slide mass (see section 2.3.3).

High resolution seismic survey of the site An HR seismic survey will be carried out to estimate slide mass internal geometry and distribution (see section 2.3.3).

Suspended sediment survey Although ambient turbidity levels are expected to be returned within 24 hours of the slide generation, a suspended sediment survey will be repeated daily until background water turbidity levels have returned to normal (see section 2.3.3).

Benthonic foraminiferal survey Grab samples will be collected one year after the slide to evaluate recolonization rates of species on barren sediment surfaces that are identified as a result of the grab sampling exercise carried out after the slide initiation (see section 2.3.3).

5.0 PUBLIC LIAISON

On June the 7th, 1990, a press release went out to all radio, television and newspaper offices operating within the Happy Valley municipality and surrounding area, announcing that a public information session was to be held on the evening of June 13th in the gymnasium of the North Star Building at Goose Bay. The session was advertised as a discussion of the environmental issues related to an upcoming test (ADFEX), in the Lake Melville, designed to help Canada understand the consequences of submarine earth slides on marine structures.

Dr. Charles Schafer and Dr. James Syvitski (Dept. Energy, Mines & Resources, Bedford Institute of Oceanography) and Mr. Paul Chenard (D.E.M.R. Environmental Affairs Office) were present in the Happy Valley region on June 13-14th to participate in the public meeting. In addition to the public meeting, a private meeting was held with Mr. Herbert D. Brett (Town Councillor) to review the project. A second meeting was held at the Happy Valley - Goose Bay town hall where the project was reviewed by Mr. Al. J.F. Durno (town Manager) and Mr. John Hicky (Deputy Mayor) along with several town officials. A third meeting was held the next day at the North West River town office where the project was reviewed in general terms with Ms. Josie Michelin and Mr. Eric McLean. A meeting was also set up with Mr. Harvey Buffet, the Harbour Master at Goose Bay (Canadian Coast Guard). A final meeting was held with Mr. Cyril Michelin, the principal trout/salmon fisherman working the Kenamu delta. In all instances, copies of this report were provided with a request that they be circulated to key members of the community. A request for criticism or clarification for aspects of the project was asked of all contacts. None have been received. In general, the project provoked casual but positive responses with those individuals contacted.

6. BIBLIOGRAPHY

Anderson, T.C. 1985. The rivers of Labrador. Canadian Special Publication of Fisheries and Aquatic Sciences 81, Dept. of Fisheries and Oceans, p. 158-160.

Asudeh, I. 1989. (personal communication). Availability of portable refraction seismographs for ADFEX study. Seismology and Electromagnetism Section, Geological Survey of Canada. 613-996-5757.

Beanlands, G.E. and Duinker, P.N. 1984. An ecological framework for environmental impact assessment. Journal of Environmental Management **18**, p.267-277.

Beanlands, G.E. and Duinker, P.N. 1983. An ecological framework for environmental impact assessment. Report, Institute for Resources and Environmental Studies, Dalhousie University, Halifax, N.S., 132 p.

Beanlands, G.E. and Duinker,P.N. 1984. Lessons from a decade of offshore environmental impact assessment. Ocean Management **9**, p.157-175.

Bobbitt, J. and Akenhead, S. 1982. Influence of controlled discharge from the Churchill River on the Oceanography of Groswater Bay, Labrador. Canadian Technical Report, Fisheries and Aquatic Sciences No. 1097,43p.

Buffet, H. 1989. (personal communication). Logistic support at Goose Bay dock. Canadian Coast Guard, Goose Bay Labrador.

Buffington, E.C. 1961. Experimental turbidity currents on the sea floor. Bulletin of the American Association of Petroleum Geologists **45**, p.1392-1400.

By, T., Forsberg, C.F., Norem, H. 1990. Submarine slides: full scale experiment, Storglomvatn, Norway. Norwegian Geotechnical Institute Report No. 522090-4, 35 p.

Canadian climate normals 1982. Solar radiation. Environment Canada, Atmospheric Environment Service, v.**1**,p.10.

Canadian climate normals 1982. Precipitation. Environment Canada, Atmospheric Environment Service, v.**3**, p. 43,219,404.

Canadian climate normals 1982. Wind. Environment Canada, Atmospheric Environment Service,v.**5**, p.116.

Canadian climate normals 1984. Atmospheric pressure, temperature and humidity. Environment

Canada, Atmospheric Environment Service, v.**8**, p.257.

Chandler, G.T. and Fleeger, J.W. 1983. Meiofaunal colonization of azoic estuarine sediment in Louisiana: mechanisms of dispersal. Journal of Experimental Marine Biology and Ecology **69**, p.175-188.

Choquette, M. Schafer, C.T., Locat, J., Syvitski, J.P.M., van Havre, B., and Poorooshasb, F. 1989. Report of C.S.S. DAWSON cruise 88-030, Lake Melville, Labrador (Hamilton Inlet). Report GGL 88-28, Department of Gelogy, Laval University,Quebec, P.Q., 50p.

Cloern, J.E. 1987. Turbidity as a control on phytoplankton biomass and productivity. Continental Shelf Research **7**, p.1367-1381.

Duinker, P.N. and Beanlands, G.E. 1983. Ecology and environmental impact assessment: an annotated bibliography. Report, Institute for Resources and Environmental Studies, Dalhousie University, Halifax, N.S., 40 p.

Duinker, P.N. and Beanlands, G.E. 1986. The significance of environmental impacts: an exploration of the concept. Environmental Management **10**, p.1-10.

Farrow, G.E., Syvitski, J.P.M. and Tunnicliffe, V. 1983. Suspended particulate loading on the macrobenthos in a highly turbid fjord: Knight Inlet, British Columbia. Canadian Journal of Fisheries and Aquatic Science **40**: 273-288.

Ferguson, Dan, 1989. (personal communication). Use of media network to publicize ADFEX plan (Aug.24,1989). Regional Communications Manager, DEMR, St. John's, Newfoundland, 709-772-4213.

Field, M.E., Gardner, J.V., Jennings, A.E., and Edwards, B.D.1982. Earthquake-induced sediment failures on a 0.25 degree slope, Klamath River delta, California. Geology **10**, p.542-546.

Greene, G.D., Engelhardt, F.R. and Paterson, R.J. 1985. Proceedings of the Workshop on

Effects of Explosive Use in the Marine Environment. Jan. 29-31st. Canada Oil and Gas Lands Administration, Environmental Protection Branch, Technical Report No. 5, 380 pp.

Imperato, D.P. 1987. A modification of the vibracoring technique for sandy sediment. Journal of Sedimentary Petrology **57**, p.788-789.

Johns, M.W., Prior, D.B., Bornhold, B.D., Coleman, J.M., and Bryant, W.R.1986. Geotechnical aspects of a submarine slope failure, Kitimat fjord, British Columbia. Marine Geotechnology **6**, p. 243-279.

Karlsrud, K. and Trond, B.1982. Stability evaluations for submarine slopes: results of new investigations of the Orkdalfjord slide. Report, Norges Geotekniske Institutt, No. 52207-9, 19p.

Krezoski, J.R. 1988. Particle reworking in Great Lakes sediments: in situ tracer studies using rare earth elements. Oceans '88, proceedings of the MTS-IEEE conference, Baltimore, Maryland, 31 October- 2 November,1988, p. 437-441.

Krezoski, J.R. 1988. In situ tracer studies of surficial sediment transport in the Great Lakes using a manned submersible. Oceans '88, proceedings of the MTS-IEEE conference, Baltimore, Maryland, 31 October- 2 November, 1988, p.442.

Krezoski, J.R. 1989. Sediment reworking and transport in eastern Lake Superior: in situ rare-earth element tracer studies. Journal of Great Lakes Research **15**, p.26-33.

Lambert, A. and Giovanoli, F. 1988. Records of riverborne turbidity currents and indications of slope failures in the Rhone delta of Lake Geneva. Limnology and Oceanography **33**, p.458-468.

Locat, J. and Bergeron, M. 1987. An updated literature review on submarine slides (1981-1986). Report GGL 87-05, Geology Department, Laval University, 75 p.

Long, B. 1989. Report of Lake Melville, Labrador, Hamilton Inlet and Kenamu delta. Report

GGL 89-21, Department of Geology, Laval University, Quebec, 14 p.

MacClean, E., 1990. (personal communication). The Happy Valley slope instability study. 1-709-896-3321.

Middleton, G.V. and Neal, J.W. 1989. Experiments on the thickness of beds deposited by turbidity currents. Journal of Sedimentary Petrology **59**, p.297-307.

Mobil Oil Canada,1984. The environmental impact of explosives near Sable Island. Environmental Planning and Management Department.

Munday, D.R., Ennis, G.L., Wright, D.G., Jeffries, D.C. McGreer, E.R. and Mathers, J.S. Development and evaluation of a model to predict effects of buried underwater blasting charges on fish populations in shallow water areas. Canadian Technical Report of Fisheries and Aquatic Sciences, No. 1418.

Norem, H., 1989. Full scale experiment to study submarine slides. Preliminary field report from the pilot study in Storglomvatnet, Norway, Sept.5,1989. Memorandum, Norges Geotekniske Institutt, 3pp.

Norem, H., 1989. Simulation of snow-avalanche flow in run-out zones. Annals of Glaciology **13**.

Patterson, R.T., MacKinnon, K.D., Scott, D.B., and Medioli, F.S. 1985. Arcellaceans ("Thecamoebians") in small lakes of New Brunswick and Nova Scotia: Modern Distribution and Holocene stratigraphic changes. Journal of Foraminiferal Research **15**, p.114-137.

Pejrup, M. 1988. The triangular diagram used for classification of estuarine sediments: a new approach. In Tide-Influenced Sedimentary Environments and Facies, P.L. de Boer et al. (eds.), D. Reidel Publishing Company, p.289-297.

Prior, D.B., Bornhold, B.D., and Johns, M.W. 1984. Depositional characteristics of a submarine debris flow. Journal of Geology **92**,p.707-727.

Prior, D.B.and Bornhold, B.D. 1986. Sediment transport on subaqueous fan delta slopes, Britannia Beach, British Columbia. Geo-Marine Letters **5**, p.217-224.

Prior, D.B., Bornhold, B.D., Wiseman, W.J.Jr., and Lowe, D.R. 1987. Turbidity current activity in a British Columbia Fiord. Science **237**, p.1330-1333.

Reynolds, S. 1987. A recent turbidity-current event, Hueneme-fan, California: Reconstruction of flow properties. Sedimentology **34**, p.129-137.

Richards,W. 1990. (personal communication). Data sources for wind records and statistics: Goose Bay area. Atmospheric Environment Service, Bedford, N.S. 426-9135.

Schafer, C.T. 1976. In situ environmental responses of benthonic foraminifera. Geological Survey of Canada Report of Activities, Part C, Paper 76-1C, p.27-32.

Schafer, C.T. and Young, J.A. 1977. Experiments on mobility and transportability of some nearshore benthonic foraminifera species. Geological Survey of Canada Paper 77-1C, p.27-31.

Schafer, C.T. 1982. Foraminiferal colonization of an offshore dump site in Chaleur Bay, N.B. Journal of Foraminiferal Research **12**, p.317-326.

Schafer, C.T., Smith, J.N. and Seibert, G. 1983. Significance of natural and anthropogenic sediment inputs to the Saguenay Fiord, Quebec. Sedimentary Geology **36**, p.177-194.

Slade, B., 1990. (personal communication). Fishing activity in the vicinity of the Kenamu delta. Dept. of Fisheries and Oceans, St. John's, Newfoundland. Tel. 709-772-4497.

Syvitski, J.M. 1989. The process-response model in quantitative stratigraphy. In Quantitative Dynamic Stratigraphy, T.A. Cross, ed., Prentice Hall, p.309-334.

Tan, F.C. and Vilks, G. 1987. Organic carbon isotope ratios and paleoenvironmental implications for Holocene sediments in Lake Melville, southeastern Labrador. Canadian Journal of Earth Sciences **24**, p.1994-2003.

Tye, R.S. and Coleman, J.M. 1989. Depositional processes and stratigraphy of fluvially dominated lacustrine deltas: Mississippi delta plain. Journal of Sedimentary Petrology **59**, p.973-966.

Vilks, G., Deonarine, B. and Winters, G. 1987. Late Quaternary marine geology of Lake Melville, Labrador. Geological Survey of Canada Paper 87-22,50 p.

White, V. 1990. (personal communication). Department of Public Works geotechnical surveys in Goose Bay, winter of 1989: Presurveys of 1990 dredge sites in Terrington and Goose Bay narrows. 426-7935 (Fax. 426-5138).

Weirich, F.H. 1984. Turbidity currents: Monitoring their occurrence and movement with a three-dimentional sensor network. Science **224**, p.384-387.

Wojcik, G.L. 1984. Local seismograms from underwater explosions off San Clemente Island. EQ Notes **55**(1) (abstract). Weidlinger Associates, Menlo Park, CA. 94025.

Wright, D.G. 1982. A discussion paper on the effects of explosives on fish and marine mammals in waters of the Northwest Territories. Department of Fisheries and Oceans. Canadian Technical Report of Fisheries and Aquatic Sciences No. 1052.

Wright, L.D., Wiseman, W.J., Bornhold, B.D., Prior, D.B., Suhayda, J.N., Keller, G.H., Yang, Z.S. and Fan,Y.B. 1988. Marine dispersal and deposition of Yellow River silts by gravity-driven underflows. Nature **332**, p.629.

Yelverton, J.T.,Richmond,D.R., Hicks,W., Sanders, ., and Fletcher,E.R.,1975. The relationship between fish size and their response to underwater blast. Defense Nuclear Agency, Department of Defense, Washington, D.C., Technical Report DNA 3667 T., 42p.

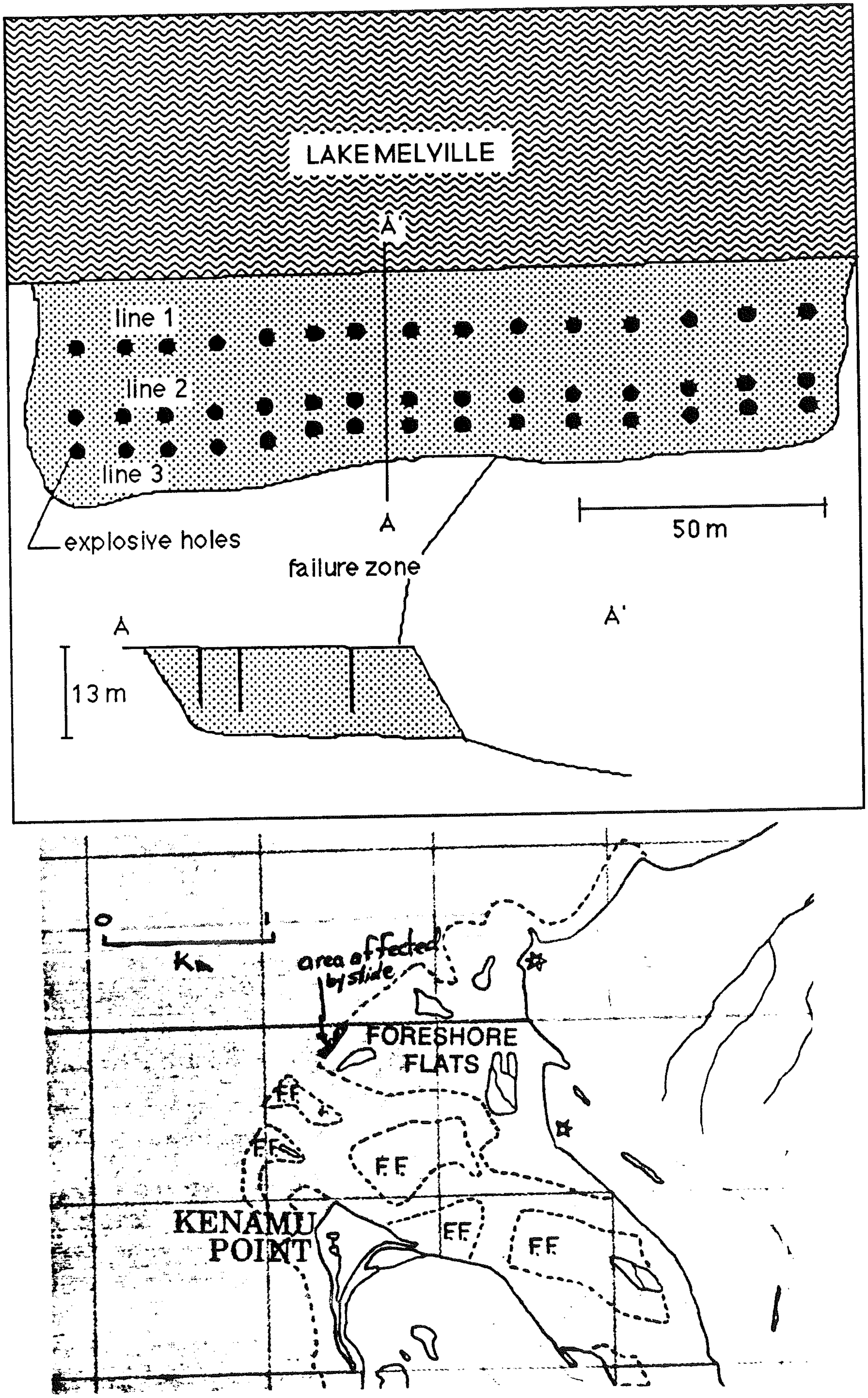

LAKE MELVILLE
A'
line 1
line 2
line 3
explosive holes
A
50 m
failure zone
A
A'
13 m
Km
area affected by slide
FORESHORE FLATS
F.F
F.F
F.F
F.F
F.F
KENAMU POINT

