Safety and Integrity of Arctic Marine Pipelines

Progress Report #1
Results of Field Study

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EXECUTIVE SUMMARY

The goal of the Pressure Ridge Ice Scour Experiment (PRISE) is to develop the capability to design pipelines and other seabed installations in regions gouged by ice, taking into account the soil deformations and stress changes which may be caused during a gouge event. Results from a continuing series of centrifuge model tests and finite element modelling are being used to adapt an existing soil/pipe interaction model for pipelines in gouge-affected soils. Pipeline design guidelines will be developed when the adapted model is complete.

The research funded by the MMS forms Phase 3d of the ongoing PRISE program being undertaken by C-CORE on behalf of oil companies, regulatory agencies and government bodies. The objective of this research is to confirm the magnitude and extent of sub-scour deformations in dilatant soil, through (1) direct field observations; (2) physical model simulations; (3) numerical model simulations; and, (4) development of an indigenous knowledge workshop. The results of this project will lead to more cost-effective designs and increased confidence in the operating integrity of buried offshore pipelines subject to ice scour and / or dragging anchors.

This progress report is the result of the field study conducted in Cobequid Bay, Nova Scotia during the spring of 1997 to study sub-scour deformations under fresh ice scours in compact silt. For scours to occur on the mudflats requires the favourable combination of a number of factors; ice conditions, tidal conditions, wind conditions, and wave conditions. There is a very limited window during the spring breakup where the seabed is thawed and ice pieces are present. It is necessary that personnel be on site when these conditions occur in order to instrument the seabed. Unfortunately, during the time of year when this was to occur, the area was hit with an unforcast blizzard which sat over the area for several days. However, during the field program, two types of markers were tested to ascertain deformations within the soil beneath the soil and limited success was achieved especially in regards to knowledge gained with respect to future field programs. The report contains a description of the field program and its daily log as well as conclusions and recommendations.

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1.0 INTRODUCTION

Pipelines on Arctic seafloors in the U.S.A., Russia and Canada are at risk to damage by the action of sea ice pressure ridge keels that gouge the seafloor. Sea ice forms during the long Arctic winters when the sea surface freezes. Storm winds during winter and early spring may put pressure on the 1-2m thick floating ice sheet, causing it to break and crush. This action creates linear mounds of piled-up ice blocks called pressure ridges; the keels of these pressure ridges may extend to 50m below sea level. Ice gouging occurs when the pressure ridge keel touches, penetrates and continues to move forward through seabed soils at velocities of several centimetres per second. The scouring action typically creates curvilinear troughs, called gouge marks, characterized by lateral mounds of soil created by the forward bulldozing action and lateral heaving induced by the scouring keel.

Oil and gas pipelines must be buried below the maximum expected gouge depth to avoid direct ice/pipeline interaction which would cause serious damage to the pipe. However, just as soil at the seabed surface is subject to large scour-induced displacements, the soil beneath a scouring keel also moves. These sub-scour deformations also must be taken into account as they may cause unacceptable shear and bending stresses in a buried pipeline.

Pipeline safety and integrity in areas affected by ice gouging must determine what constitutes a safe burial depth. The "safe" burial depth will not be the same for every region of the seafloor. This is dependent on three factors: (1) the maximum expected depth of ice gouging, which will determine the absolute minimum top-of-pipe depth of burial; (2) the soil type and condition which will affect the response of sub-scour soils to ice-induced stresses, and (3) the mechanism of load transfer from the deforming soil to the buried pipe. Thus the problem of pressure ridge ice gouging is, for each case, to determine a safe burial depth that not only avoids direct ice/pipeline interaction, but also minimizes the risk of damage due to sub-scour soil movements.

2.0 BACKGROUND LEADING UP TO THE CURRENT RESEARCH

The Pressure Ridge Ice Scour Experiment (PRISE) is an ongoing jointly-funded, international, multiphase program. The goal is to develop the capability to design pipelines and other seabed installations in regions scoured by ice, taking into account the soil deformations and stress changes within the soil which may be caused during a scouring event. The need for this capability was identified during a round-table discussion with several oil companies and federal government representatives in 1990 during an international workshop on ice scour held in Calgary.

This innovative high risk study, initiated and performed by C-CORE confirmed the possibility of deep-seated soil deformations beneath gouging ice keels. The study included a detailed and thorough analysis of deformation structures preserved in clay soil beneath ancient scour marks in the Winnipeg area of Manitoba. Mapping and measurement of the 10,000 year-old gouge marks, excavated by backhoe, proved conclusively that sub-gouge deformations in cohesive soils were both extensive (several metres below gouge base) and involved significant soil movements (up to 3.5 m along slip surfaces). The study provided the impetus for continued work to quantify the mechanisms and magnitudes of gouge-induced forces and soil movements. Since 1991 considerable progress has been made in this area, mostly through PRISE, which is led by C-CORE and joined by regulatory agencies.

With respect to gouge-induced soil deformation, the seabed may be viewed as three progressively deeper zones, Palmer (1990). The top of Zone 1 is the seabed, and the base is the bottom of the expected gouge. As a gouging keel approaches a pipe buried in this zone, initially it will be lifted into the frontal mound of bulldozed soil. At first the pipeline will be pushed ahead of the ice keel but very soon axial tension will pull the pipe through the soil until it contacts the ice. At this point much of the ice force will be transferred directly to the pipe. For a large gouge, an ice force on the order of 200 MN may be expected (Woodworth-Lynas *et al.*, 1996). This is about 20 orders of magnitude larger than the pullover forces applied by dragging ship anchors which are known to damage pipelines severely. Clearly, a pipe buried in this zone will be damaged.

Zone 2 is the soil layer immediately below the bottom of the ice gouge in which the soil deforms plastically but is never in direct contact with the ice. A pipeline buried in this zone will be dragged forward and perhaps pushed downwards by the moving soil, Palmer (1990). The pipeline section below the central region of the gouge will move with the soil, and will be relatively insensitive to such mass movements. However, below the margins of the gouge a pipe will be bent and stretched by relative movements between the dragged soil below the gouge and the non-moving soil outside the gouge, Nixon *et al.* (1996). Bending strains calculated for a conventional pipe below the gouge margin indicate that although it may be severely bent the pipe could withstand the large deformations without failing, Palmer *et al.* (1990). Thus some burial depth within Zone 2 may be acceptably "safe".

Zone 3, below Zone 2, is in the region where a pipe would experience loading from gouge-induced soil stresses, but the soil around the pipe would not move significantly. A pipeline in this zone generally will be safe. However trenching a pipeline into Zone 3, typically several scour depths below the seabed, is beyond the reach of conventional trenching equipment; although this Zone is desirably safe, it would likely be an uneconomic option.

Phases 1 & 2 of the PRISE project included phenomenological (field) studies, theoretical studies, and physical experiments, C-CORE (1993). Due to continuing industry interest, partly because of the potential offshore hydrocarbon developments around Sakhalin Island, Russia, Phase 3 of PRISE was initiated. This phase will extend the database of physical experimentation and adapt an existing commercially-available engineering model to the design of pipelines, C-CORE (1995a,b), Hynes (1996) and Lach (1997)).

Post-scour examination of the Phase 3a PRISE centrifuge model tests have shown that surface and sub-surface scour-induced deformation structures observed from the Phase 2 full-size scour marks in the field can be reliably modelled in the large C-CORE centrifuge. Sub-scour soil deformation empirical relationships for the ice/soil interaction at steady state were developed from examination of the physical centrifuge model test data. The observed extent and magnitude of sub-scour deformations for mean scour events were much larger than previously anticipated.

These PRISE tests provided data for scour depths and widths as large as 1.49 and 30m respectively in clay and 2.14 and 30 m in sand. However, extreme events on the order of a 5 m depth and/or a 100m width, might be expected in areas with development potential. Phase 3c of the program concentrated on determining the forces and soil deformation effects of *extreme* full-scale ice keel scour events in medium dense sand and stiff clay through the use of centrifuge modelling. These new experimental data are being used to expand the empirical relationships to include extreme scour events.

The Phase 3c tests have also indicated large and extensive normalised sub-scour deformations for extreme ice scour events. This test series has been extended to simulate both the ice scour conditions expected for the pipeline developments for Northstar, Alaska in silt and for Sakhalin Island, Russia in sand. The new tests conducted in a dilatant silt have also shown large and extensive normalised sub-scour deformations. These normalised deformations are apparently larger than those observed in compressible materials. It is this observation from centrifuge model tests that needs to be confirmed by further field evidence and numerical simulations.

A 3-day workshop is planned for January 1998 on Ice Scour and Arctic Marine Pipelines at the Sakhalin Oil and Gas Institute (SOGI) in Okha, (Sakhalin Island), Russia. The workshop is being organised by SOGI and C-CORE. The general aims of the workshop will be to review progress in understanding the mechanics of ice keel scour, the ability to model the scouring process and the application of models to pipeline burial and protection. Sakhalin is an appropriate venue because of the offshore oil and gas development off the north and east coasts. The workshop has attracted over 60 scientists and engineers from Canada, Russia, U.S.A., Japan, U.K. and Norway.

3.0 RESEARCH OBJECTIVES

The principal objective of the work being conducted for the MMS is to examine the magnitude and extent of sub-scour (Zone 2) deformations in a dilatant soil, such as a compact silt. This information is essential to achieve the PRISE goal of designing pipelines and other seabed installations for regions gouged by ice, taking into account the soil deformations and stress changes which may be caused during a gouge event.