Fig. 2.3.1

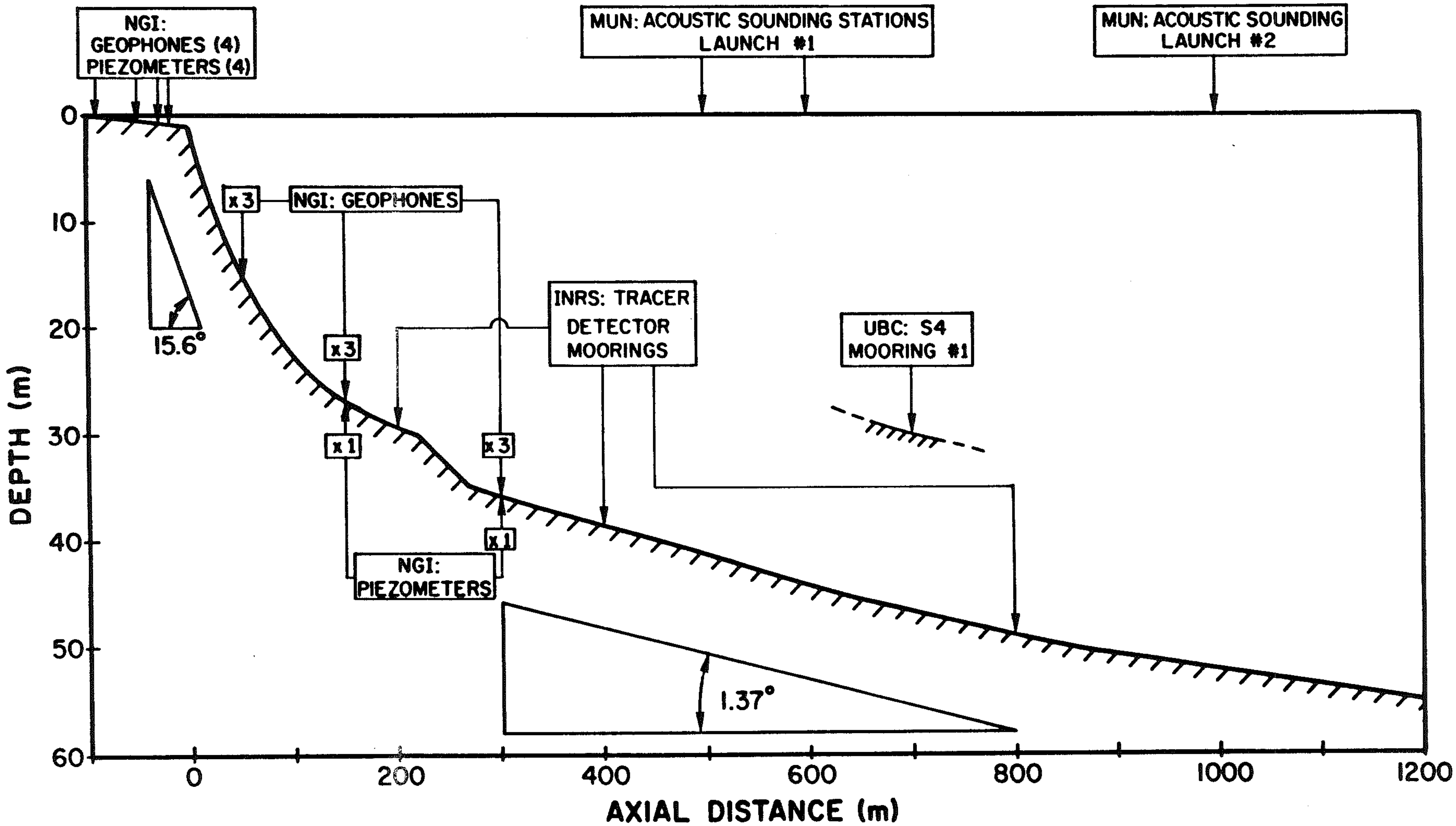

NGI:
GEOPHONES (4)
PIEZOMETERS (4)
MUN: ACOUSTIC SOUNDING STATIONS
LAUNCH #1
MUN: ACOUSTIC SOUNDING
LAUNCH #2
x 3
NGI: GEOPHONES
15.6°
x 3
x 1
x 3
x 1
INRS: TRACER
DETECTOR
MOORINGS
UBC: S4
MOORING #1
NGI:
PIEZOMETERS
1.37°
DEPTH (m)
0
10
20
30
40
50
60
0
200
400
600
800
1000
1200
AXIAL DISTANCE (m)

Figure 2.3.2.

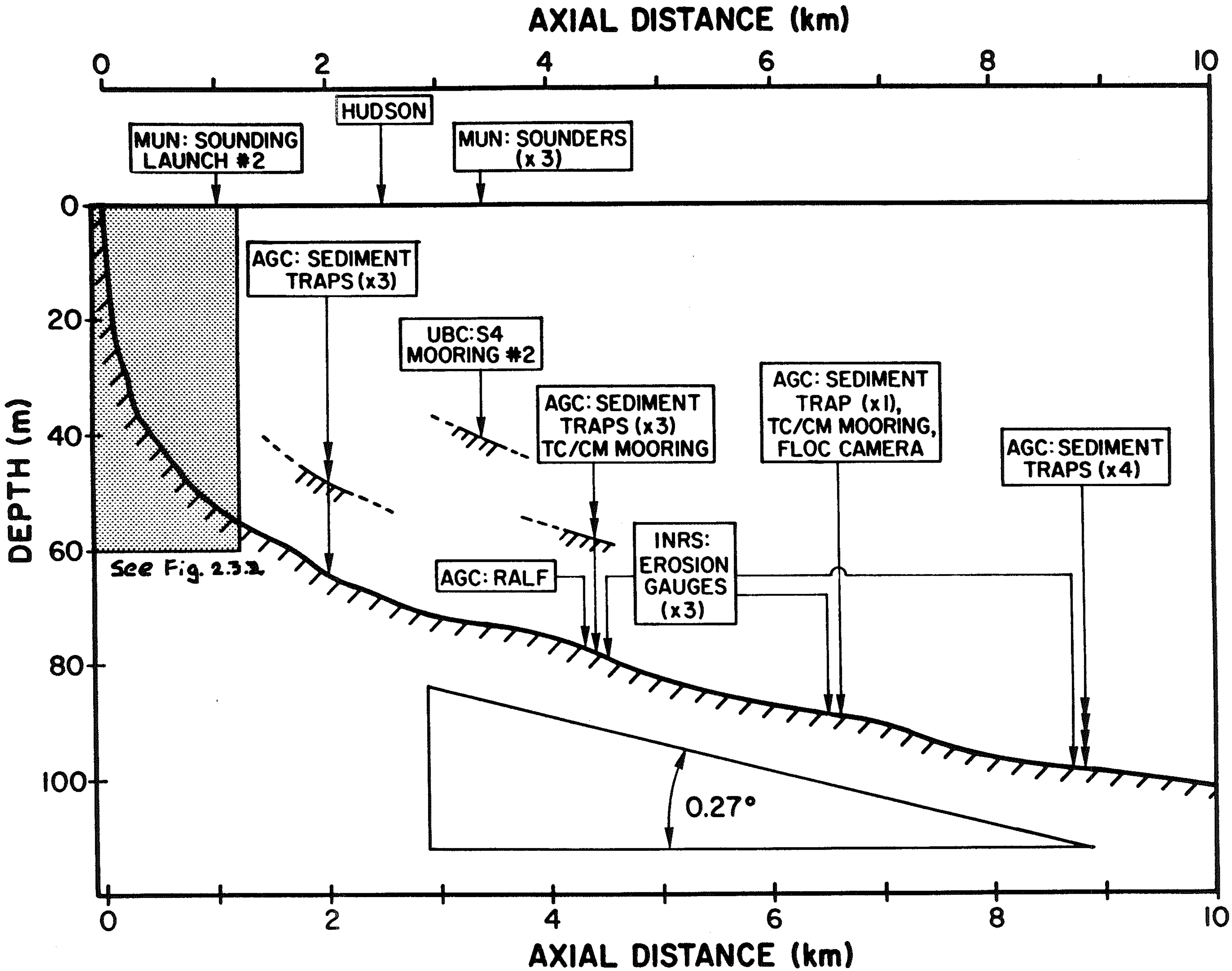

AXIAL DISTANCE (km)
0
2
4
6
8
10
HUDSON
MUN: SOUNDING LAUNCH #2
MUN: SOUNDERS (x 3)
AGC: SEDIMENT TRAPS (x3)
UBC:S4 MOORING #2
AGC: SEDIMENT TRAPS (x3) TC/CM MOORING
AGC: SEDIMENT TRAP (x1), TC/CM MOORING, FLOC CAMERA
AGC: SEDIMENT TRAPS (x4)
INRS: EROSION GAUGES (x3)
AGC: RALF
See Fig. 2.3.2
0.27°
DEPTH (m)
0
20
40
60
80
100
AXIAL DISTANCE (km)

Figure 2.3.3.

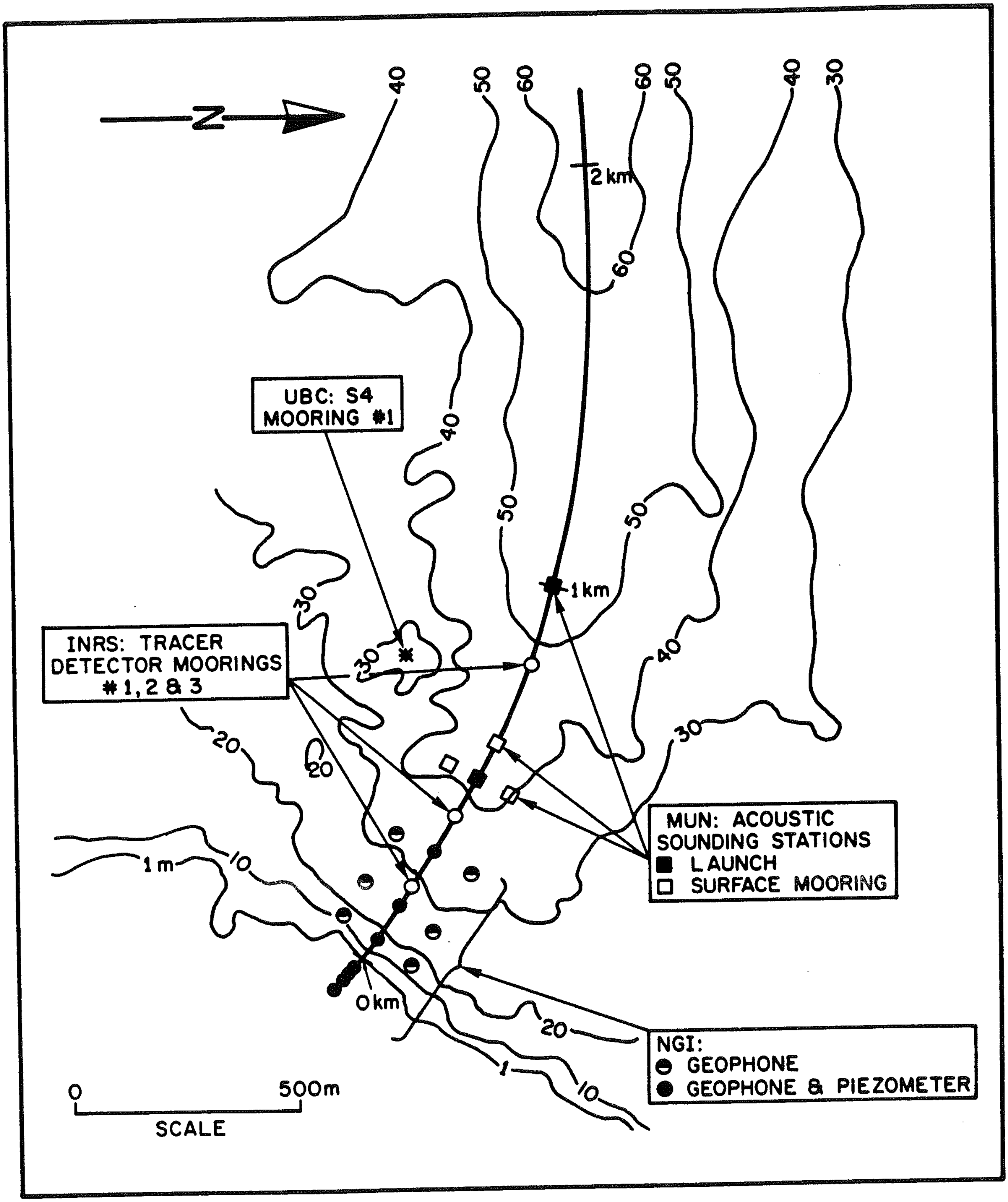

N
UBC: S4
MOORING #1
INRS: TRACER
DETECTOR MOORINGS
#1, 2 & 3
MUN: ACOUSTIC
SOUNDING STATIONS
LAUNCH
SURFACE MOORING
NGI:
GEOPHONE
GEOPHONE & PIEZOMETER
2 km
1 km
0 km
0
500m
SCALE
40
50
60
60
50
40
30
60
40
50
50
40
30
30
30
20
20
20
10
1 m
1
10

Figure 2.3.4.

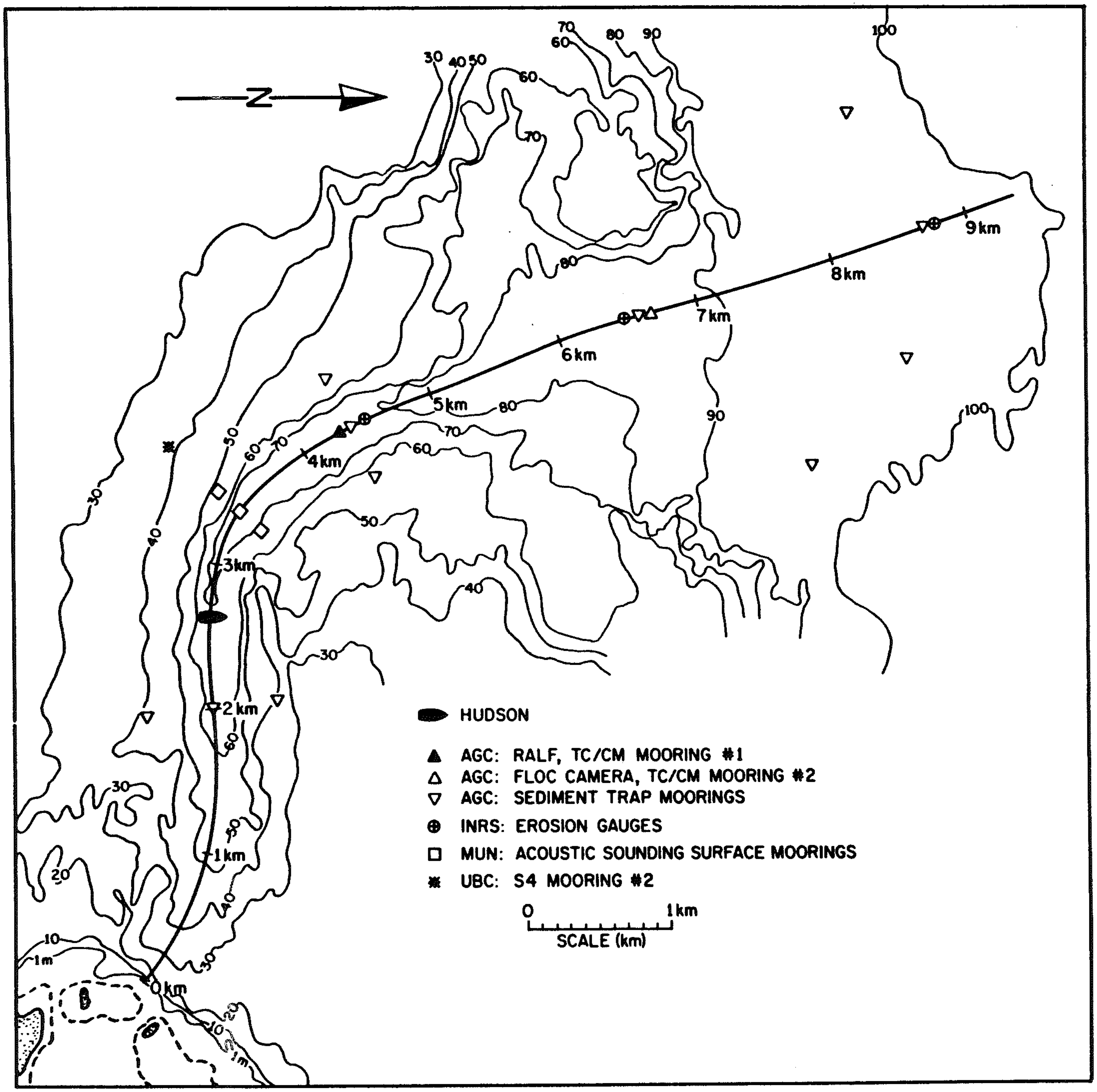

N
HUDSON
AGC: RALF, TC/CM MOORING #1
AGC: FLOC CAMERA, TC/CM MOORING #2
AGC: SEDIMENT TRAP MOORINGS
INRS: EROSION GAUGES
MUN: ACOUSTIC SOUNDING SURFACE MOORINGS
UBC: S4 MOORING #2
0 1km
SCALE (km)
0km
1km
2km
3km
4km
5km
6km
7km
8km
9km

Figure 2.3.5.

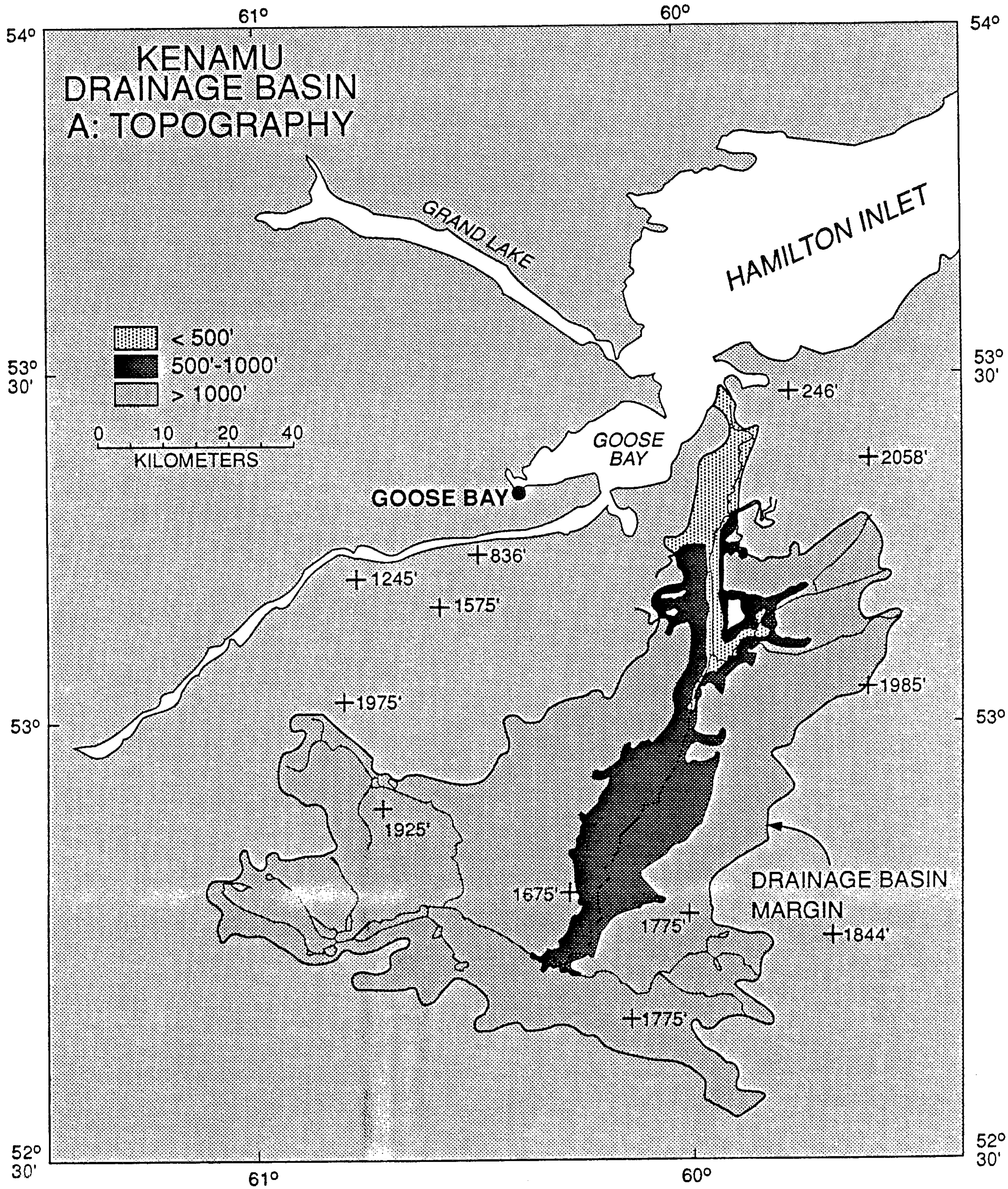

KENAMU
DRAINAGE BASIN
A: TOPOGRAPHY
61°
60°
54°
53° 30'
53°
52° 30'
< 500'
500'-1000'
> 1000'
0 10 20 40
KILOMETERS
GRAND LAKE
HAMILTON INLET
GOOSE BAY
GOOSE BAY
246'
2058'
836'
1245'
1575'
1985'
1975'
1925'
1675'
1775'
1844'
1775'
DRAINAGE BASIN
MARGIN

Figure 3.1.1.A.

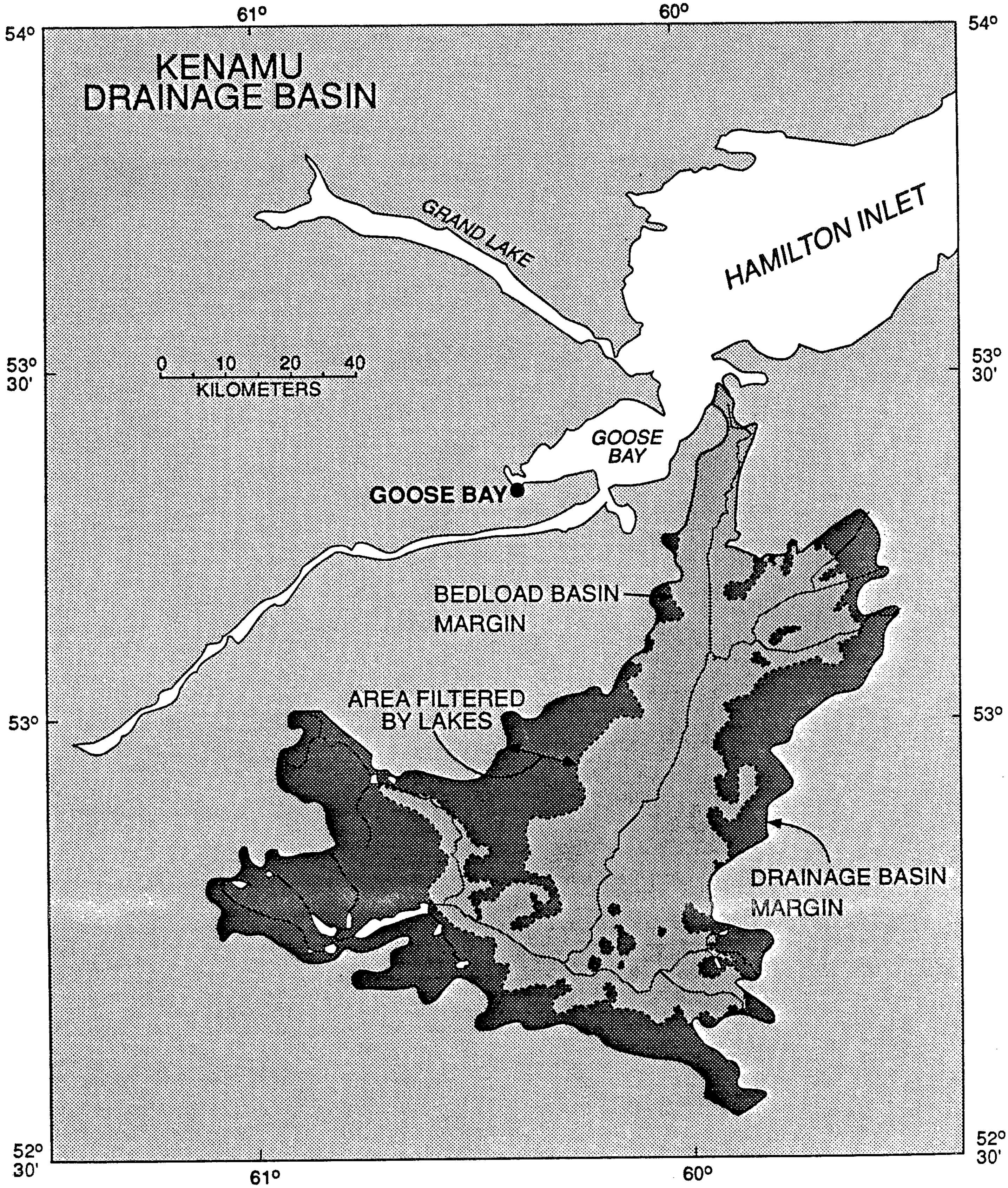

61°
60°
54°
54°
KENAMU
DRAINAGE BASIN
GRAND LAKE
HAMILTON INLET
53° 30'
53° 30'
0 10 20 40
KILOMETERS
GOOSE BAY
GOOSE BAY
BEDLOAD BASIN MARGIN
AREA FILTERED BY LAKES
53°
53°
DRAINAGE BASIN MARGIN
52° 30'
52° 30'
61°
60°

Figure 3.1.1.B.

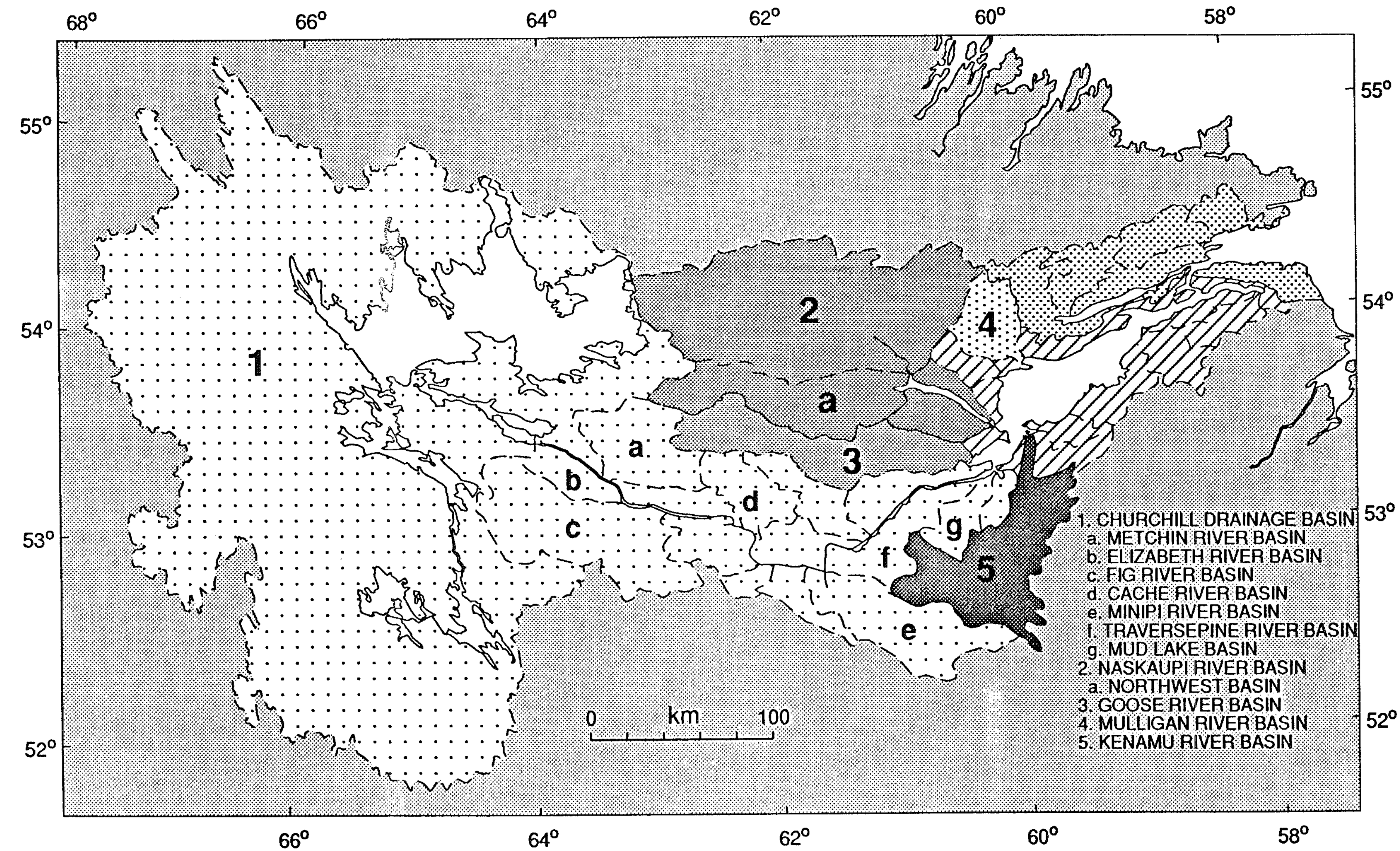

68°
66°
64°
62°
60°
58°
55°
54°
53°
52°
1
2
3
4
5
a
b
c
d
e
f
g
0 km 100
1. CHURCHILL DRAINAGE BASIN
a. METCHIN RIVER BASIN
b. ELIZABETH RIVER BASIN
c. FIG RIVER BASIN
d. CACHE RIVER BASIN
e. MINIPI RIVER BASIN
f. TRAVERSEPINE RIVER BASIN
g. MUD LAKE BASIN
2. NASKAUPI RIVER BASIN
a. NORTHWEST BASIN
3. GOOSE RIVER BASIN
4. MULLIGAN RIVER BASIN
5. KENAMU RIVER BASIN
CHURCHILL RIVER DRANAGE

Figure 3.1.2.

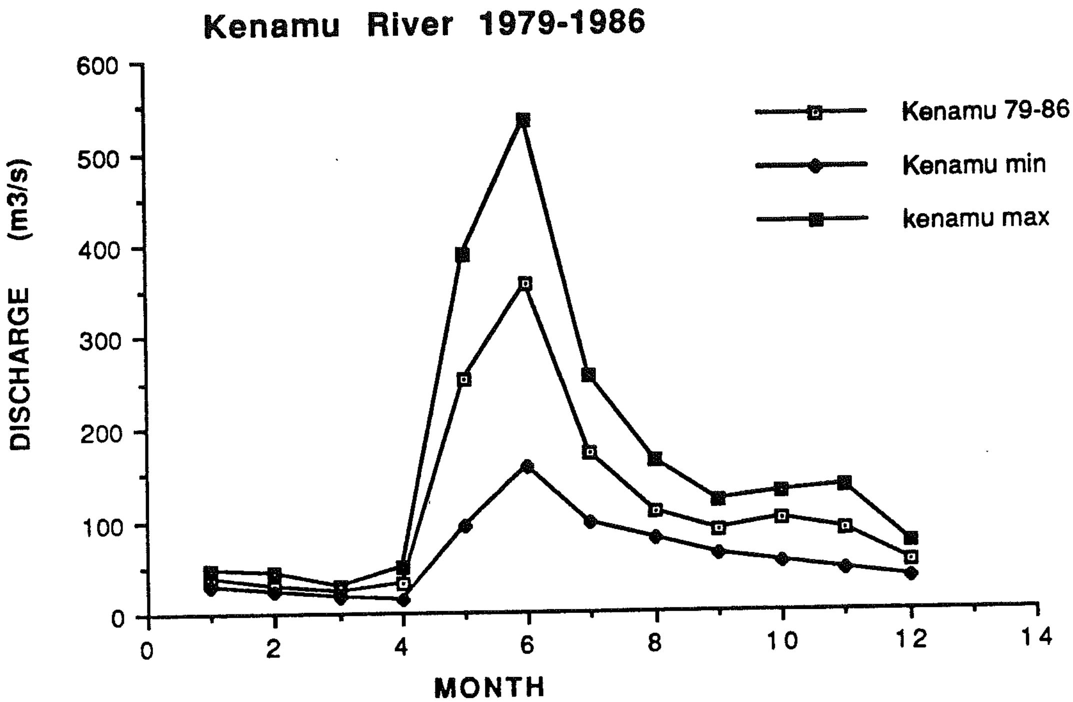
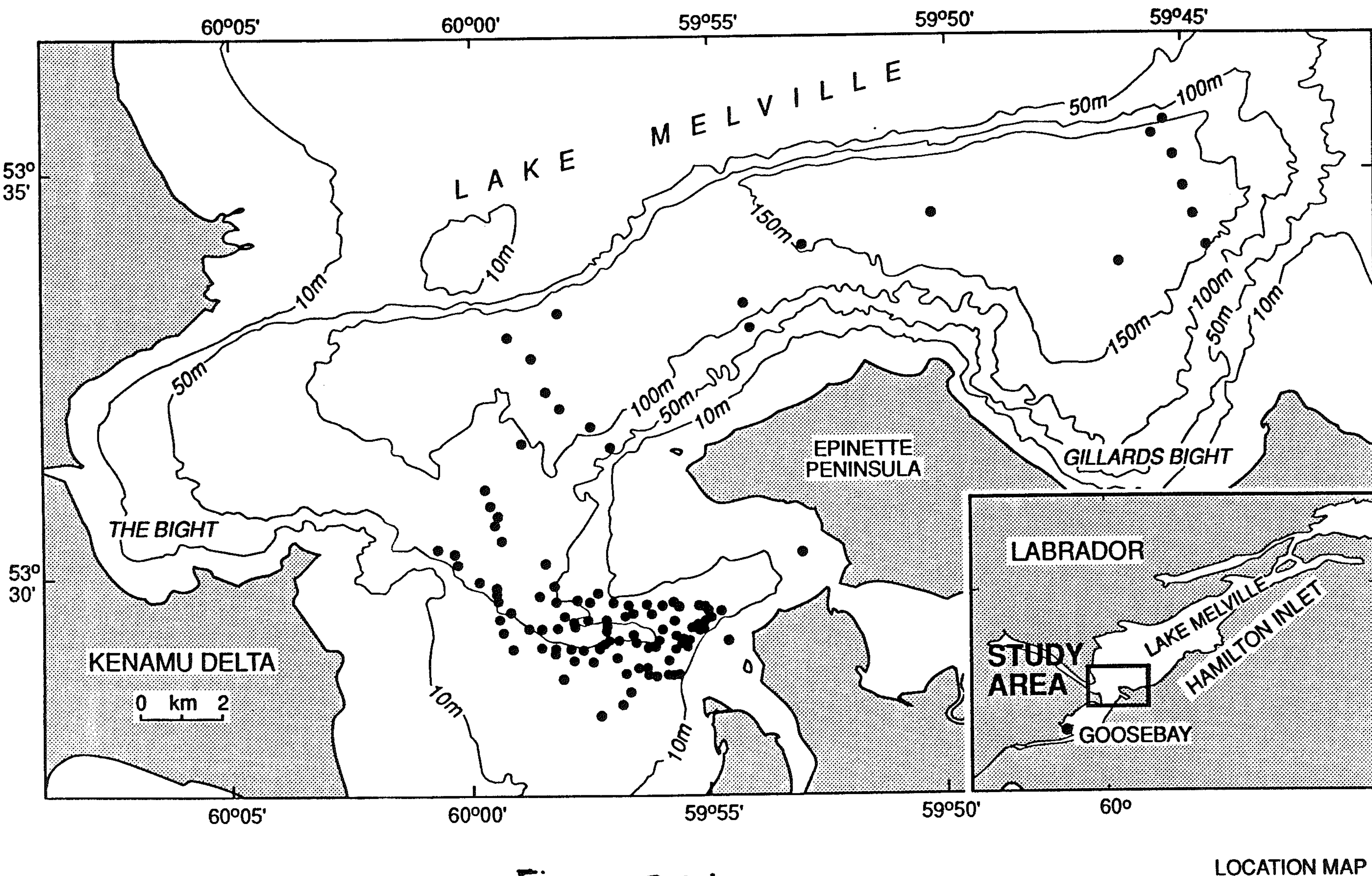

Kenamu River 1979-1986
DISCHARGE (m3/s)
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
MONTH
Kenamu 79-86
Kenamu min
kenamu max

Figure 3.1.3.