The objective will be achieved through four activities:

(1) Direct field observation of sub-scour deformations under fresh ice scours in compact silt in a tidal estuary;

(2) Simulation of these field ice scour events by centrifuge modelling;

(3) Development of the existing numerical model to predict sub-scour deformation profiles in dilatant materials, such as compact silt; and

(4) Assistance in developing the MMS Alaskan workshop on indigenous knowledge in technology.

This work is being carried out as Phase 3d of PRISE.

Activity (1) is addressed in this report.

4.0 PROPOSED RESEARCH APPROACH

It was proposed that a field study would permit direct observation of sub-scour deformations under fresh ice scours in compact silt in a tidal estuary. This field study was conducted in late spring 1997 during the ice break up in the Bay of Fundy, around Cobequid Bay, Nova Scotia (See Figure 1). This was the site of a previous field study undertaken by C-CORE, as reported by Woodworth-Lynas (1992).

In this previous field study, transverse cross-sections were excavated across recent ice scours; this revealed only the extent and magnitude of the vertical deformations. These vertical deformation profiles compared favourably with the recent observations from the physical model tests. However, the physical model tests have indicated that lateral or longitudinal deformations (that is in the direction of ice scour) are significantly larger than the corresponding vertical deformations under an ice-scour.

It was proposed that the field study would investigate fresh ice scours, which were typically 1m wide and 20cm deep in a compact silt. This would involve excavating longitudinal sections along these ice scours to reveal the sub-scour lateral (longitudinal) deformation profiles. Vertical deformation profiles were inferred previously from the stratigraphic layers within the silt deposit. It is unlikely that such marker horizons will indicate lateral deformations. It was proposed that artificial vertical passive markers would therefore be installed around a prospective grounded ice piece.

It was originally proposed that the field study proceed as follows:

a) Prospective ice pieces grounded in an area of silt would be identified during an ebb tide.

b) After the silt flats had been exposed, up to twelve, 1 metre long vertical flexible tubes would be installed vertically, at 30 degree intervals, around each grounded ice piece.

c) The returning tidal bore would lift the ice pieces and cause them to scour the seabed.

d) During the next ebb tide, the resulting ice scours and the vertical tubes intersected by said scours would be surveyed. Each selected scour would be photographed and measured. The intersected tubes would be cleaned out and filled with grout. Soil samples and strength measurements would be made in and around the ice scour.

d) After the grout had set and after a subsequent ebb tide, the grouted tubes would be excavated from the seabed in a longitudinal section through the selected ice scour. The deformed profile of the grouted tube would be recorded.

The methodology proposed for the field study was very similar to that used previously by Woodworth-Lynas (1992). The new development was the use of the vertical deformation tubes which have been used successfully to measure deformation profiles within large pipeline/soil interaction testbeds. The deformation tubes consist of flexible plastic tubing connected to a metal tip. The tubes and attached tips are driven the complete depth of the testbed using a metal rod which runs down the tubing and rests in a recess in the metal tip. The rod is then withdrawn and the tube is free to deform with the soil. Following the test, the tubes are then injected with a fibreglass resin which is allowed to cure prior to beginning excavation. The excavation is carefully conducted to minimise disturbance of the tubing. A tube used in the study is depicted in Figure 2.

It was also decided to experiment with a second type of deformation marker during the field program. These deformation markers consisted of 1/4" copper tubing which had been cut in 10mm lengths. These tubes were then threaded onto a rigid rod with a diameter slightly smaller than the inner diameter of the copper tubes. The treaded tubes and inner rod could then be pushed into soft sediments and the rigid inner rod removed. In this way, a vertical segmented marker is placed within the testbed. A copper tube line used in the study is depicted in Figure 3.

It was originally proposed that a scientist/engineer and a technician would undertake the field study over a 5 day period. It was also originally proposed that a small boat would be hired to safely transport equipment and to store it at the work site; after reconsideration, it was decided that the small boat was not required.

5.0 DAILY LOG OF FIELD STUDY

This section has been transcribed directly from the engineer's daily log which was kept over the duration of the field study.

Monday, March 31

Departed St. John's in the morning. Arrived Port aux Basques in the afternoon. Depart via Ferry to North Sydney in the evening.

Tuesday, April 1

Arrived at North Sydney at approximately 08:00 hours and experienced a storm during the drive to Truro. Arrived at Truro at approximately 13:00 hours. Attempted to scout out potential area including Black Rock but near zero visibility allowed no decision to be made as to prospective or alternative sites.

Wednesday, April 2

Proceeded to Black Rock in the morning. The route along the way suggested that the ice covering the mud flats is old and weathered and does not move under normal tide cycles. The layout of the Black Rock area is presented in Figure 4 as well as in Photos 1-3. Based on observations, it would appear that previously observed scours, Woodworth-Lynas (1992), occurred in Area 2 or Area 3 during extreme spring breakup. However, on the sand flats, depressions were noted which appeared to be gouges. These gouges are depicted in Figure 5. These were in Area 5 and appeared to be in partially frozen seabed. During fall of the tide, there appeared to be only one potential piece of ice that might be instrumented. Other ice pieces were hung up on the rock outcrops and would not have scoured during an incoming tide. No potential for scour at that time was observed on the mudflats (Area 2).

A survey of the ice piece before it was fully exposed indicated that it was grounded through the frozen layer of the sand bed. The keel extended at least 0.5m below the unscoured bed.

Approximate dimensions of ice were 5m in length, 2.5m in width, and 2.5m in height. The tide continued to fall to the point where the ice and its initial gouge became exposed. It is depicted in Figure 6. Nineteen vertical deformation tubes were placed through the frozen sand around the ice piece and the existing scour. Three sets of copper markers were also installed as indicated in the figure. Again, adverse weather conditions (-7° C, 100km/hr winds) made working difficult.

Thursday, April 3

The engineer and technician proceeded to Masstown Flats in the morning; however, the tide in channel appeared to be too high to proceed safely onto flats from Fort Belcher (Photos 4-6). A channel was visible from shore as were many pieces of grounded weathered dirty ice. It was decided to wait until water in the channel dropped to check the area near the channel, Figure 7, to see if there was an unfrozen tidal zone which might be scoured.

An attempt was made to proceed to Selmah Bar, Lower Selmah. The vehicle, however, got stuck en route, and needed to be towed out. Again, adverse weather conditions were experienced with near zero visibility, white-out conditions, a temperature of -4° C, and 80-90km/hr winds. An attempt was made to proceed to Black Rock twice without success as the roads were impassable.

When the team Returned to Masstown Flats, Figure 7, the water in the channel had dropped to a level where it was thought that travel to the edge of the channel would be safe and dry. Upon closer inspection, virtually all of the weathered dirty ice was found to be frozen to the mudflats which were also frozen (Photos 7-9). This was observed all along the route indicated in Figure 7 to the channel. The channel was approximately 30-40 feet deep and 70-80 feet across (Photos 10-11). The bottom of the channel remained full of water and the channel walls were shear. There appeared to be no safe access to the channel nor a safe landing once there; the amount of exposed channel bed was minimal and no potential ice pieces were spotted.

It is postulated that scours observed by Woodworth-Lynas (1992) might have been isolated events and not a common occurrence. During warmup, the mudflats would thaw as would some of the smaller ice pieces. However, some of the larger ice pieces would remain, sitting on thawed mudflats. During a high-high tide, these ice pieces might break free and scour their way towards the faster flowing channel. Longer observation of the mudflat would be needed to confirm/disprove this hypothesis.

The team then proceeded to Black Rock, the road to which was ploughed (Photo 12 and Photo 13). Proceeded to the location of Iceberg #1, Figure 6. The area was heavily disturbed as if the iceberg had wallowed in its original pit and obliterated the incoming scour which had been previously visible. The scour pit was approximately 750mm deep and only one exposed tube could be found (Photo 14 and Photo 15) within the pit which could not be excavated due to the presence of water.

The exposed tidal sand flats appeared to be even more frozen than the day before. However, two suitable pieces of ice were located on the sand flats. Attempts to instrument these ice pieces proved difficult due to the frozen sand. Even when a pilot hole was driven, the tubes were virtually impossible to insert. Only one tube could be inserted at each ice piece; at the rear side when facing the incoming tide.

Each ice piece was approximately 8-10 feet high and 8-10 feet in diameter. One piece had penetrated the seabed (Iceberg #2 - Photo #16) while the second (Iceberg #3 - Photo #17) was simply sitting on the frozen sand.

Friday, April 4

As the roads had become clear and the weather had improved (-3 ° C, light winds), it was decided to check out other potential test sites to the north-west including Lower Debert Beach, Spencers Point, and Saint's Rest (Figure 1b). It was not possible to get to Econony Point; however, it was possible to make it down to Cove Road. In all locations, ice conditions were minimal; there were a few pieces of larger ice with some snow/slush ice. During the reconnaissance, the tide was coming in and, at times, ice was noticed popping to the water surface. This indicated that ice might not gouge during an incoming tide but rather might remain rooted or seated until buoyancy forces overcame selfweight and adhesion to the seabed releasing it vertically. Shore conditions appeared to be primarily sand mixed with some gravel.

An area to the west, Lower Selma Park, was also scouted. This was the Selma Bar area described by Knight and Dalrymple (1976). The exposed seabed at the park was primarily composed of sand with some gravel and outcrops of bedrock. There was very little competent composite ice in this area and that which was present tended to be small (Photo 18). There was an abundance of snow/slush ice which could easily be broken up with one's foot.