LAKE MELVILLE
60°05'
60°00'
59°55'
59°50'
59°45'
53° 35'
53° 30'
10m
50m
100m
150m
EPINETTE PENINSULA
GILLARDS BIGHT
THE BIGHT
KENAMU DELTA
0 km 2
LABRADOR
LAKE MELVILLE
HAMILTON INLET
STUDY AREA
GOOSEBAY
54°
60°
LOCATION MAP

Figure 3.2.1

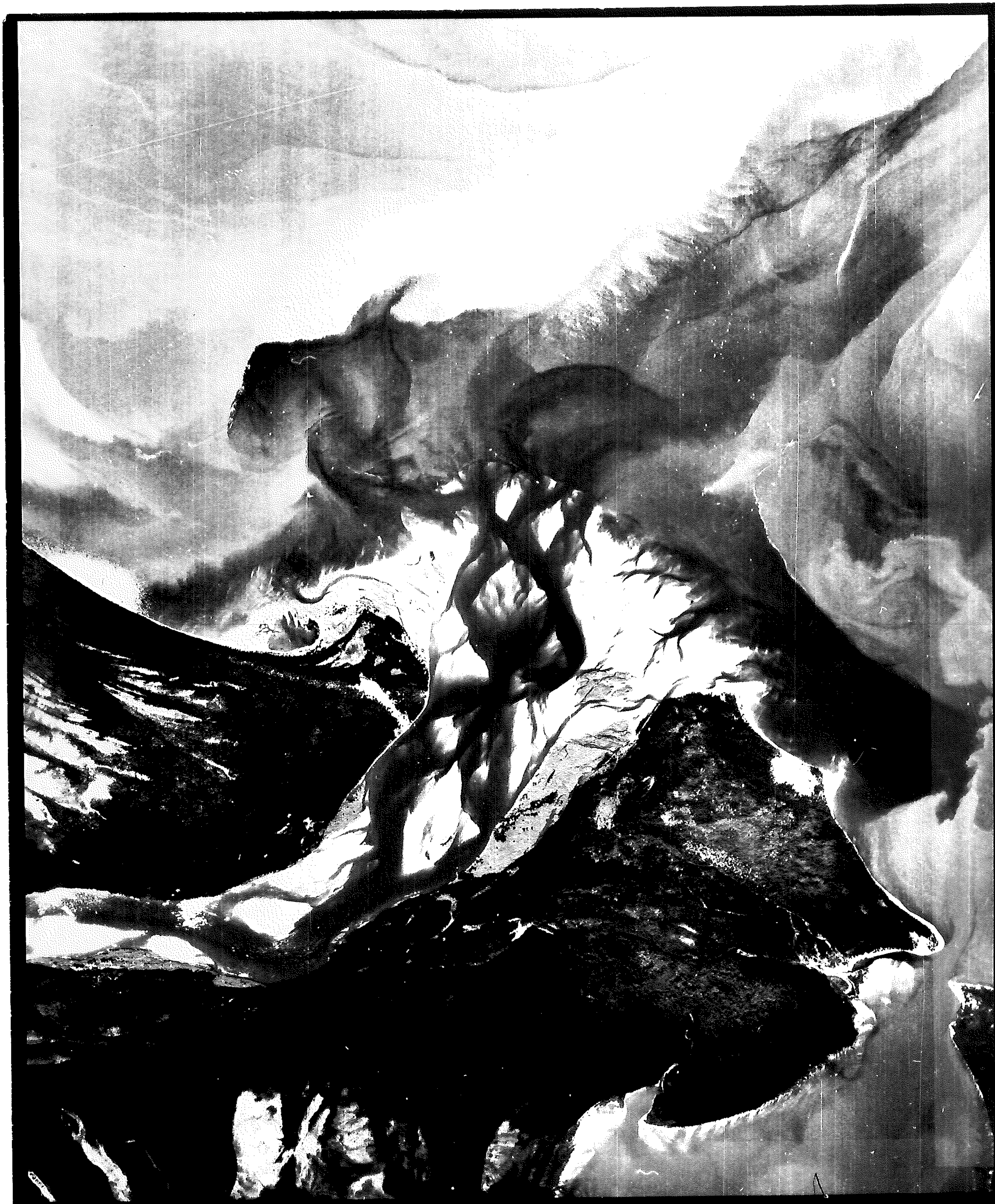


Figure 3.3.1.

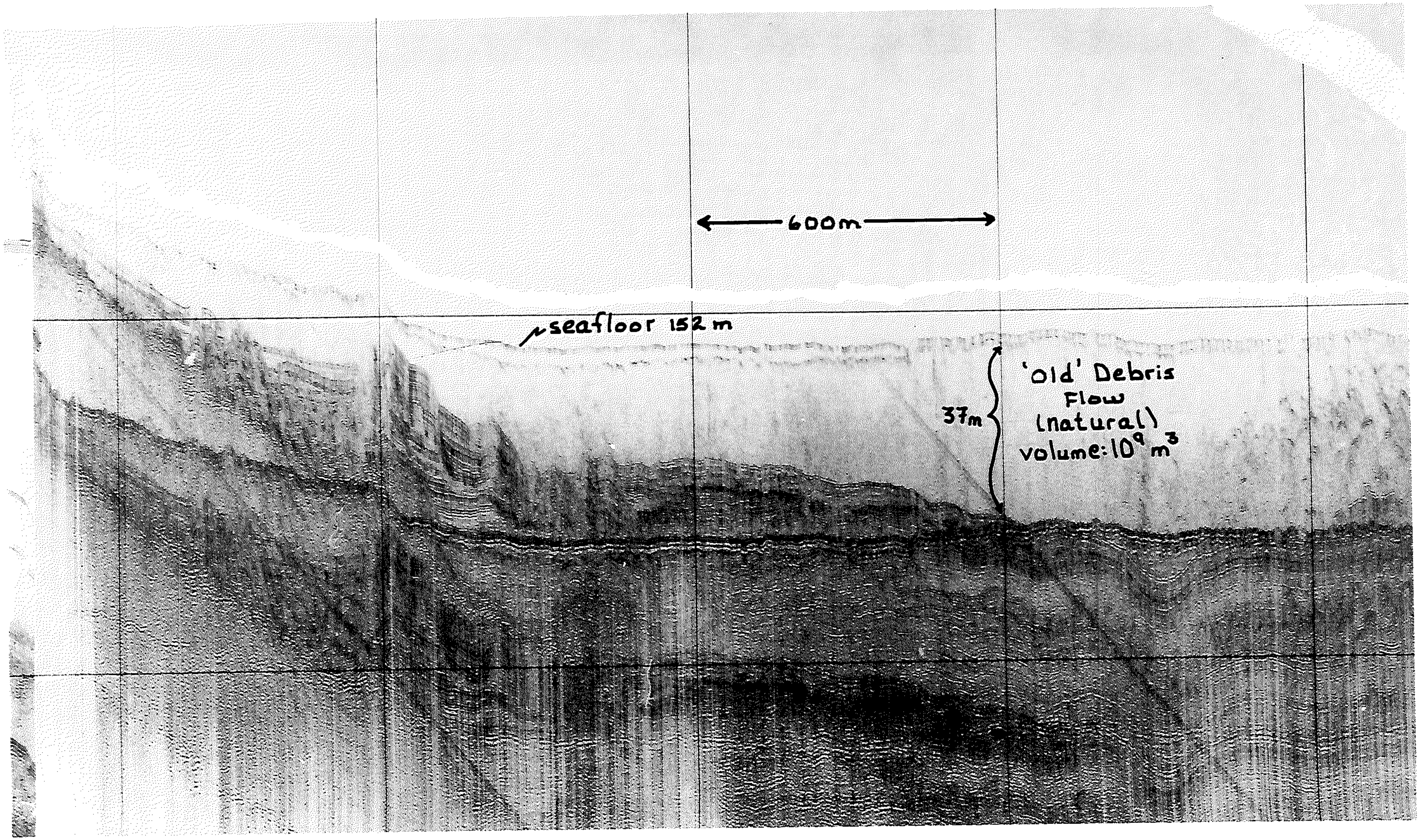

600m
seafloor 152 m
37m
'Old' Debris
Flow
(natural)
volume: 10^9 m^3

Figure 3.5.1.

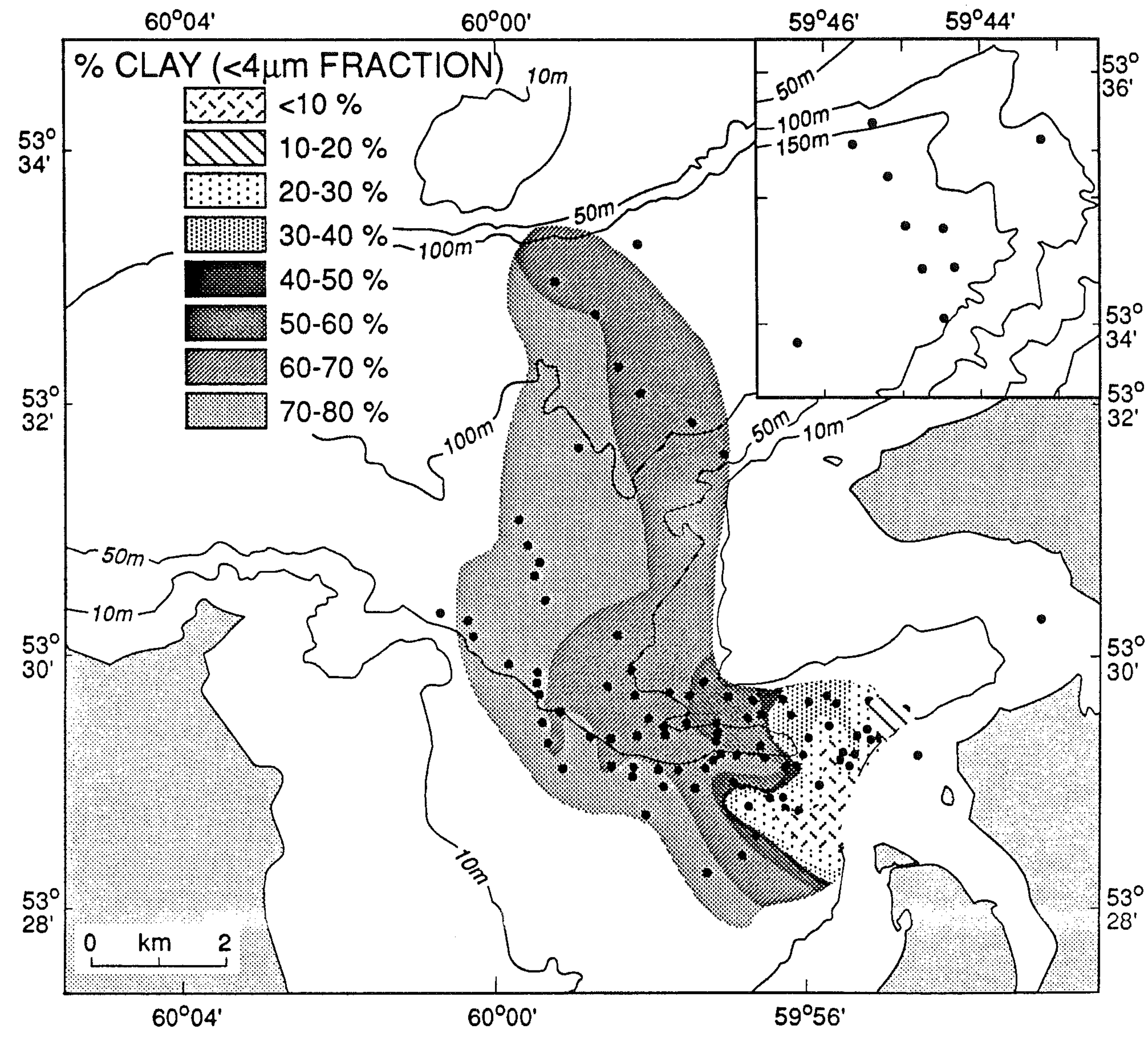
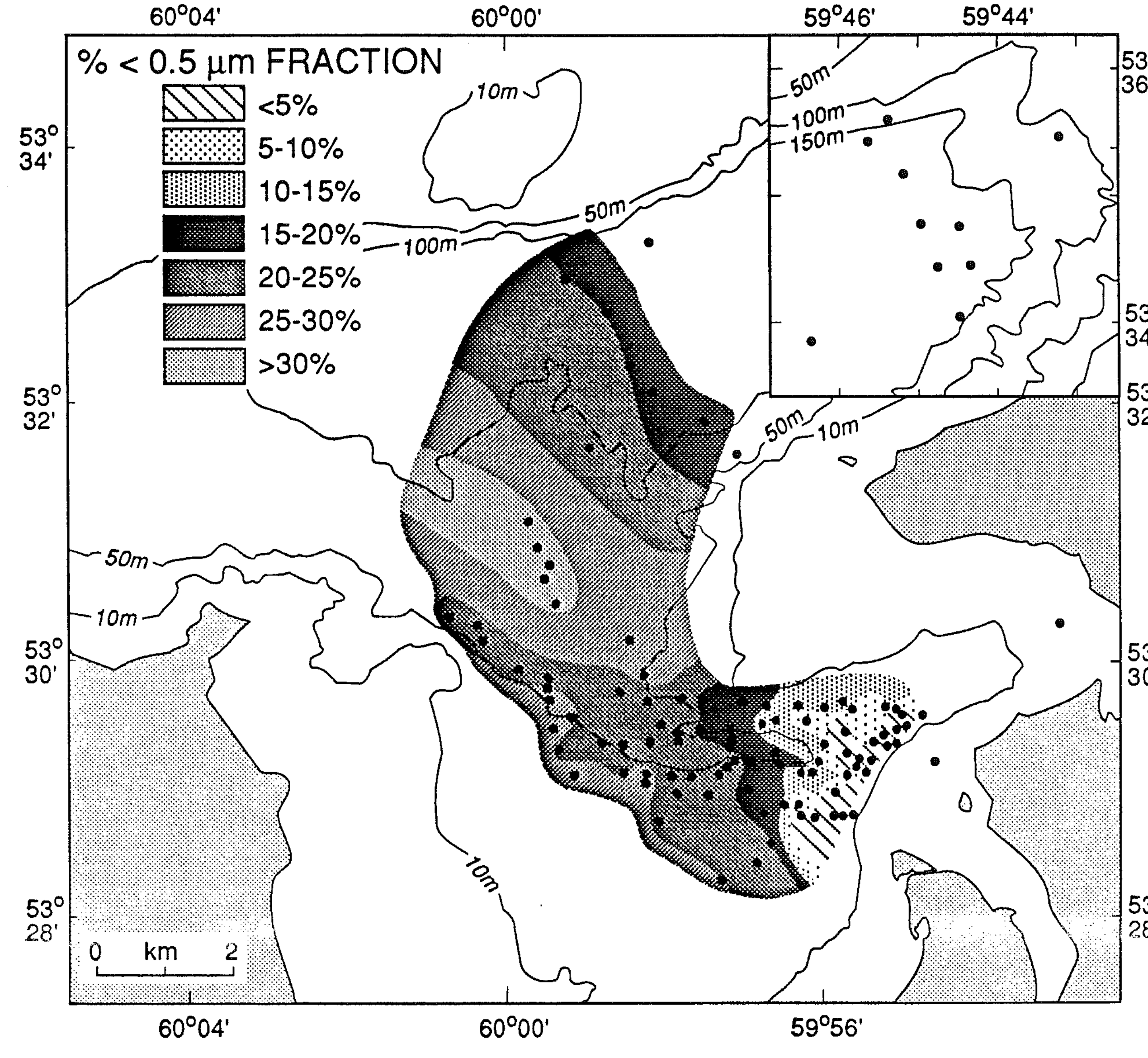

% CLAY (<4μm FRACTION)
<10 %
10-20 %
20-30 %
30-40 %
40-50 %
50-60 %
60-70 %
70-80 %
60°04'
60°00'
59°46'
59°44'
59°56'
53° 34'
53° 32'
53° 30'
53° 28'
53° 36'
10m
50m
100m
150m
0 km 2

Fig. 3. 6.1.



% < 0.5 µm FRACTION
<5%
5-10%
10-15%
15-20%
20-25%
25-30%
>30%
60°04'
60°00'
59°46'
59°44'
59°56'
53° 34'
53° 32'
53° 30'
53° 28'
53° 36'
10m
50m
100m
150m
0 km 2

Fig. 3.6.2.

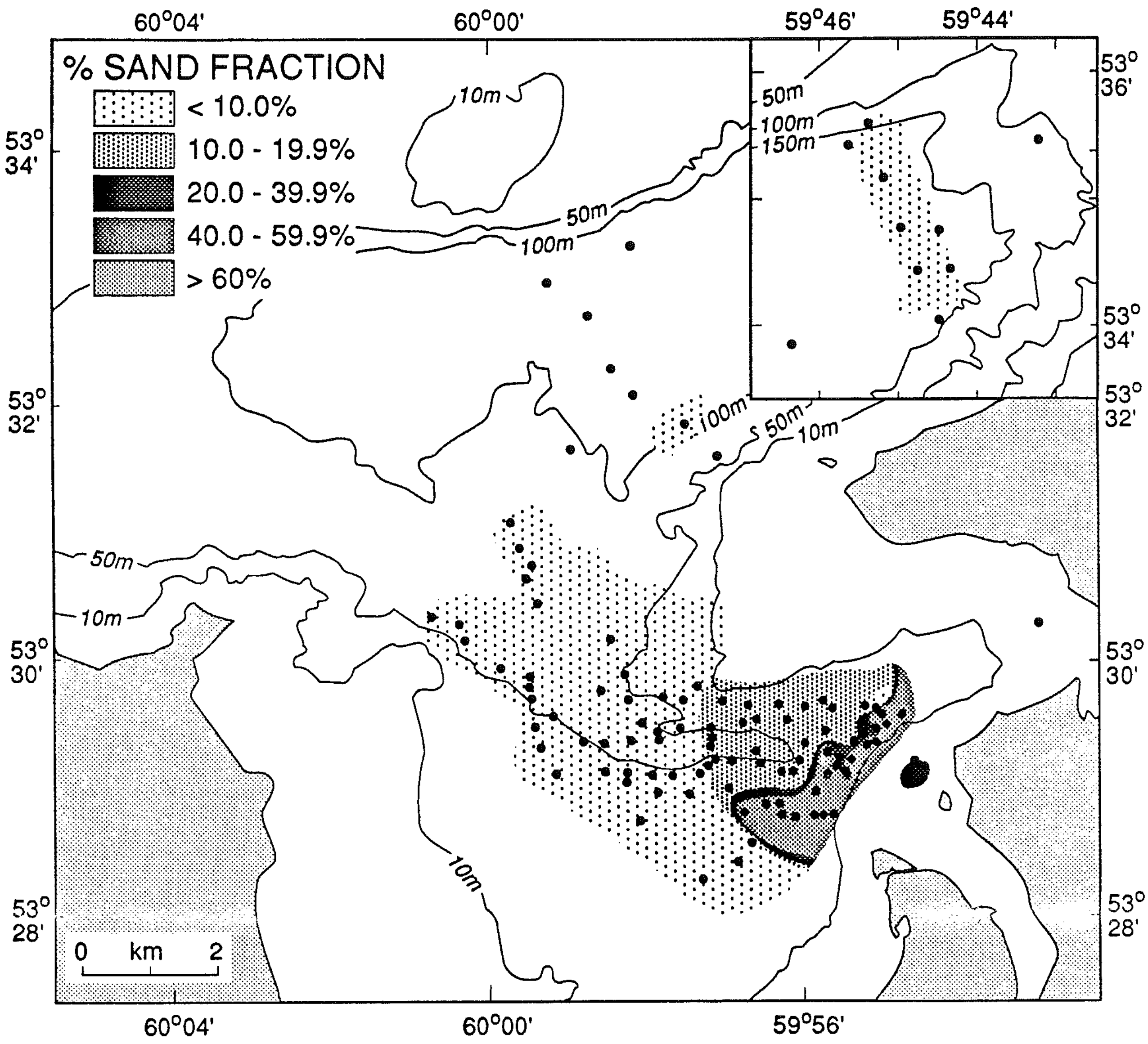
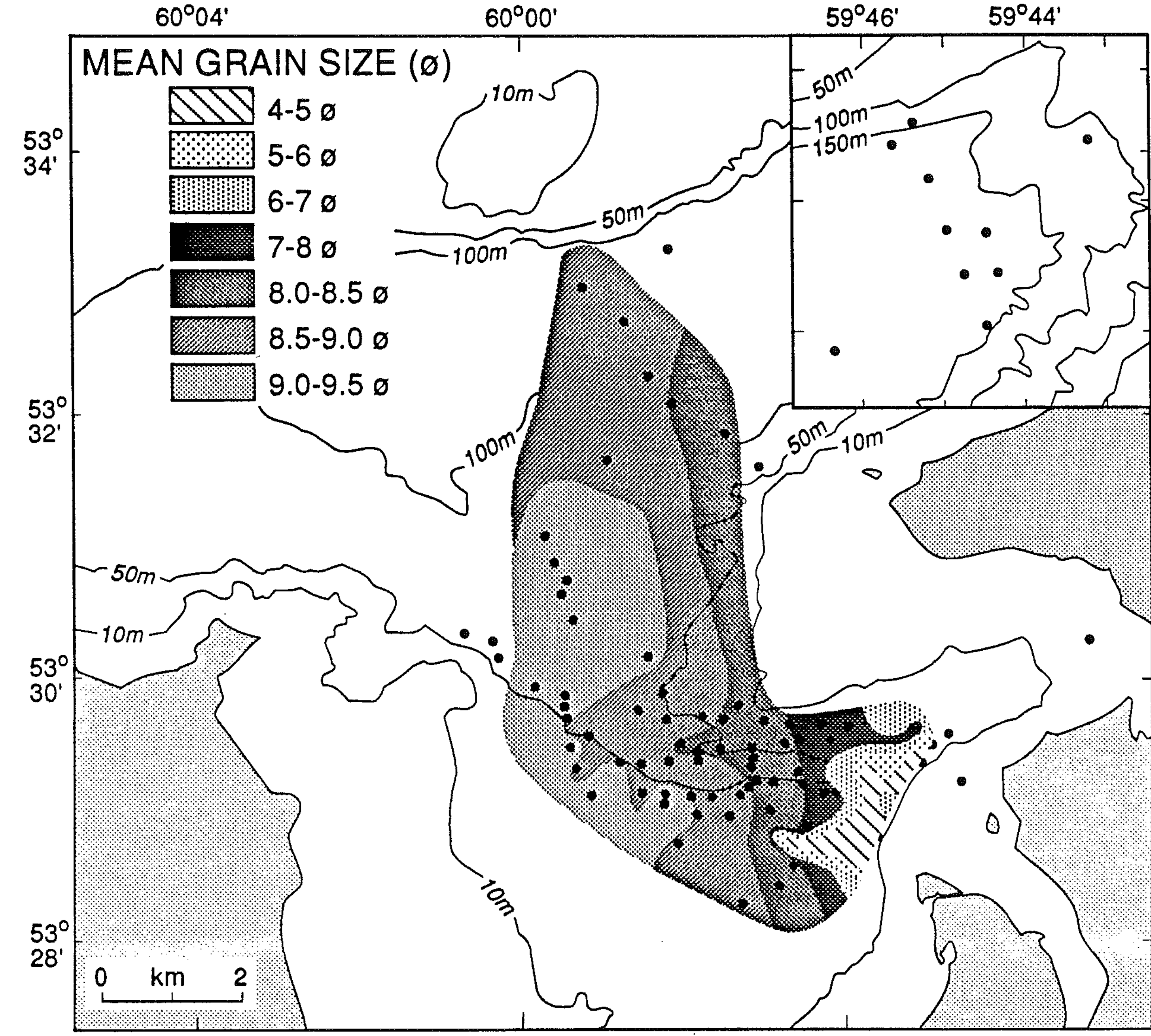
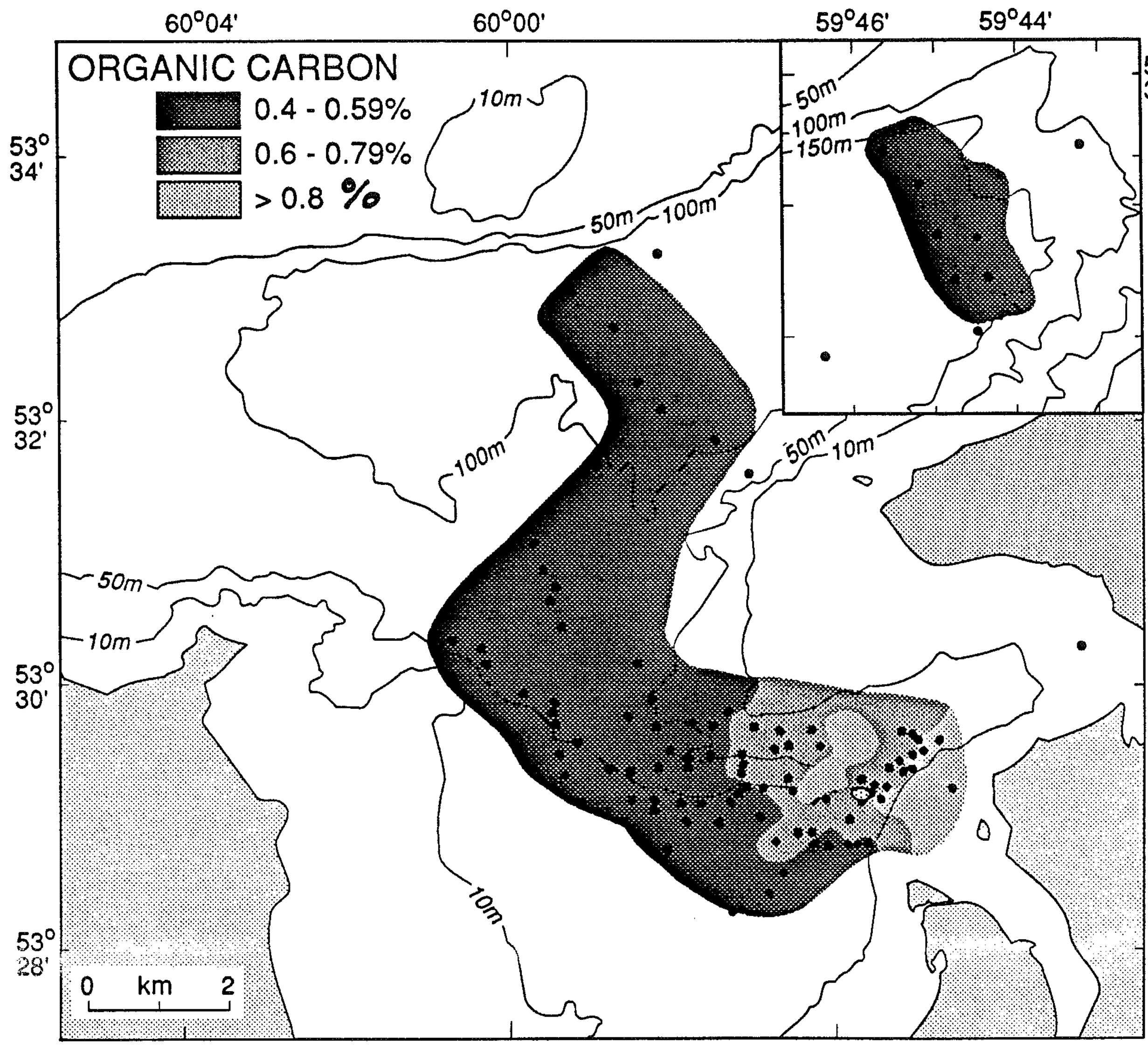

% SAND FRACTION
< 10.0%
10.0 - 19.9%
20.0 - 39.9%
40.0 - 59.9%
> 60%
60°04'
60°00'
59°46'
59°44'
59°56'
53° 36'
53° 34'
53° 32'
53° 30'
53° 28'
10m
50m
100m
150m
0 km 2

Fig. 3.6.3.



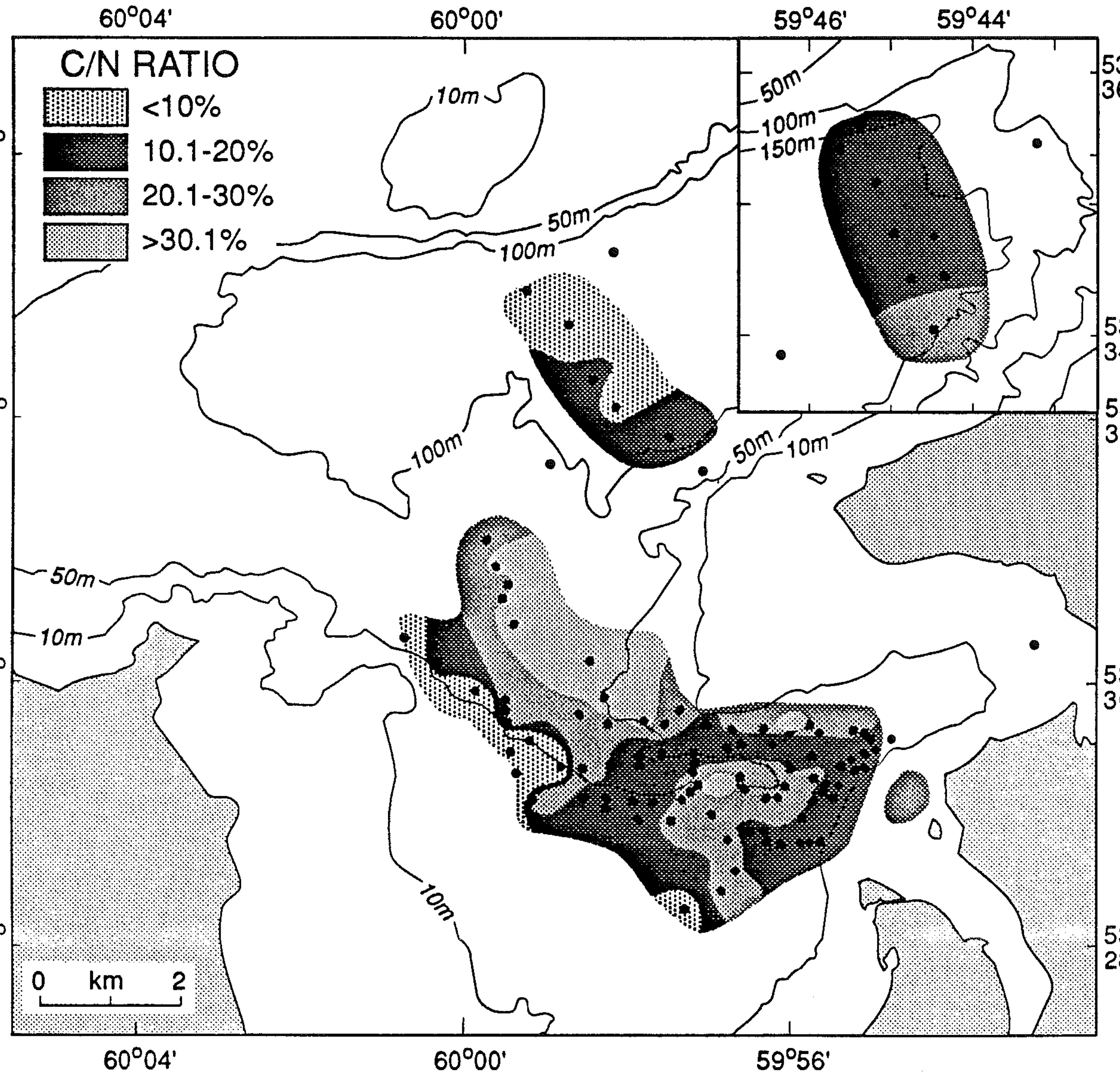
MEAN GRAIN SIZE (ø)
4-5 ø
5-6 ø
6-7 ø
7-8 ø
8.0-8.5 ø
8.5-9.0 ø
9.0-9.5 ø
60°04'
60°00'
59°46'
59°44'
59°56'
53° 34'
53° 32'
53° 30'
53° 28'
53° 36'
10m
50m
100m
150m
0 km 2

Fig. 3.6.4.