The engineer and technician then proceeded back to Black Rock where the tide was on its way out. The mudflats still appeared to be somewhat frozen. The original position of the ice, the location of the VDT from Iceberg #2 and the resulting scour are presented in Figure 8. The scour/pit is presented in Photo 19. There was no apparent scour around the VDT but rather there was a scour/pit opposite to where the ice was located originally as shown in the figure. Around the VDT there was fairly soft material until a depth of 100mm where 25-50mm of ice frozen soil was encountered. Excavation of the VDT did not reveal any apparent subscour deformation; the only curvature in the VDT might have been there when the VDT was put in (Photo 20).

The single VDT of Iceberg #3 was also found and excavated; it revealed no apparent deformation. It was quite difficult to excavate the sand flat around the VDT as it was frozen and it was necessary to use a maul to break through the surface. The sandbed was like cement; approximately 5mm of sand followed by 50-75mm of frozen soil. Therefore, in areas like this under environmental conditions like these, it might be obvious why scours can't be seen. Only shallow lineations, essentially scrapes in the sandbed could be created.

Iceberg #4 was instrumented as shown in Figure 9. This iceberg was on the sand flats which contained a frozen layer ≈ 6cm below the unfrozen layer. This frozen layer was approximately 25-50mm thick. The ice was sitting in a pit which extended approximately 1m below the intact soil surface. The ice piece was coherent and approximately 12 ft high and 18 ft in diameter (Photo 21 and Photo 22). The VDT's were inserted by first driving a pilot hole.

Iceberg #5, located on the sandflats, was also instrumented as shown in Figure 10 (Photo 23). This piece of ice had not broken through the frozen sandbed but was considerably smaller than Iceberg #4. Inspection of the sandbed indicated approximately 25mm of sand covering approximately 50mm of frozen soil. The VDT's were inserted by first driving a pilot hole. There were no apparent scour marks around the ice; this may have been due in part to the frozen seabed and also in part due to the hydrodynamic regime during tide out which may have obliterated any scours.

Saturday, April 5

Several individuals around Truro and the Masstown Flats were asked about local ice conditions. Apparently, the ice had been out by this time last year and usually, the ice is gone by mid-April. One individual felt the ice could start to melt and break up perhaps as early as the coming week. Also, apparently, some large pieces of ice are usually left after breakup and melting. An individual who lived at Masstown Flats reiterated this. He stated that he was always amazed at how he could wake up one morning and the ice would be gone. However, there were usually some straggling pieces of ice left and sometimes silt could build up to as much as 14 feet thick.

A revisit to Masstown Flats indicated that considerable thaw had occurred over the past couple of days. Areas were found approximately 40 ft by 40 ft which appeared to have had completely thawed (Photo 24). Excavation of these areas with a shovel indicated fine layers (stratification) of what appeared to be silt and mud (Photo 25). The ice appeared to be breaking up although no suitable pieces were found for marking.

The engineer and technician then proceeded to the old Irving Oil dock area (Photo 26). The mudflats were still partially frozen but it appeared that the major problem might be the intense hydrodynamic regime in the area. This appeared to have created hydrodynamic scour around grounded ice which might make instrumentation and measurement difficult.

Black Rock was then revisited. No new icebergs were located on the mudflats although the mudflats appeared to be sufficiently thawed to be scoured if ice had been present. The composite ice appeared to be breaking up and some was present on the semi-frozen sand flats.

Two tubes of Iceberg #4 were found but it was not possible to determine which two tubes they were as the permanent marker had come off the high visibility tape. The tubes could be excavated somewhat even though a frozen layer was present within the sand (Photo 27). There was approximately 100mm of sediment overlying 20mm of ice-rich frozen soil. A sketch (plan view) is presented in Figure 11. Based on the size and shape of the pool, either the ice had wallowed or hydrodynamic scour had caused the pit to expand (Photo 28). Vertical deformation tubes from Iceberg #5 could not be found.

Observations of grounded icebergs on the sand flats led to the conclusion that the hydrodynamic scour in the area was too intense; scours were obscured from one tide to the next and probably even during the same tidal cycle. It seemed probable that if any scour was to be discovered and instrumented, it would have to be on the mudflats. Some small scours were found; these were approximately 10mm deep and 200-300mm wide. It appeared that the ice was starting to break up at all locations.

Based on comments made by individuals, forecasted weather conditions, and the fact that the highest tides of the month would be on April 9th, the decision was made to stay an additional 4 days. It seemed that if any potential ice pieces were to be found, they would be found during the next few days.

Also, based on the ice observed so far, it appeared that scours were made during the outgoing tide. There were no indications that scours were made during an incoming tide. It was possible that the embedded ice simply popped up and did not move horizontally with the incoming tide. However, one way scours could occur with the incoming tide would be if the ice progressed onshore, up slope, due to a strong onshore wind. As the tide rose, the wind could force ice nearer and nearer to shore.

To scour on the mudflats would probably require a certain number of conditions to be present; ice, tidal, wind, and wave.

Sunday, April 6

The engineer and technician proceeded to Black Rock to observe incoming tide/high tide conditions. Water was well over the mudflats (Photo 29a and 29b) but very little ice was observed passing over the mudflat area. It would seem that a strong onshore wind would be needed to drive the ice pieces in the channel over the mudflats. Pieces of ice were often noticed "popping" to the water surface. This somewhat confirmed the suspicion that grounded ice might not move horizontally and scour but simply "pop" up vertically as it breaks its embedment from the sandbed. It was then decided to proceed to Masstown Flats and return to Black Rock during outgoing tide.

At Masstown Flats, the ice was continuing to melt and break up. More mudflat was becoming exposed but no suitable pieces of grounded ice were found. It appeared that many of the ice pieces which broke free with the incoming tide went out the channel with the outgoing tide. A significant amount of the continuous landfast or grounded ice appeared to be pan-shaped, 6-10 inches thick, and covering most of the mudflat area. This layer was cracked and breaking up.

Black Rock was revisited where the mudflats were becoming more unfrozen and difficult to proceed through. Typically, mud approximately 75-100mm thick was underlain by what appeared to be silt. People on foot would typically sink 100mm but in some cases they would sink deeper up to their knees. These mudflats were very sloppy and hard to excavate; a vertical face would not stand. Some scours were present and these were approximately 500mm wide and 50mm deep.

A scour which terminated at a grounded piece of ice was found (Photo 30). This scour was approximately 600mm wide and ranged in depth but was typically 25-40mm deep (Photo 31). It appeared most of the scours observed on these mudflats were being created by ebb tides not incoming tides. The scours appeared to end at pieces of grounded ice or at small pits where ice had been previously grounded. Even though the scour was small and the ice was deteriorating, it was decided to instrument the perimeter of the ice. The ice piece was approximately 10 feet high and 10 feet in diameter and butted up against the shore fast ice (Photo 32). A total of 9 tubes were put around the ice piece (Iceberg #6) as shown in Figure 12. It was decided to proceed back to Black Rock on Monday morning.

Monday, April 7

The engineer and the technician proceeded at sun-up to Masstown Flats. The ice continued to breakup in this area. Mudflat areas which were previously exposed were covered with ice rubble and chunks of ice. The was no apparent scouring; however, this area was hydrodynamically more active than Black Rock and, therefore, scouring might not have been readily apparent.

At Black Rock, the scours and footprints were still readily visible from the previous day. This area appeared to be the most promising area to find preserved scours. The deformation tubes were still intact at the location of Iceberg #6 (Photo 33). There was no sign of scouring during the incoming tide; it appeared that the ice just lifted off after the tide had come in as the area within the tubes was disturbed.

More small scours were observed on the Black Rock mudflats (Photo 34, Photo 35, Photo 36). These scours were typically 20-40cm wide and 10-20mm deep and extended in length for 100's of metres. Generally, side berm material was noticed to the sides of scours but typically on one side or the other, not both. This material was generally broken up and sloughed out to the side.

A new piece of ice was discovered, Iceberg #7. This ice is shown in Photo 37. This ice was approximately 12 feet high and 12 feet in diameter. This piece of ice was butted up against another piece of ice as depicted in Figure 13. The scour leading up to the ice was 900-1200mm wide and generally 30-80mm deep (Photo 38 and Photo 39). Side berm material was present as indicated and was sloughed generally to one side. Ten vertical deformation tubes were inserted as shown in the Figure and in Photo 40. During insertion, the tubes generally passed through 4 inches of softer material followed by approximately 14 inches of stiffer material. Below this, the material was even stiffer to penetrate; it was not determined if this was stiffer material or material which contained some ice.

In the afternoon, the engineer and the technician proceeded back to Black Rock. There was one noticeable new scour approximately 1200mm wide with a maximum depth of 100mm present on the mud flats. This scour extended several hundred metres but there was no ice piece located at the end of scour (scour just trailed off).

The location of Iceberg #7 was revisited. The iceberg was still there and did not appear to have moved although the ice had deteriorated to approximately three-quarters of its original size. All of the vertical deformation tubes were still intact although further away from the ice perimeter which was expected as the ice had reduced in size. The ice piece was still approximately 8 feet high and 6-8 feet in diameter. Therefore, the tubes were left in place.

It also appeared that when the ice became rooted (during an outgoing tide) it might remain rooted for some time. It appeared that if and when the ice broke free from its root, it might leave some ice embedded in the mudflat. Evidence on the flats suggests that these roots can remain and appear to melt out leaving depressions. This evidence further decreased the probability of finding ice which scoured on incoming tide.

As the probability was decreasing of finding ice which would scour on the incoming tide, it was decided to insert a "line" of tubes in the mudflat approximately perpendicular to the direction of known scouring. A total of 26 tubes were inserted along this line as depicted in Figure 14 and Photo 41. The mudflat condition was similar to that described earlier except the tubes generally could be pushed all the way in. It was decided to return the following day to see if anything had been "caught" and to perhaps insert another line of tubes.

Tuesday, April 8th

It was decided to proceed to Fort Belcher where the ice continued to deteriorate. The mudflats were exposed but there were no apparent scours or grounded potential ice pieces. The area past Lion's Head was investigated but this was a salt marsh (Photo 42). Some scours were present but these were very small and only occurred in unfrozen sediments (50mm) over frozen salt marsh.

The engineer and the technician then proceeded back to Black Rock where one scour had occurred directly over one of the vertical deformation tubes. This scour was approximately 25-30mm deep and approximately 500mm wide (Photo 43 and Photo 44). Small amounts of berm material were evident to the sides of the scour. The vertical deformation tube was partially grouted using a quantity of grout and an air supply to force the grout into the tube. Grouting proceeded slow and the air supply was exhausted; the air tank could not be refilled in Truro. It was assumed that scour occurred on outgoing tide although there was no concrete evidence to substantiate this. It was decided to return after the afternoon tidal cycle to excavate the tube.

Prior to leaving, two additional rows of tubes were inserted; one with 16 tubes and one with 7 tubes. These rows were placed approximately 5m apart as shown in Figure 14. Iceberg #7 was checked and found to still be in position although still deteriorating. Its size was estimated to be approximately 6 feet high and 6 feet in diameter.

In the late afternoon, Black Rock was revisited and another 4 scoured tubes were discovered. All scours were approximately 25-40mm deep and approximately 200-600mm wide. Occasional parts of scours were deeper; up to 80-100mm in depth. In general, it appeared that narrower scours were deeper.

The winds at the time were rather strong and blowing onshore. A significant amount of ice was grounded on the frozen salt marsh. It appeared that most of the scours had crossed the tubes at an angle as shown in Figure 15. It could not be confirmed if the scours had occurred on an incoming tide although it was suspected that they had occurred due to the strong onshore wind.

Excavation of Vertical Deformation Tube #1 began by scraping the softer mud off. This was approximately 30mm in thickness. An excavation was made parallel to the scour adjacent to the tubes. The tube appeared to be deformed horizontally approximately 20mm which extended approximately 30mm into the stiffer layer (Figure 16 and Photo 45). In all photos, the thumb indicates the outgoing tidal direction.

The same pattern of tube deformation was noticed in all of the tube excavations (Photo 46 and Photo 47); most tubes were orientated towards the direction of the wind and waves. To determine if the deformation of the tubes was due to the natural curvature of the tubes plus the wind and wave action, a control tube (one which had not been scoured over) was excavated. There were no discernable differences between the scoured tubes and the control tube (Photo 48). All tubes except the first were excavated without grouting.

Excavation of the tubes proved to be somewhat difficult. The upper layer of mud was very sloppy and difficult to work on. It was very wet and often had pooled water or drainage channels running through it. This water had to be diverted prior to excavation. Cold temperatures ($\approx 0\,^{\circ}C$) and high winds also made working difficult. Generally, a 30cm deep vertical excavation was possible with some difficulty.

A larger v-notch scour, which was 10-15cm deep at its deepest point, was discovered outside the lines of deformation tubes (Photo 49). The soft surficial sediments were scrapped off which revealed the v-notched depression shown in Photo 50. An attempt was made to do an excavation perpendicular to the scour to see if silt laminations would reveal any vertical deformation; however, the laminations could not be distinguished.

<u>Wednesday, April 9</u>

The engineer and the technician proceeded first to the Irving Oil docks (Photo 51). This area again appeared to be a highly hydrodynamic area and no scours were found on the lower mudflats. On the upper mudflats and on the shore (salt marsh), very small scours (5-10mm) were apparent. A fair amount of ice was left on the upper mudflats with the high tide as these were the highest tides of the month.

Black Rock was then revisited. Several new scours were obvious, the deepest being approximately 20cm deep and 20cm wide and U-shaped. No new scours were observed across the lines of vertical deformation tubes. The location of Iceberg #7 was checked and it was discovered that the iceberg was still there, but was now only approximately 4 feet high and 4 feet in diameter.

Another 10 vertical deformation tubes were placed in a line in the mudflats. As well, 8 rows of copper markers were put in place. The vertical deformation tubes were placed 1m apart and the copper rings were placed equidistant between 8 pairs of tygon tubes.

Black Rock was revisited in the afternoon. One scour had passed over a tube as depicted in Figure 17 and Photo 52. The ribbon had been pulled off the top of the tube (Photo 53). The excavation started by creating small channels to drain water away from the excavation. The soft mud (approximately 70mm deep) was then scraped away from the tube and a vertical excavation made in front of the tube parallel to the scour (Figure 18 and Photo 54).

A control tube which was known not to have been scoured over was also excavated. Photos were taken (Photo 55) and a sketch of the excavation is presented in Figure 19. A difference could not be ascertained between the deformation of Figure 18 and Figure 19. It appeared that there might be limitations in using the vertical deformation tubes as they might have been too stiff both vertically and laterally.

Several other scours were observed in the area which were thought to be the result of a strong onshore wind; however, none had passed over the copper tubing line. Some of these new scours were as deep as 15cm. Again narrower scours appeared to be deeper than wider scours.

Water content/grain size samples were also taken from the test area. Vane testing in the surface mud was conducted using a Pilcon hand vane (vane height = 29mm; vane diameter = 19mm). The mud exhibited an undrained shear strength of 2-3kPa. Pilcon tests were also conducted at depths of 100mm, 150mm and 200mm from the bottom of the vane. These results are presented below. Reported depths were from the top of the silt layer to the base of the vane; the mud layer was scraped away. All tests were conducted in the scour of Figure 17 except for the italicized values which were taken at the control tube location. Detailed laboratory test results from three samples are presented in Appendix A.

DEPTH (mm)	**TRIAL 1 (kPa)**	**TRIAL 2 (kPa)**	**TRIAL 3 (kPa)**
100	14.5	14.5	15
150	11	13	14
200	*21*	*19.5*	19.5

Thursday, April 10

The grounded ice continued to deteriorate at Black Rock (Photo 56). Ice continued to scour the mudflats due to an onshore wind but most pieces were small with a diameter of 1m or were pan-shaped (Photo 57). Iceberg #7 was revisited (Photo 58); it was still in place but had deteriorated severely. No new scours were discovered over the original tube line.

However, there appeared to be a faint scour over one of the copper tube lines. It was hard to distinguish new scours in this area as there were numerous small scours and the area was significantly remoulded. The scour is depicted in Figure 20. Also, due to the significant remoulding, it was hard to determine the exact scour depth but the scour appeared to be 20-30mm deep.

Excavation started by scraping the top 10mm of soft mud off the top of the scour. The mud below this layer was frozen which made excavation difficult and impossible to determine the soft/stiff material interface (Photo 59). Due to soil/weather conditions, cracks formed around the perimeter of the excavation and the excavation partially started to collapse around the edges (Photo 60). However, the excavation did not collapse entirely but generally the cracks only opened slightly around the edges.

There were apparent deformations in the subscour zone as depicted in Figure 21. At least one piece of copper tube was misplaced during excavation as depicted in the Figure. Photos 60 and 61 show the excavation and Figures 22 and 23 provide details on the photos. It appeared that there was approximately 33-35mm of horizontal deformation at the soft mud/silt interface decreasing to no deformation 30mm below the soft mud/silt interface.

The engineer and the technician then proceeded back to St. John's via North Sydney to arrive in St. John's, Friday, April 11 in the afternoon.

6.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A field study was conducted in late spring 1997 during the ice break up in the Bay of Fundy, around Cobequid Bay, Nova Scotia to study sub-scour deformations under fresh ice scours in compact silt. Vertical deformation tubes and markers were developed which could be placed in a tidal estuary at low tide. During the next tidal bore, scours were created, some of which intersected the tubes and markers. Excavation of the markers permitted direct observation of subscour deformations.

Direct observation of ice indicated that the ice in this area might not scour on each tidal cycle. It appeared that when the ice becomes embedded or rooted during an outgoing tide, it may remain so for some time. Pieces of ice were observed to simply "pop up" on a high tide which probably did not leave a scour. It also appeared that if and when the ice broke free from its root, it might leave some ice embedded in the mudflats. For scours to occur on the mudflats probably requires the combination of a number of factors; ice conditions, tidal conditions, wind conditions, and wave conditions.

During excavation of marker tubes, a control tube which was known not to have been scoured over was also excavated. A difference could not be ascertained between the deformation of this and a tube over which a scour was known to have occurred. There may be limitations in using the vertical deformation tubes as they may have been too stiff both vertically and laterally. It is believed that, since the subscour deformation was shallow, it would have been more appropriate, and have increased resolution if a layered marker with less thickness than the copper tubes was used. This technique might have more potential than the flexible tubing if excavation tools and methods were refined.

Based on observations made and knowledge gained from the field study, it is recommended that a future field study be carried out using a thin-layered marker system in order to (a) eliminate vertical and lateral stiffness in the marker system and (b) increase resolution of the variation in deformation with depth.