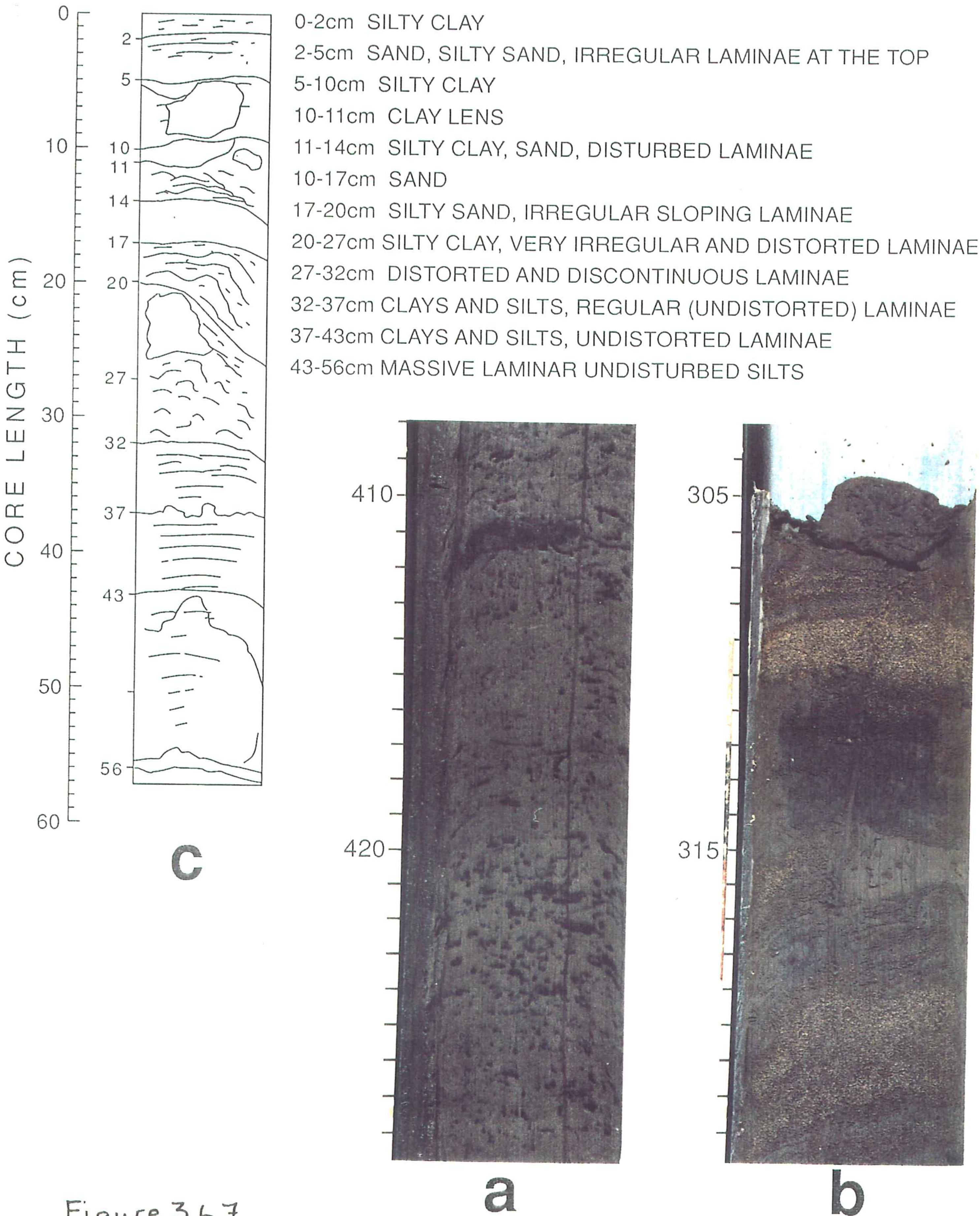
ORGANIC CARBON
0.4 - 0.59%
0.6 - 0.79%
> 0.8 %
60°04'
60°00'
59°46'
59°44'
59°56'
53° 34'
53° 32'
53° 30'
53° 28'
53° 36'
10m
50m
100m
150m
0 km 2

Figure 3.6.5.



C/N RATIO
<10%
10.1-20%
20.1-30%
>30.1%
60°04'
60°00'
59°46'
59°44'
59°56'
53° 34'
53° 32'
53° 30'
53° 28'
53° 36'
10m
50m
100m
150m
0 km 2

Figure 3.6.6.



CORE LENGTH (cm)
0
10
20
30
40
50
60
2
5
10
11
14
17
20
27
32
37
43
56
0-2cm SILTY CLAY
2-5cm SAND, SILTY SAND, IRREGULAR LAMINAE AT THE TOP
5-10cm SILTY CLAY
10-11cm CLAY LENS
11-14cm SILTY CLAY, SAND, DISTURBED LAMINAE
10-17cm SAND
17-20cm SILTY SAND, IRREGULAR SLOPING LAMINAE
20-27cm SILTY CLAY, VERY IRREGULAR AND DISTORTED LAMINAE
27-32cm DISTORTED AND DISCONTINUOUS LAMINAE
32-37cm CLAYS AND SILTS, REGULAR (UNDISTORTED) LAMINAE
37-43cm CLAYS AND SILTS, UNDISTORTED LAMINAE
43-56cm MASSIVE LAMINAR UNDISTURBED SILTS
c
410
420
a
305
315
b

Figure 3.6.7.

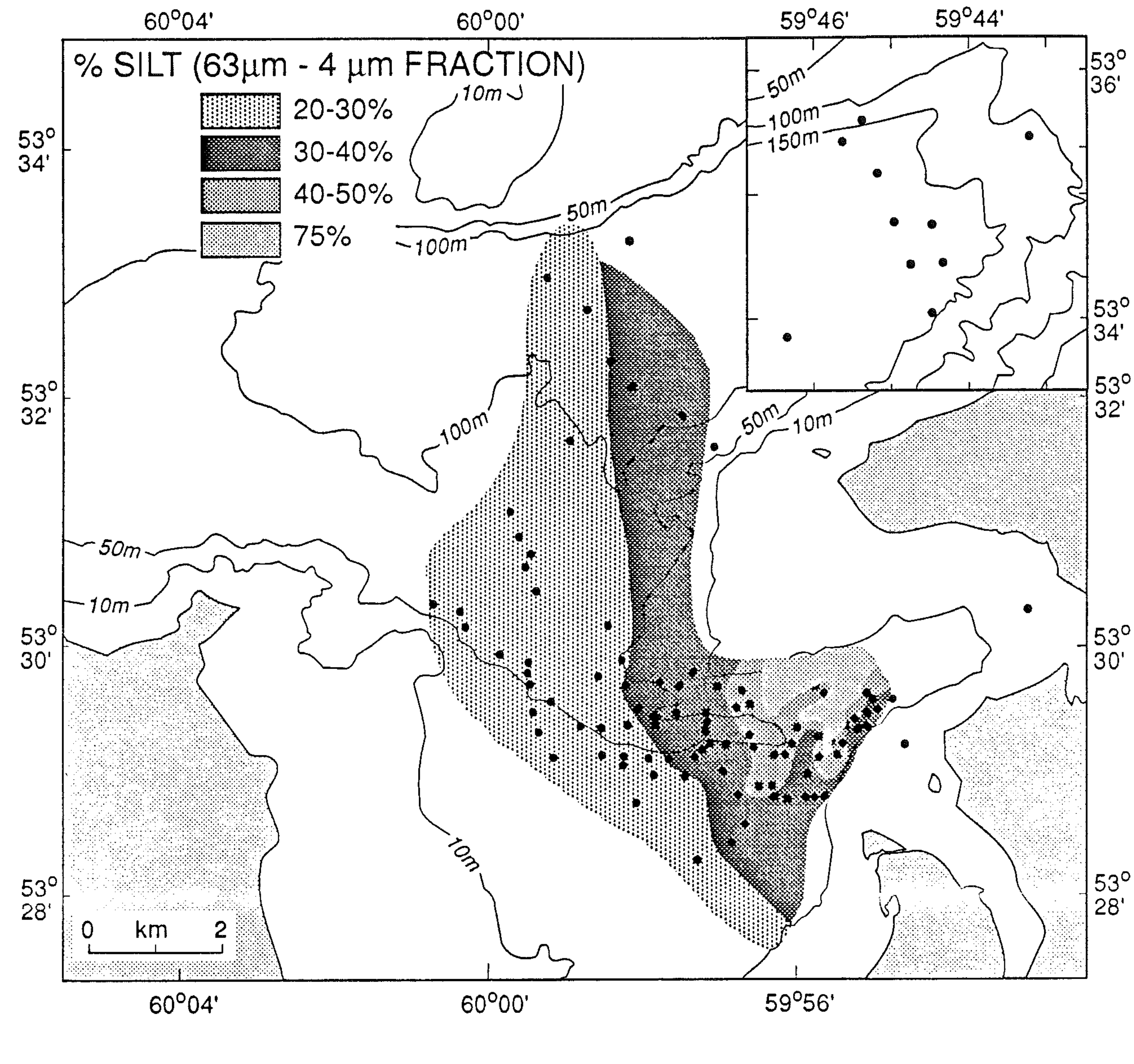
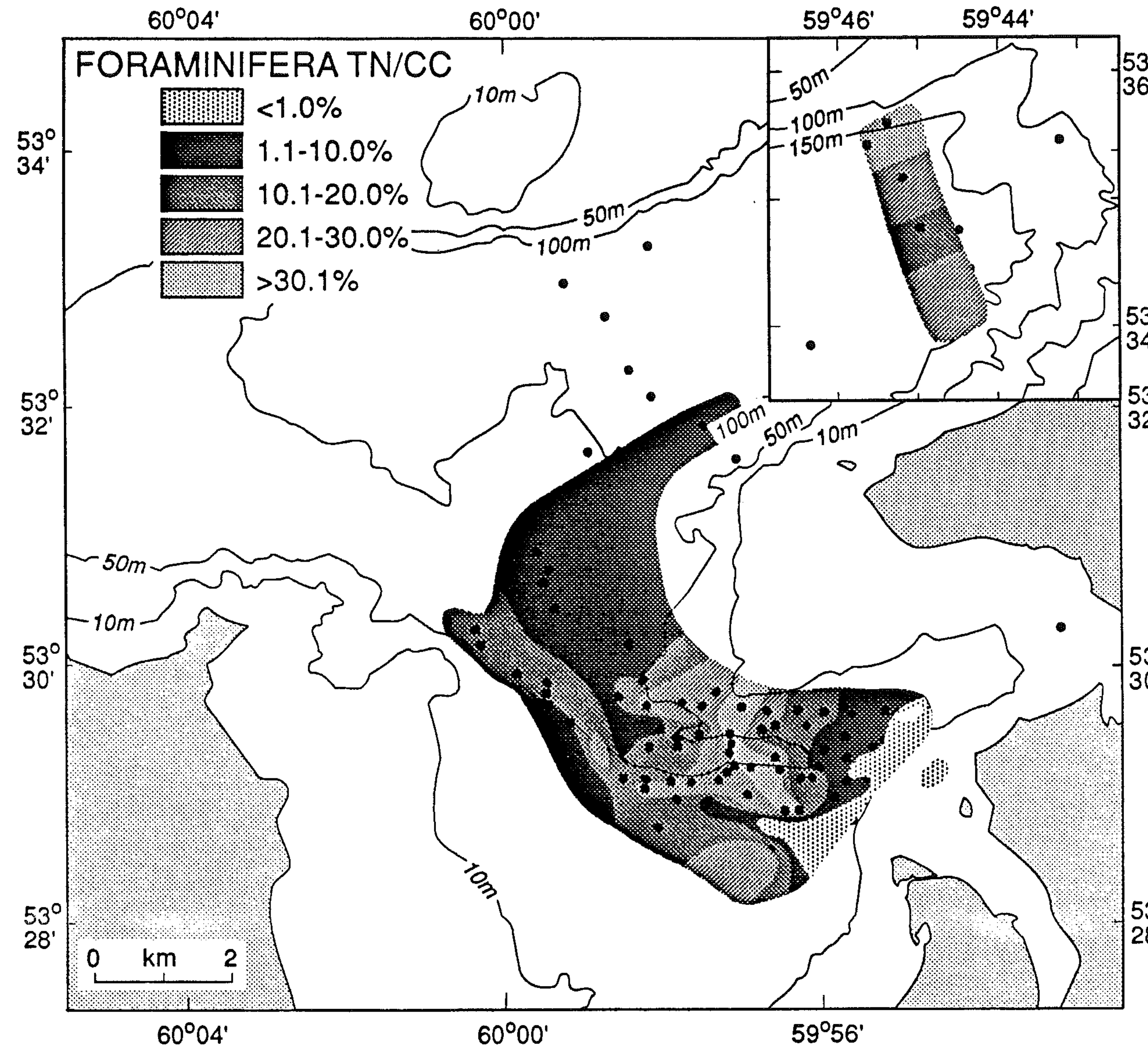

% SILT (63µm - 4 µm FRACTION)
20-30%
30-40%
40-50%
75%
60°04'
60°00'
59°46'
59°44'
59°56'
53° 34'
53° 32'
53° 30'
53° 28'
53° 36'
10m
50m
100m
150m
0 km 2

Figure 3.6.8.



FORAMINIFERA TN/CC
<1.0%
1.1-10.0%
10.1-20.0%
20.1-30.0%
>30.1%
60°04'
60°00'
59°46'
59°44'
59°56'
53° 34'
53° 32'
53° 30'
53° 28'
53° 36'
10m
50m
100m
150m
0 km 2

Figure 3.7.1.1.