7.0 REFERENCES

C-CORE (1993). Pressure Ridge Ice Scour Experiment (PRISE) Phase 2 Progress Report. C-CORE Contract Report 93-C4. March 1993.

C-CORE (1995a). Pressure Ridge Ice Scour Experiment (PRISE) Phase 3: Centrifuge Modelling of Ice Keel Scour: Draft Final Report. C-CORE Contract Report 95-C12, April 1995.

C-CORE (1995b). Pressure Ridge Ice Scour Experiment (PRISE) Phase 3: Engineering Model Application: Draft Final Report. C-CORE Contract Report 95-C19, August 1995.

Hynes, F. (1996). Centrifuge Modelling of Ice Scour in Sand. Master of Engineering Thesis, Faculty of Engineering & Applied Science, Memorial University of Newfoundland.

Knight, R.J. and Dalrymple, R.W. (1976). Winter Conditions in a Macrotidal Environment, Cobequid Bay, Nova Scotia. Revue Geographie de Montreal, Vol. XXX (1-2), pp. 65-85.

Lach, P.R. (1997) Centrifuge Modelling of Large Soil Deformation Due to Ice Scour. Doctoral Thesis, Faculty of Engineering & Applied Science, Memorial University of Newfoundland.

Nixon, J.F., Palmer, A. and Phillips, R. (1996). Simulations for Buried Pipeline Deformations Beneath Ice Scour. In, *Offshore Marine and Arctic Engineering*, Florence, Italy: 10 p.

Palmer, A. (1990). Design of Marine Pipelines in Seabed Vulnerable to Ice Scour. In, *Workshop on Ice Scouring and the Design of Offshore Pipelines.* Invited Workshop, Calgary, April 18-19. C-CORE/COGLA: 167-178.

Palmer, A.C., Konuk, I., Comfort, G. and Been, K. (1990). Ice Gouging and the Safety of Marine

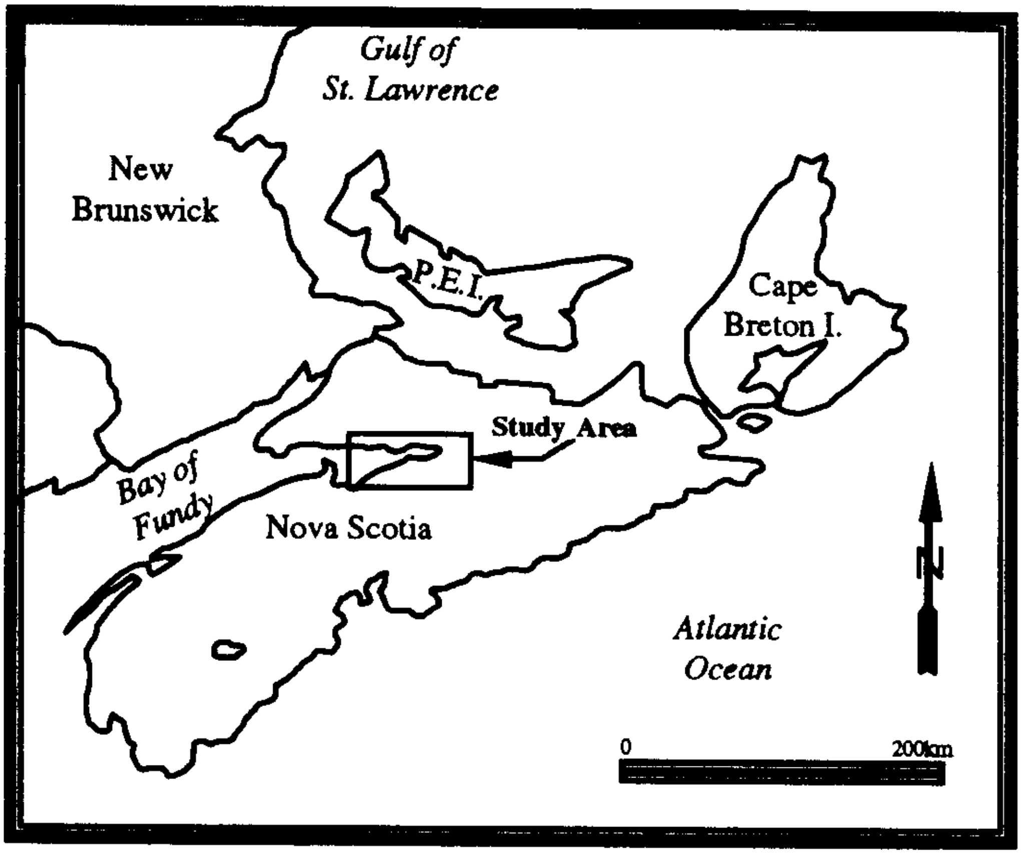
Pipelines. *Offshore Technology Conference*, Houston, vol. 3: 235-244.

Woodworth-Lynas, C. (1992). The Geology of Ice Scour. Doctoral Thesis, University of Wales.

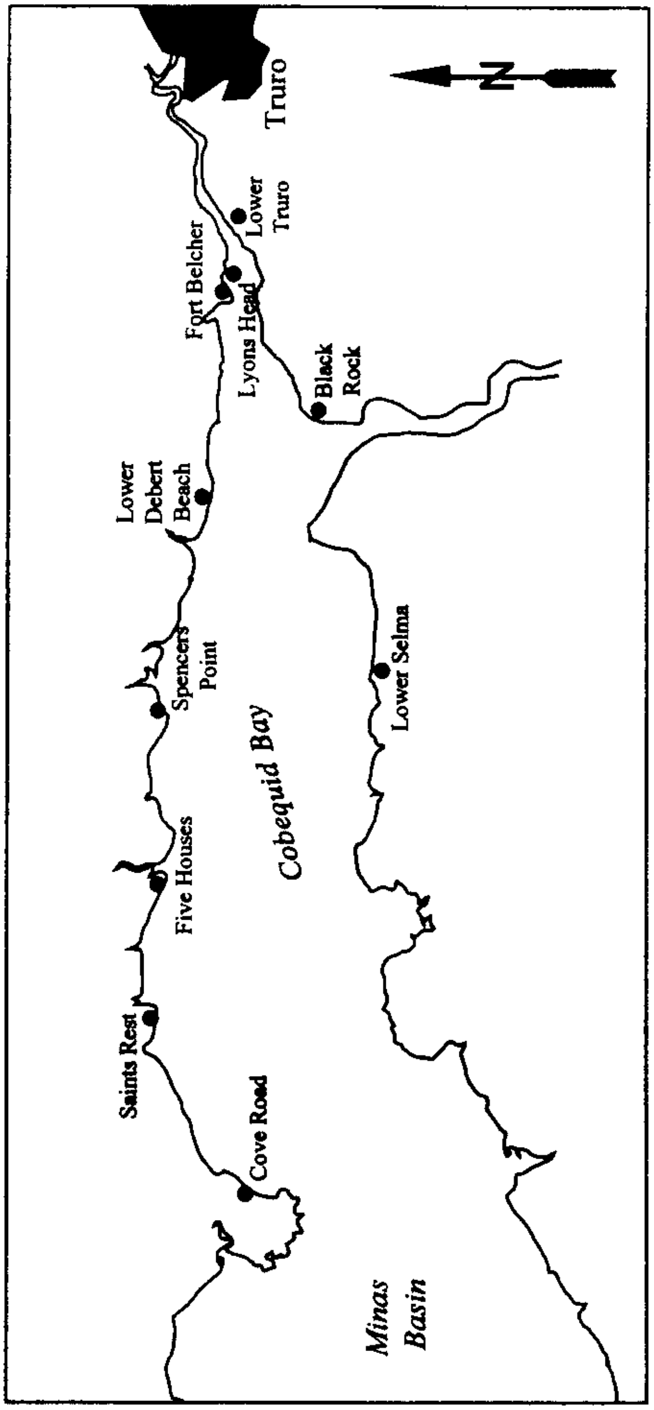
Woodworth-Lynas, C., D. Nixon, R. Phillips and A. Palmer. 1996. Subgouge deformations and the security of Arctic marine pipelines. *Offshore Technology Conference*, Houston, May 6-9: 8p.

Appendix A

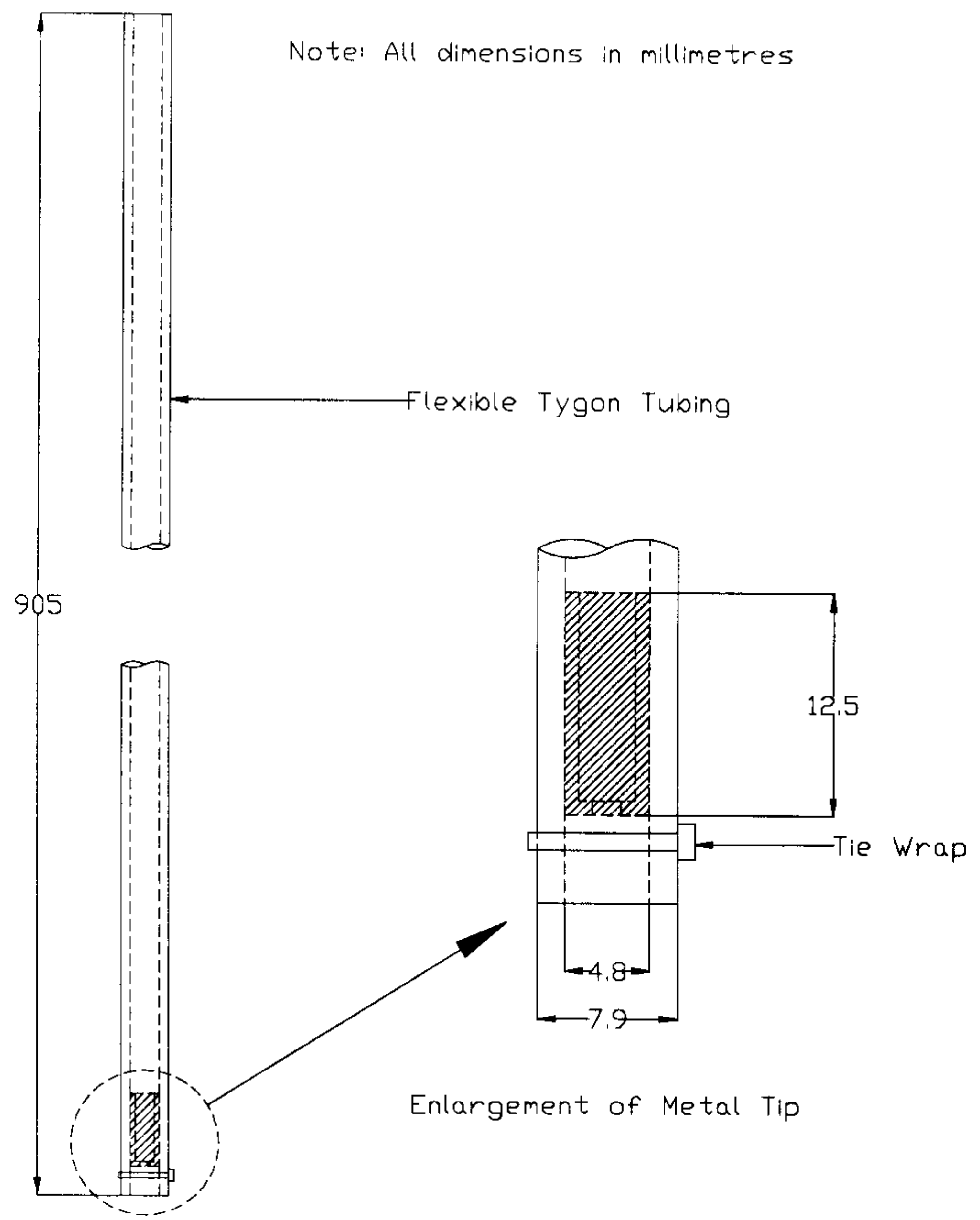
Report Figures



C-CORE	Study Area	Figure # 1a



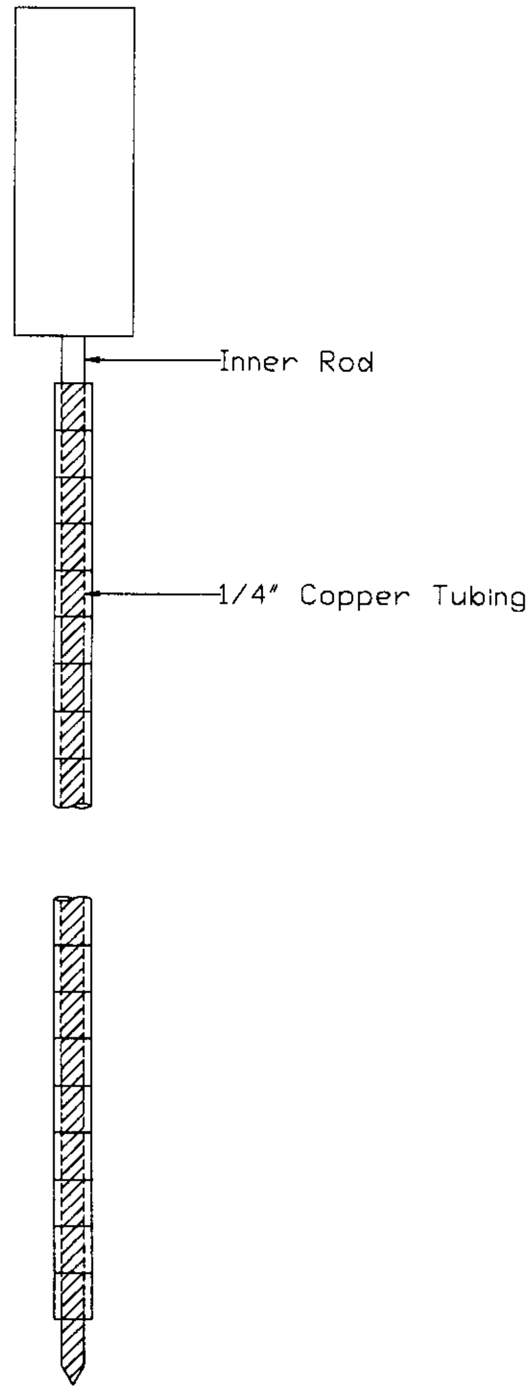
C-CORE	Inset of Study Area	Figure # 1b



C-CORE

Vertical Deformation Tube

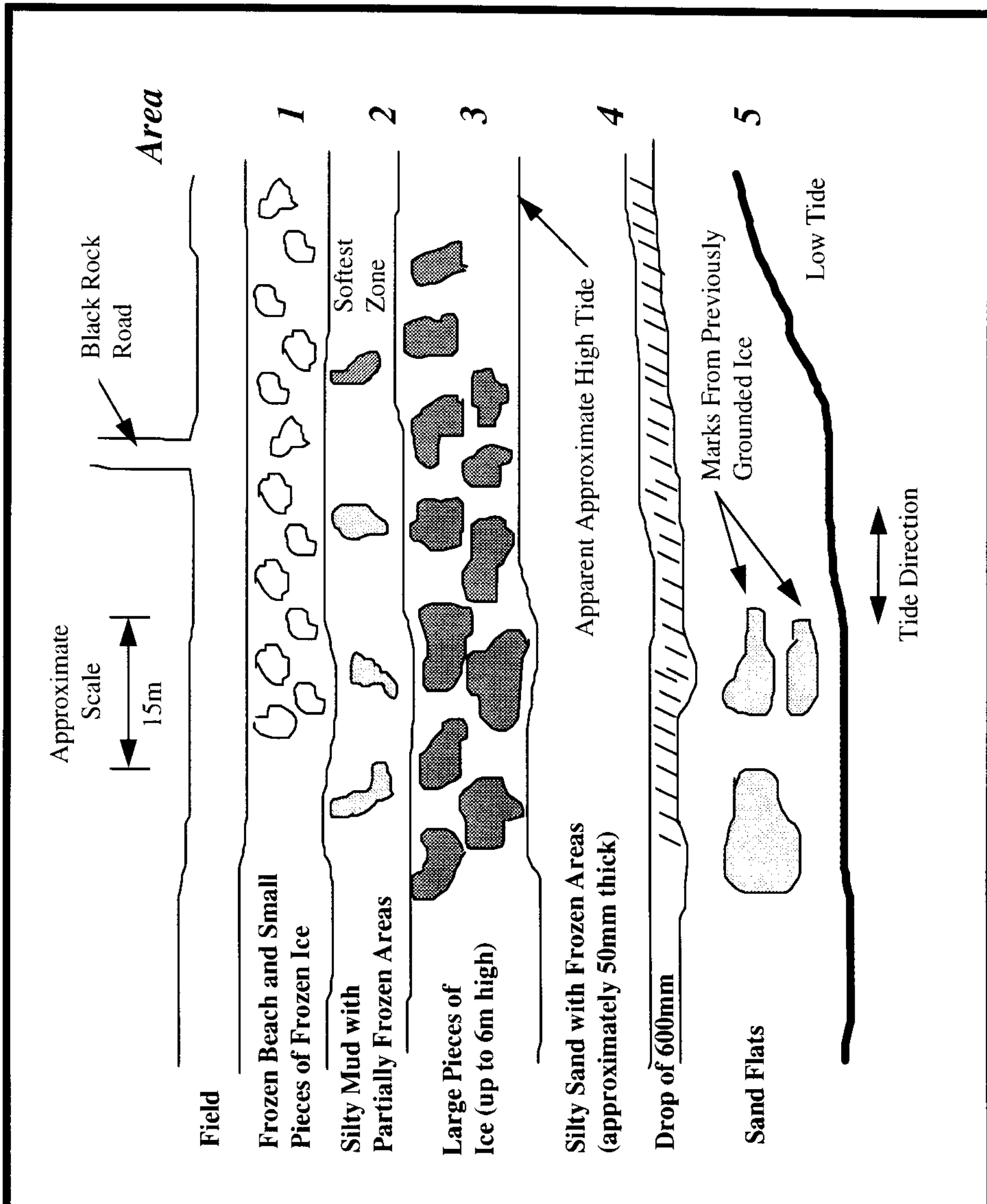