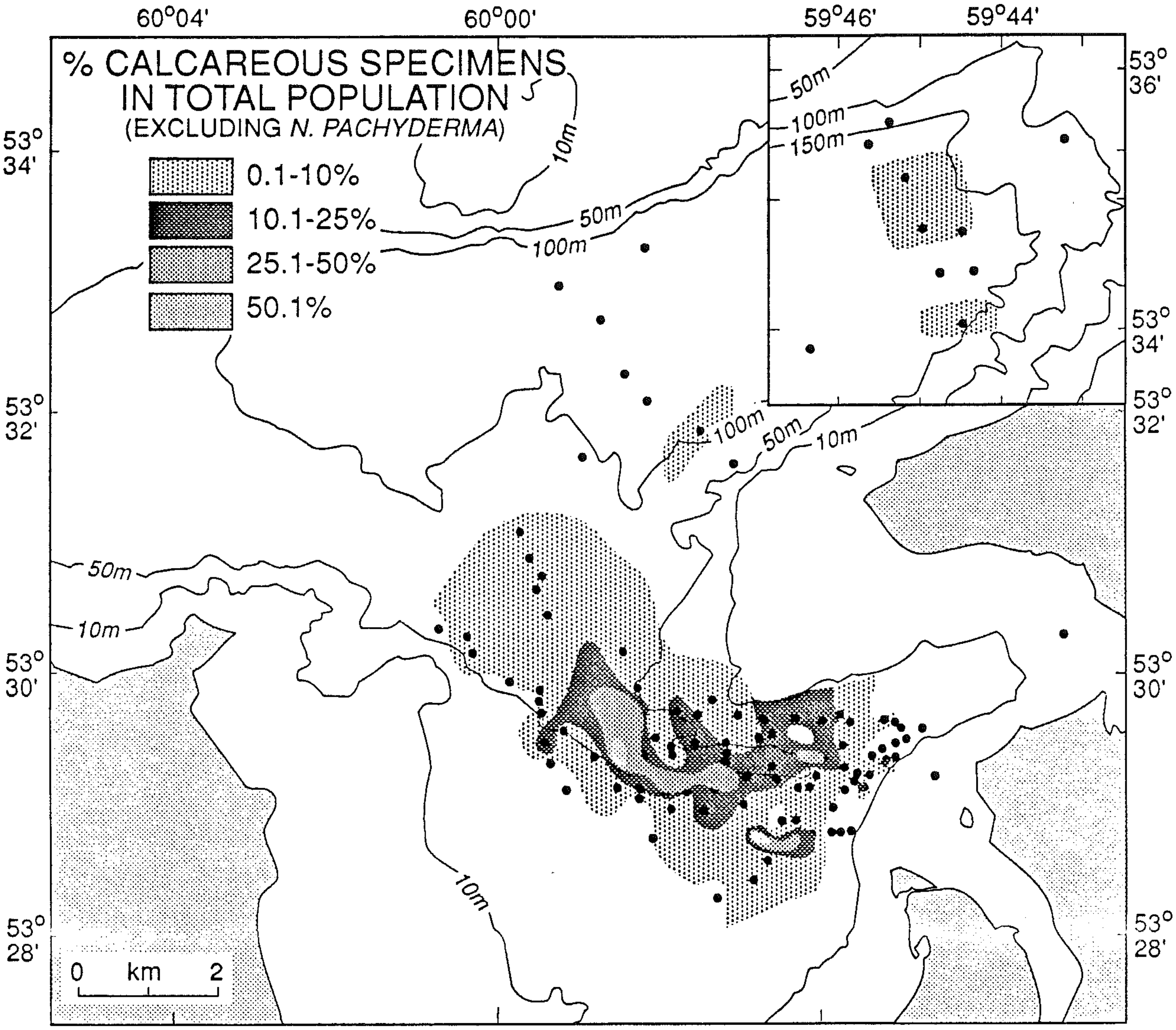
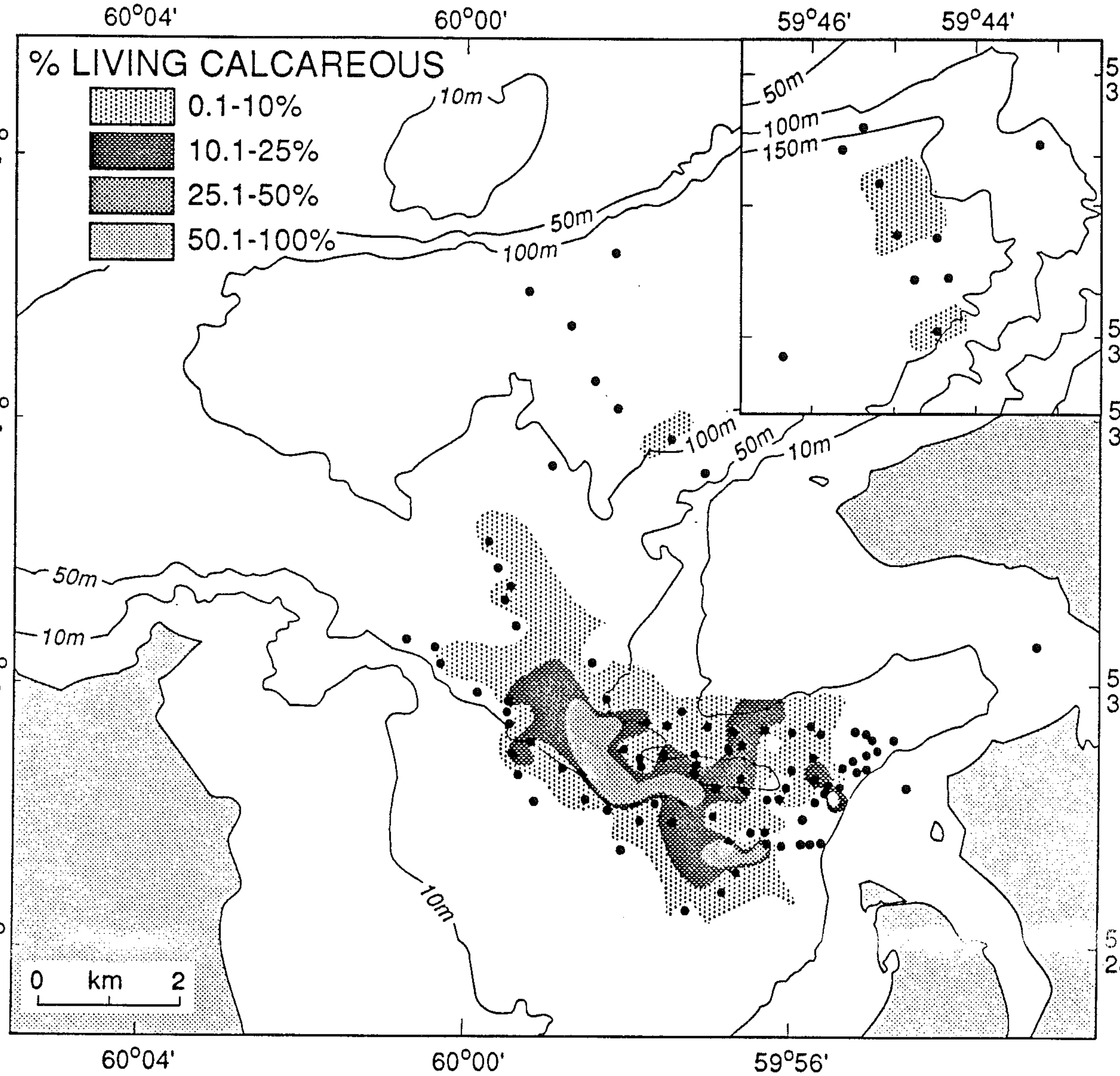

% CALCAREOUS SPECIMENS IN TOTAL POPULATION
(EXCLUDING N. PACHYDERMA)
0.1-10%
10.1-25%
25.1-50%
50.1%
60°04'
60°00'
59°46'
59°44'
59°56'
53° 36'
53° 34'
53° 32'
53° 30'
53° 28'
10m
50m
100m
150m
0 km 2

Figure 3.7.1.2.



% LIVING CALCAREOUS
0.1-10%
10.1-25%
25.1-50%
50.1-100%
60°04'
60°00'
59°46'
59°44'
59°56'
53° 36'
53° 34'
53° 32'
53° 30'
53° 28'
10m
50m
100m
150m
0 km 2

Figure 3.7.1.3.

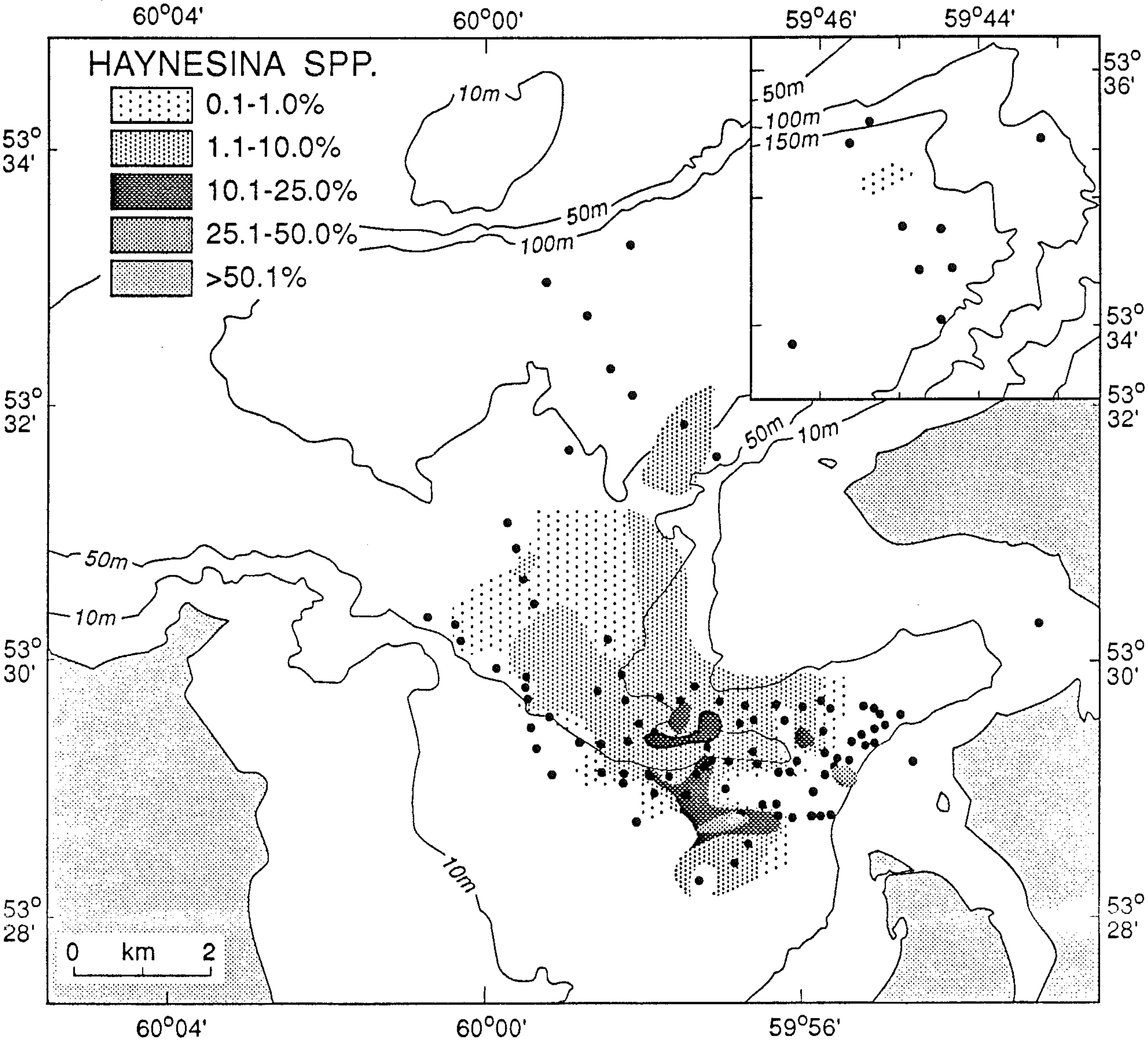

HAYNESINA SPP.
0.1-1.0%
1.1-10.0%
10.1-25.0%
25.1-50.0%
>50.1%
60°04'
60°00'
59°56'
59°46'
59°44'
53° 36'
53° 34'
53° 32'
53° 30'
53° 28'
10m
50m
100m
150m
0 km 2

Figure 3.7.1.4.

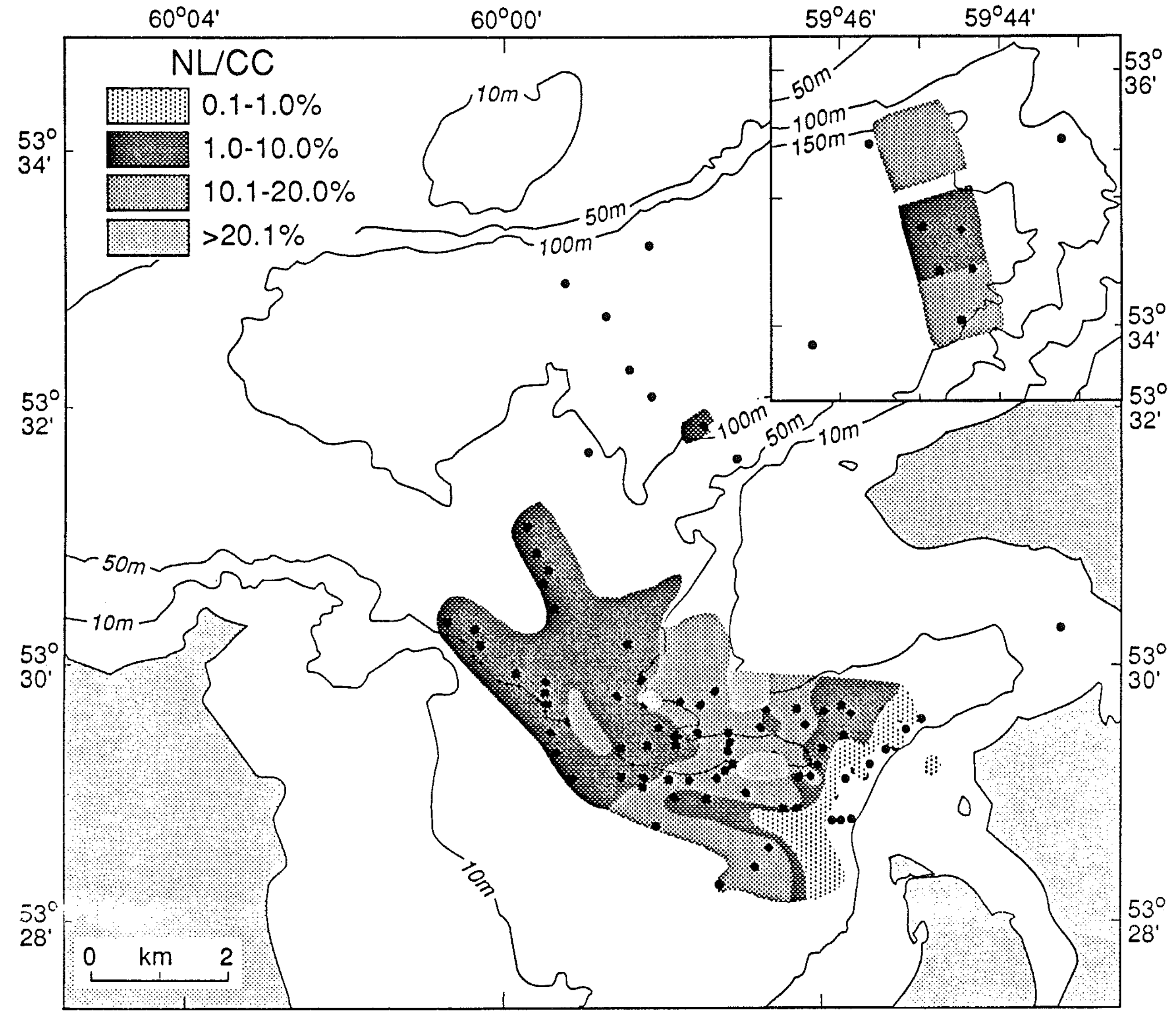
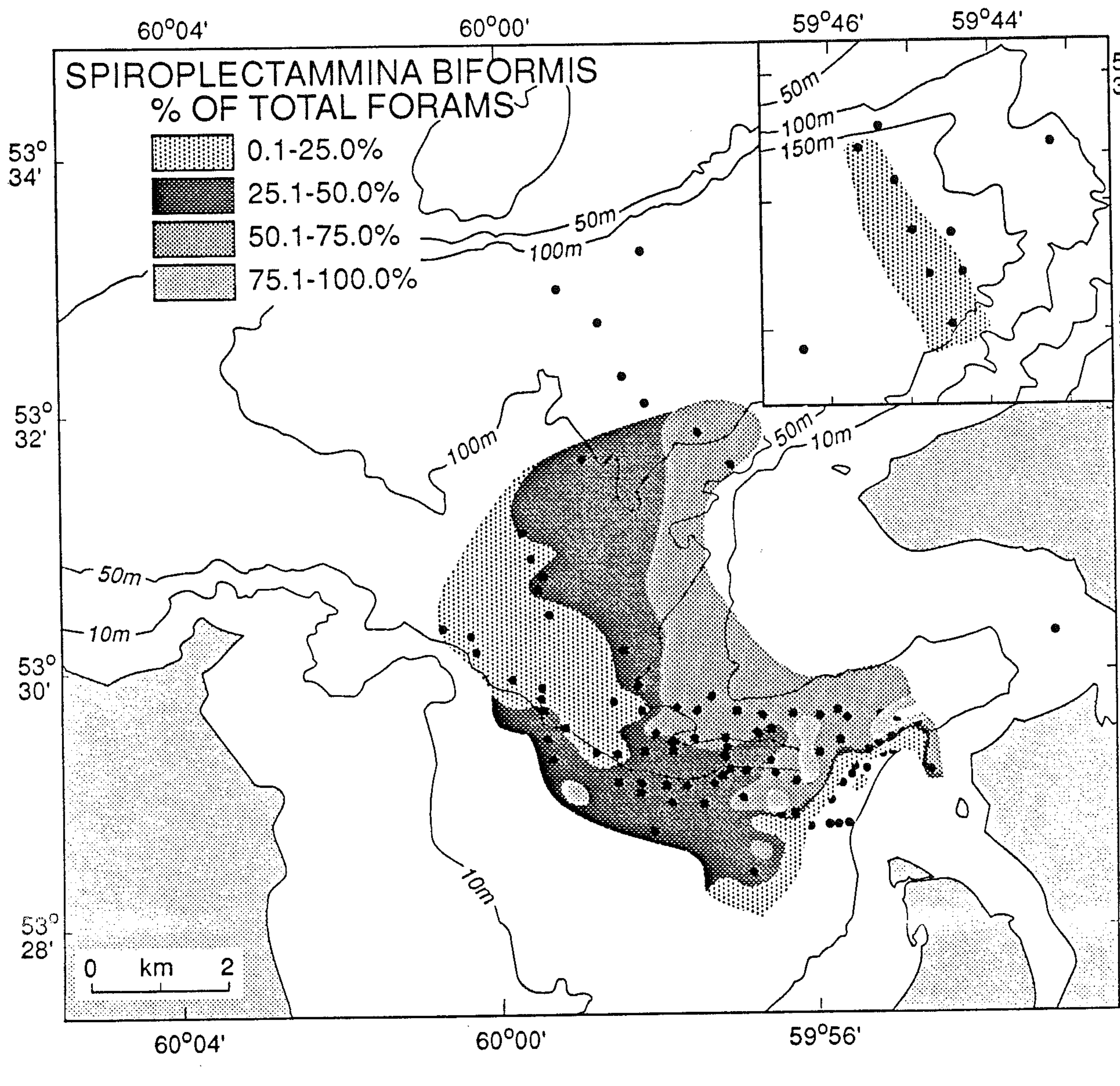

NL/CC
0.1-1.0%
1.0-10.0%
10.1-20.0%
>20.1%
60°04'
60°00'
59°46'
59°44'
59°56'
53° 34'
53° 32'
53° 30'
53° 28'
53° 36'
10m
50m
100m
150m
0 km 2

Figure 3.7.2.1.



SPIROPLECTAMMINA BIFORMIS
% OF TOTAL FORAMS
0.1-25.0%
25.1-50.0%
50.1-75.0%
75.1-100.0%
60°04'
60°00'
59°46'
59°44'
59°56'
53° 34'
53° 32'
53° 30'
53° 28'
53° 36'
50m
100m
150m
10m
0 km 2

Figure 3.7.2.2.