Figure # 2



C-CORE

Copper Tube String

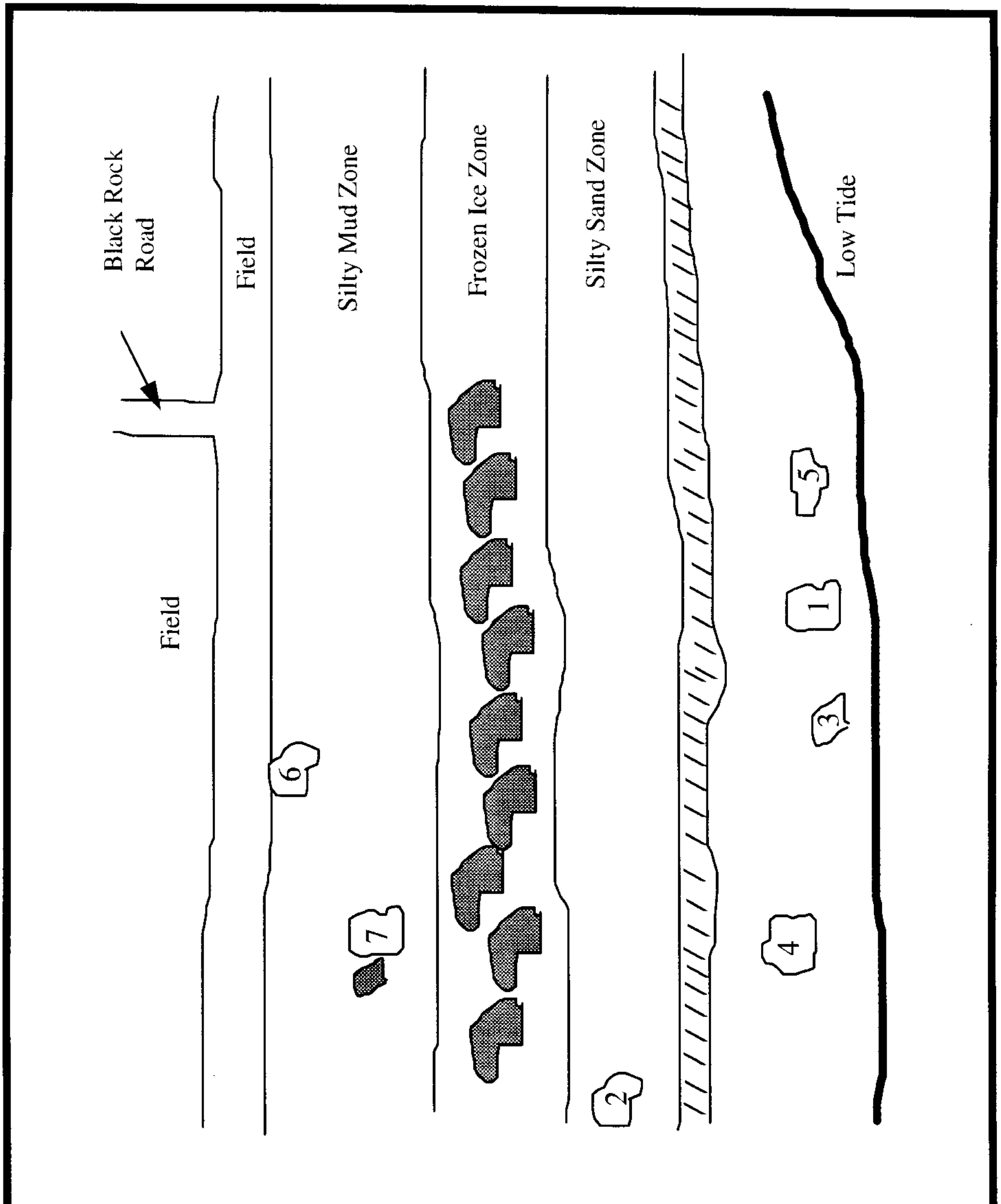
Figure # 3



C-CORE

Layout of Black Rock Area

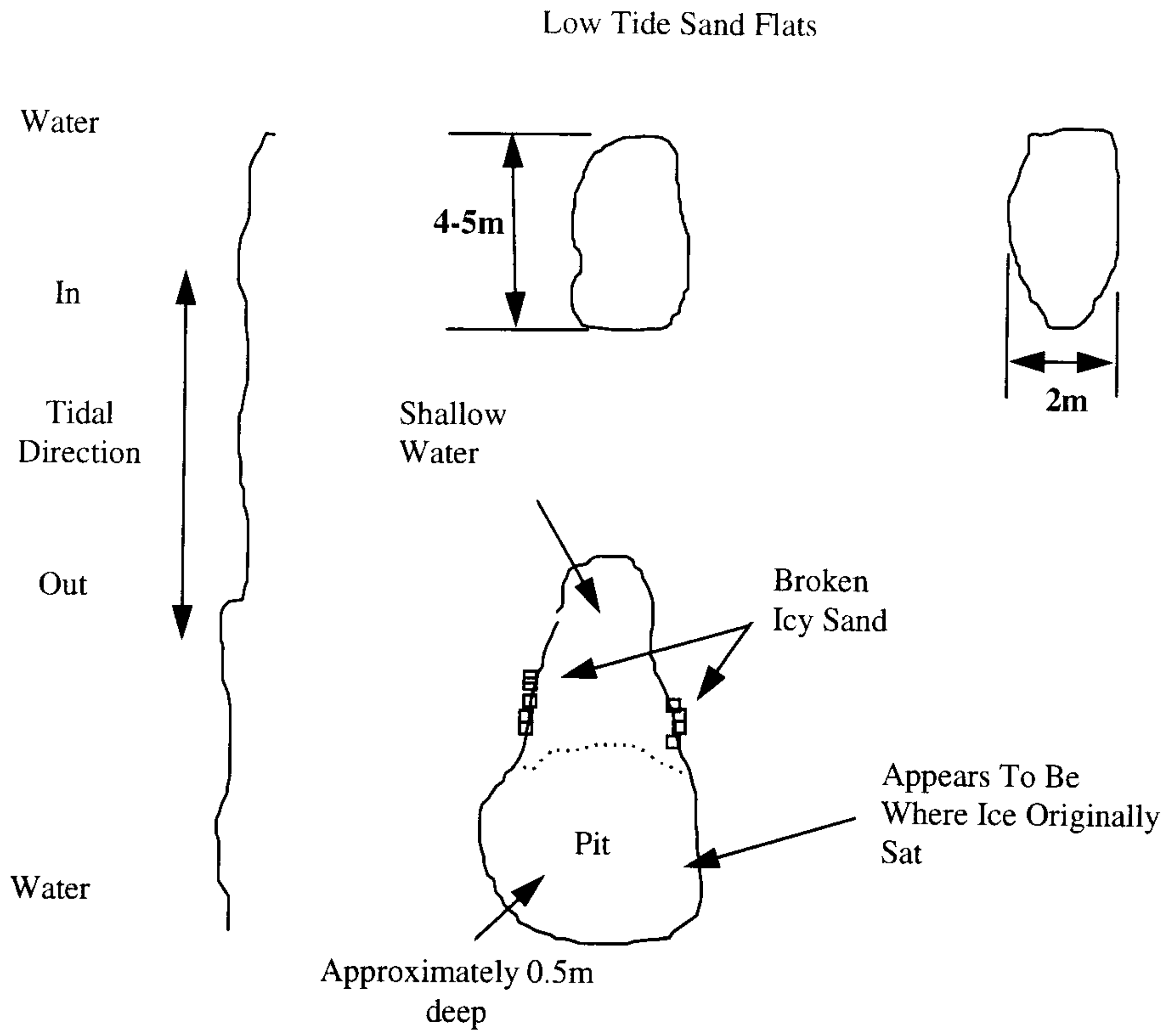
Figure # 4a



C-CORE

Location Map of Icebergs Studied in Black Rock Area