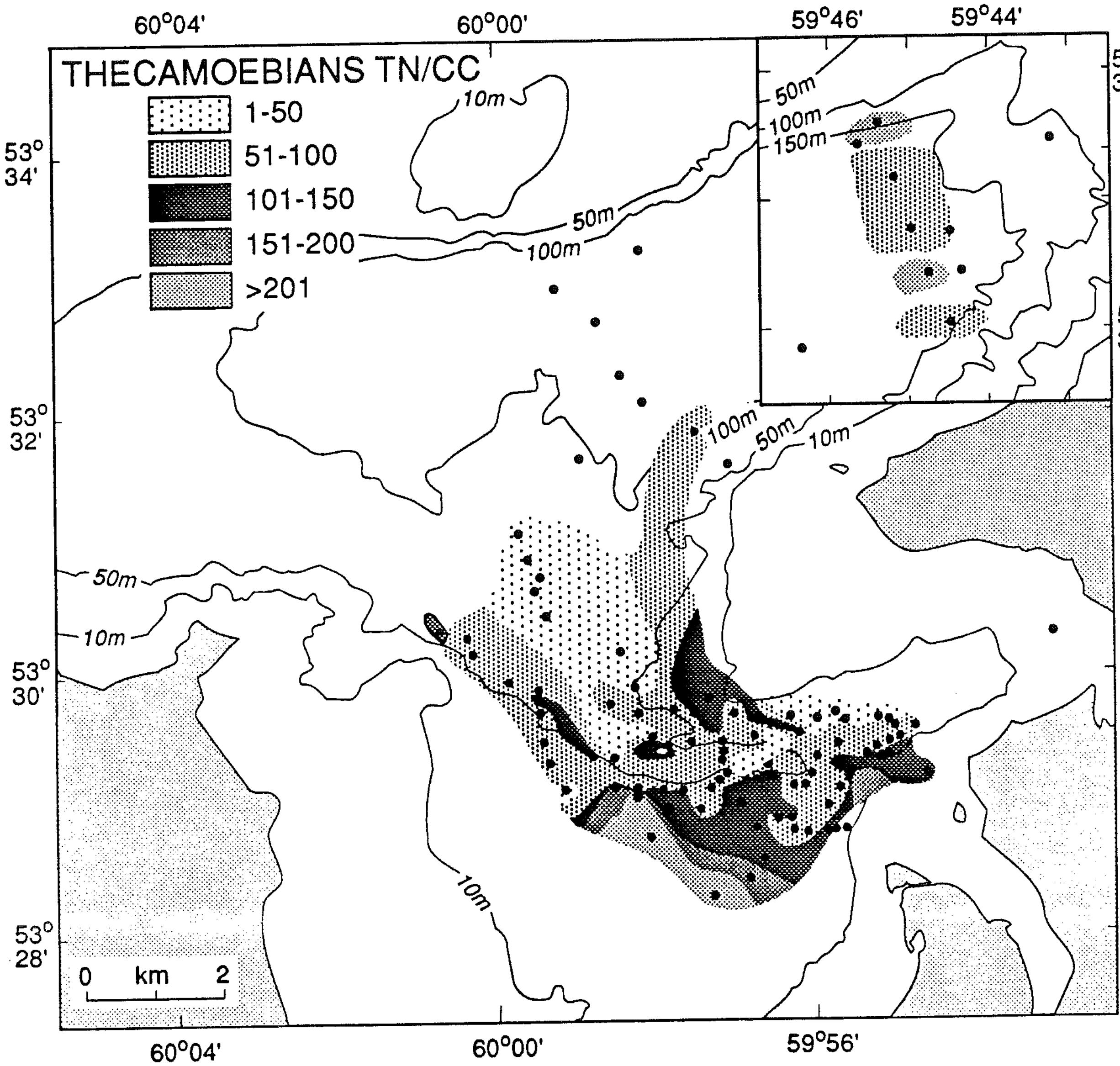
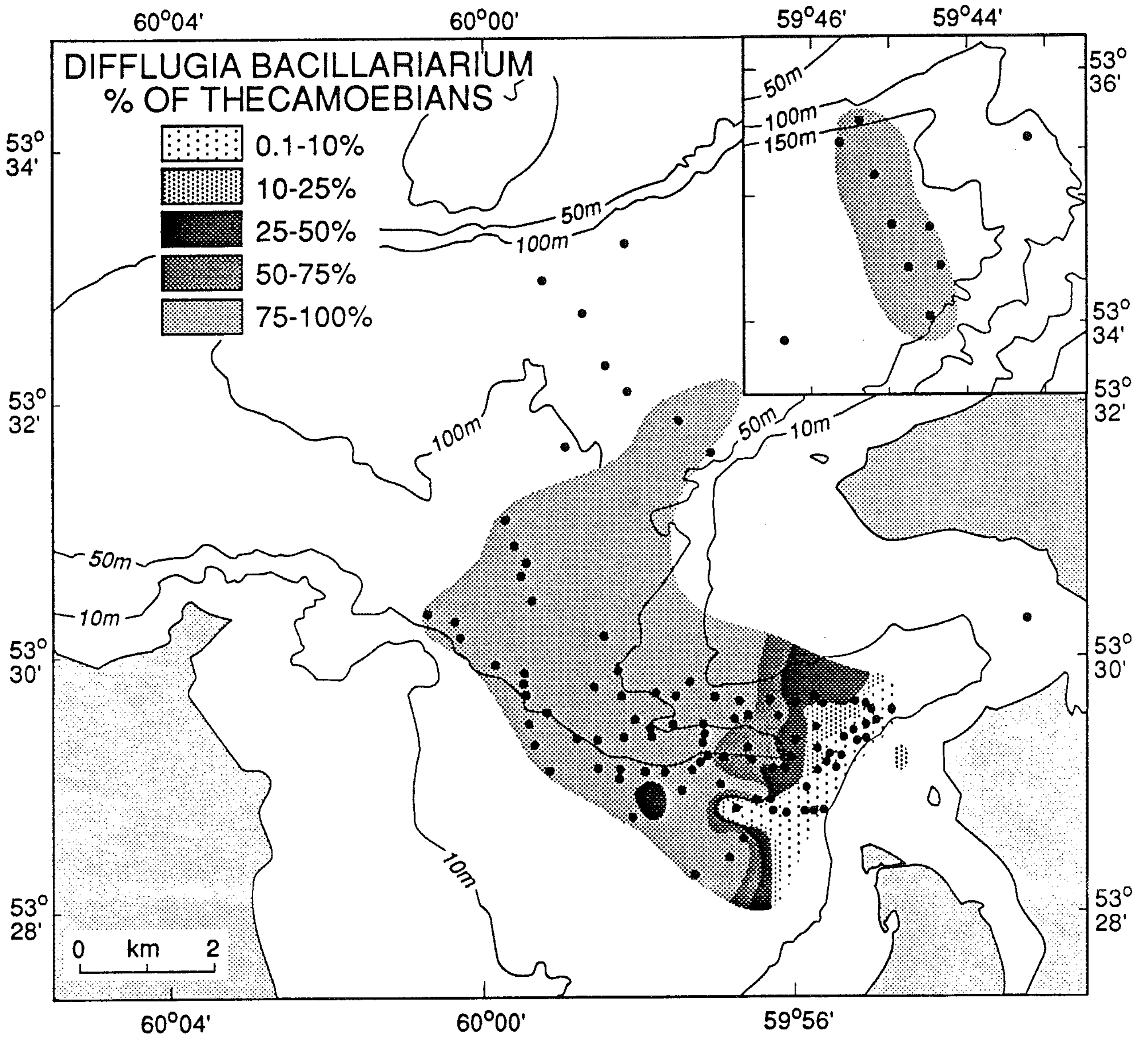

THECAMOEBIANS TN/CC
1-50
51-100
101-150
151-200
>201
60°04'
60°00'
59°46'
59°44'
59°56'
53° 34'
53° 32'
53° 30'
53° 28'
53° 36'
10m
50m
100m
150m
0 km 2

Figure 3.7.2.3.



DIFFLUGIA BACILLARIARIUM
% OF THECAMOEBIANS
0.1-10%
10-25%
25-50%
50-75%
75-100%
60°04'
60°00'
59°46'
59°44'
59°56'
53° 36'
53° 34'
53° 32'
53° 30'
53° 28'
50m
100m
150m
10m
0 km 2

Figure 3.7.2.4.

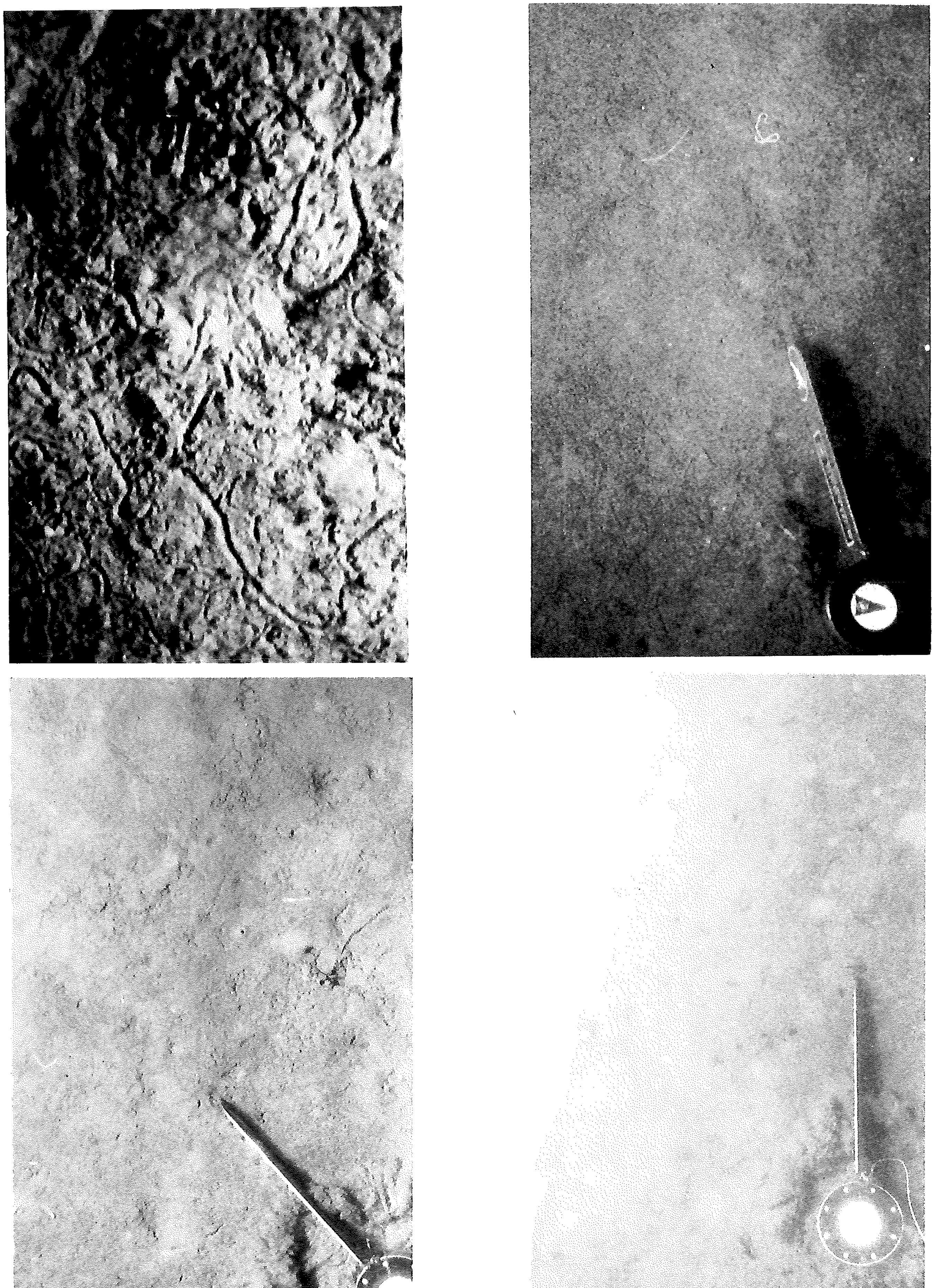
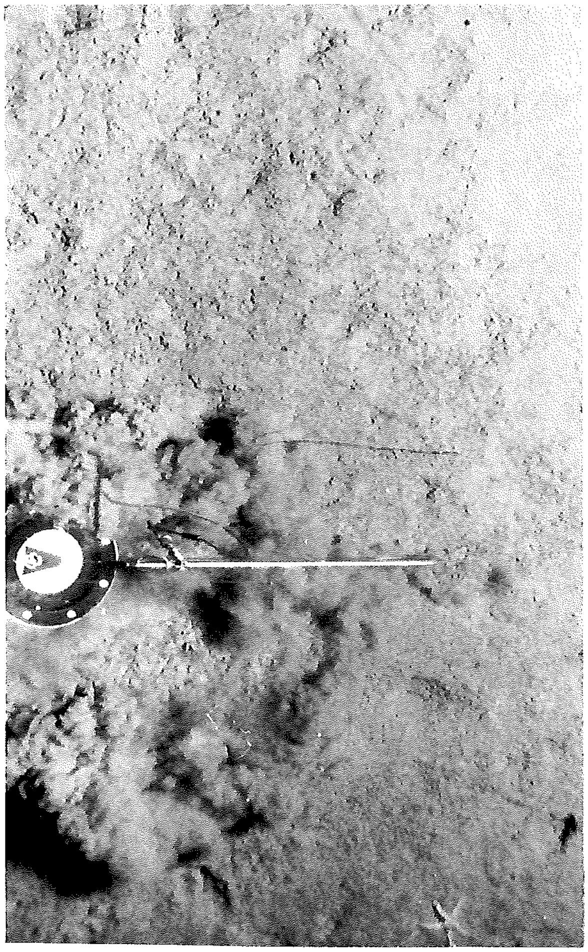
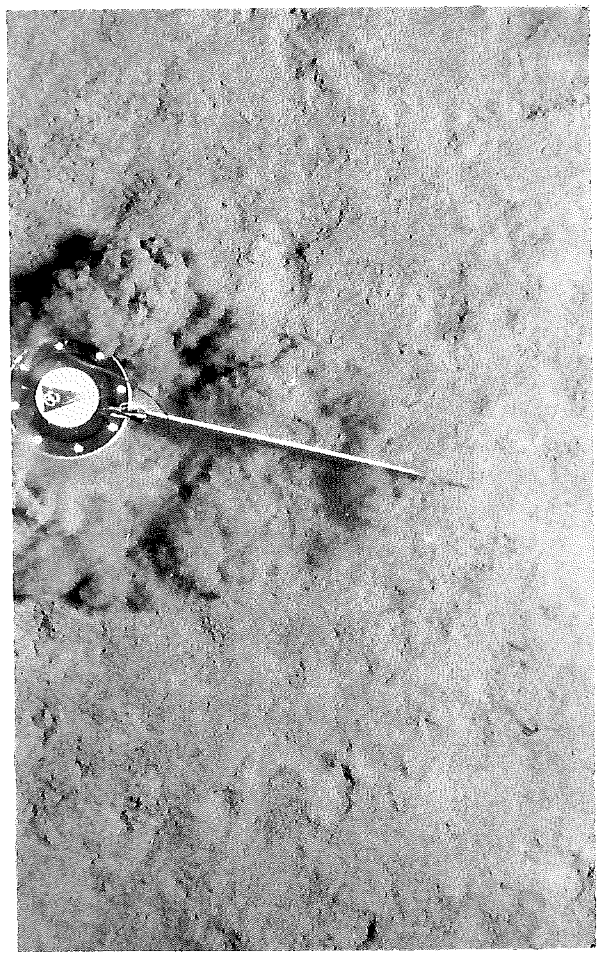


PLATE 1.





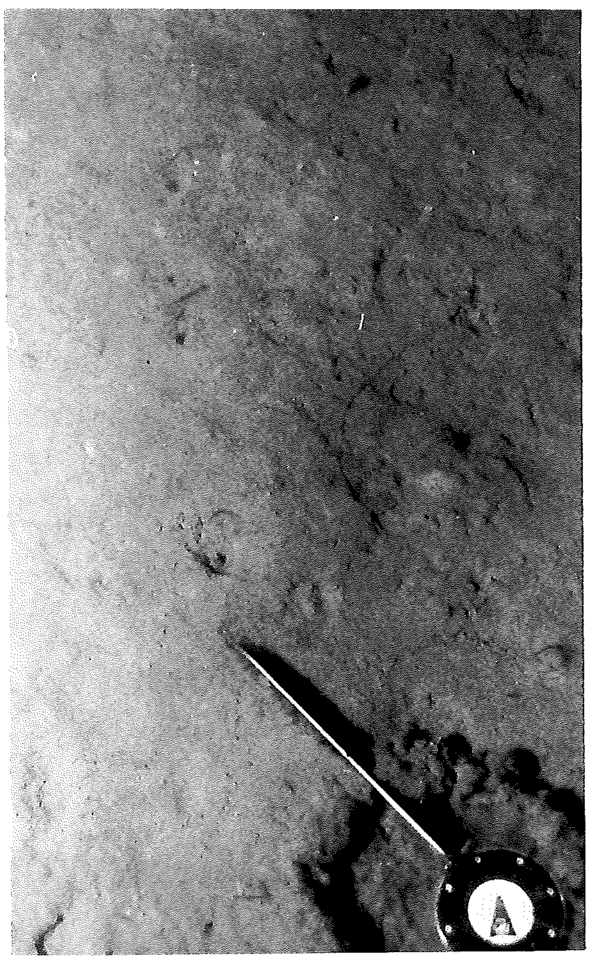


PLATE 2.

PLATE 3.