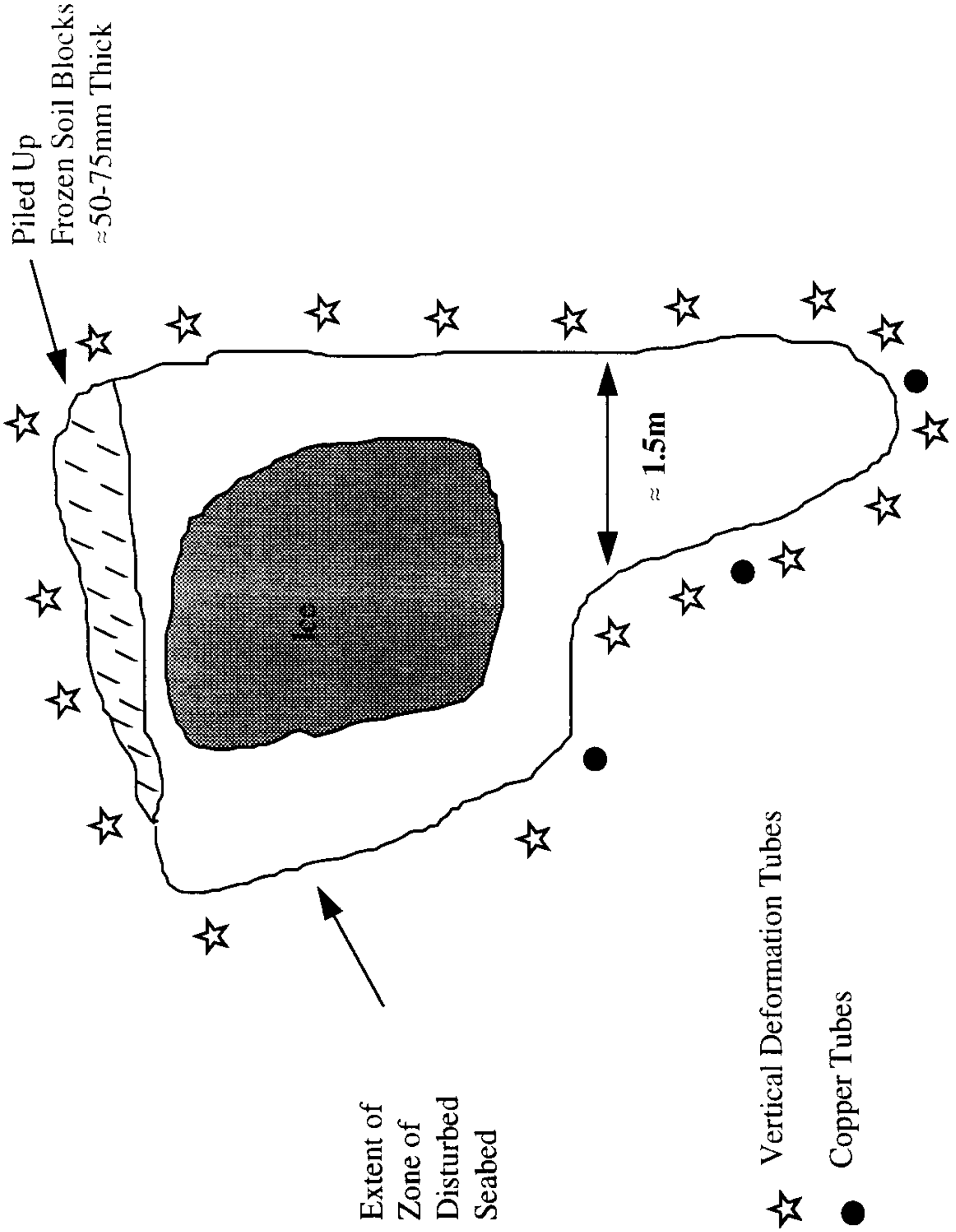
Figure # 4b



C-CORE

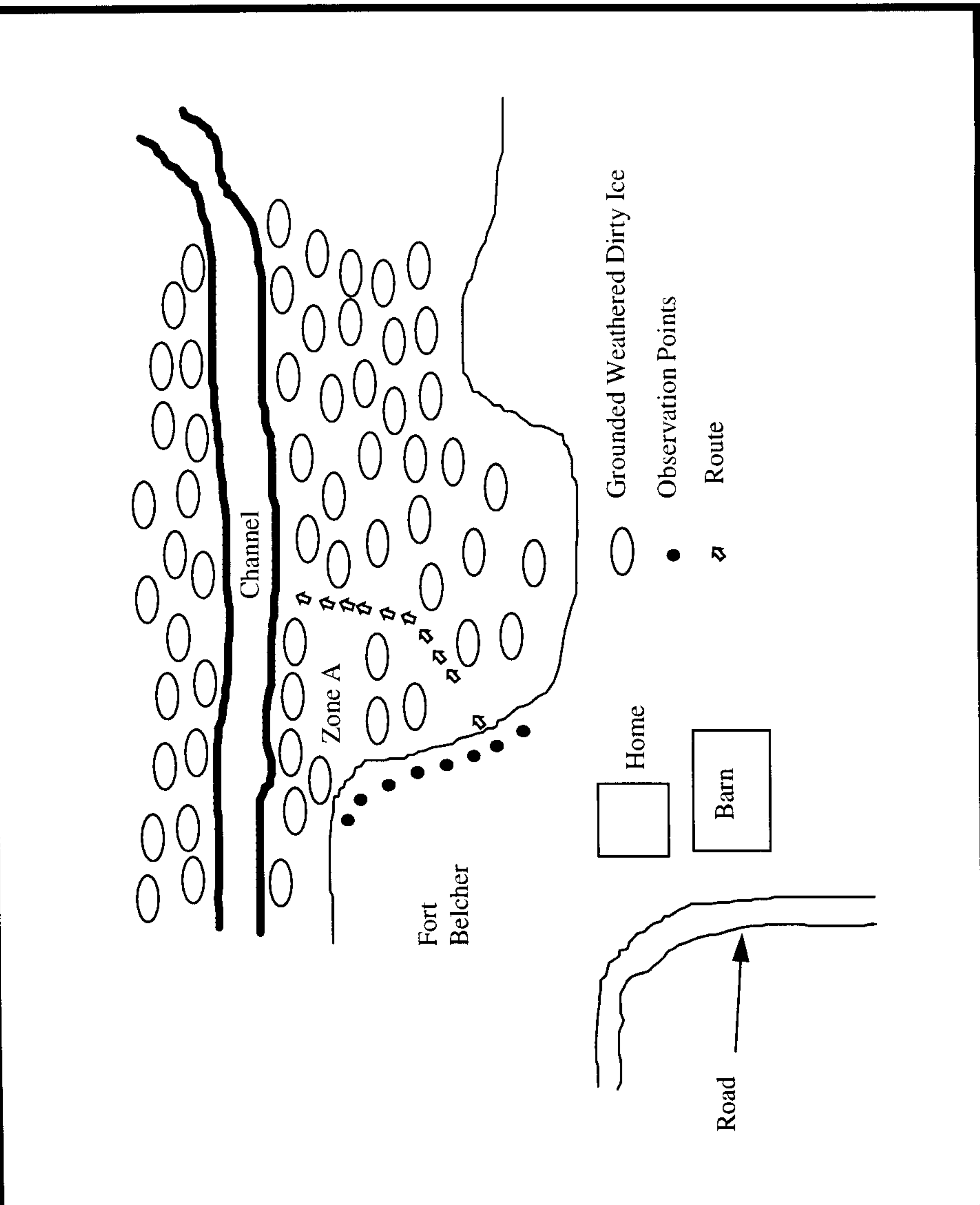
Size and Location of Gouges found on Frozen Sand Flats

Figure # 5



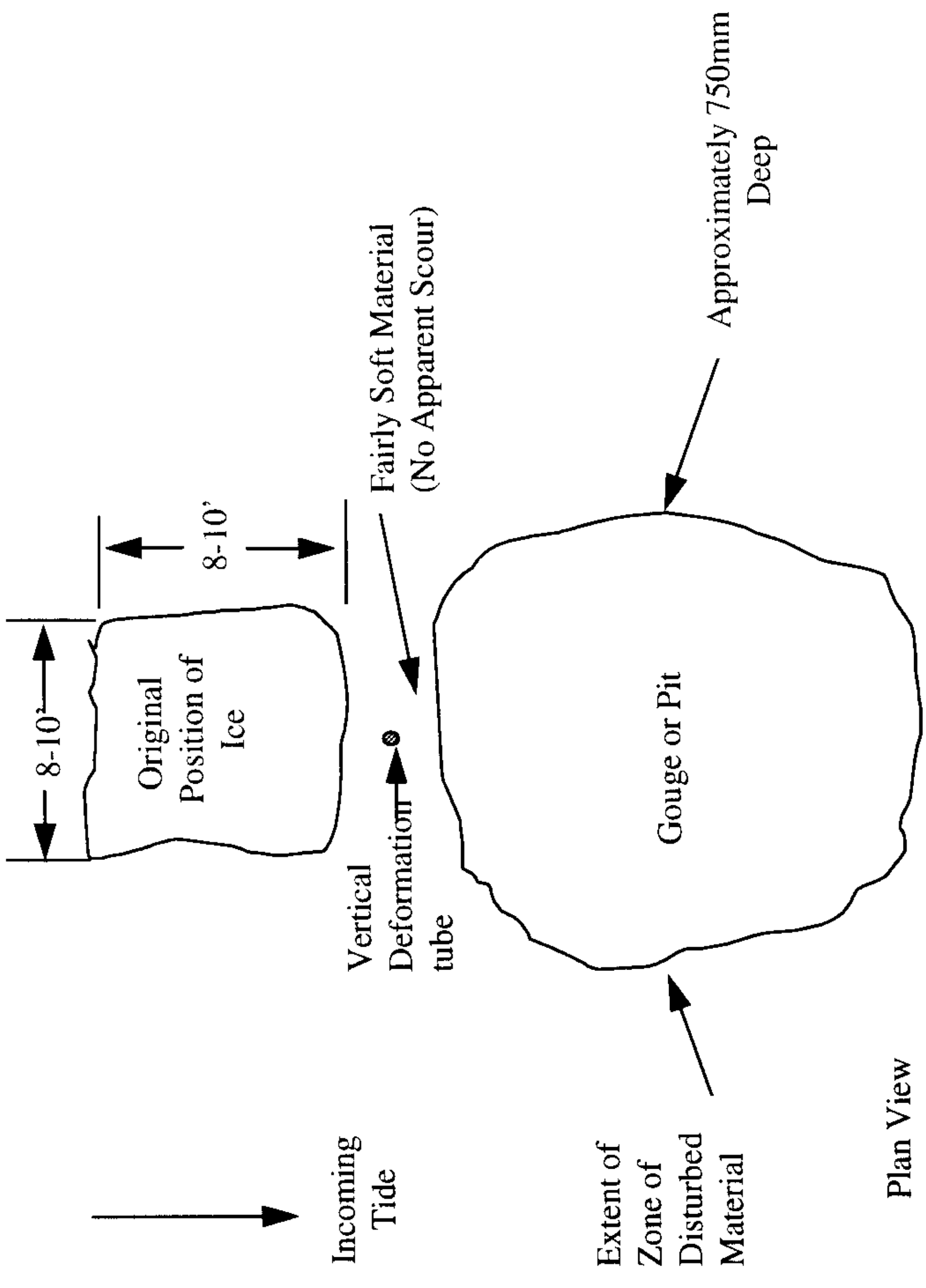
Iceberg #6

Figure #
6



Masstown Flats / Fort Belcher Area

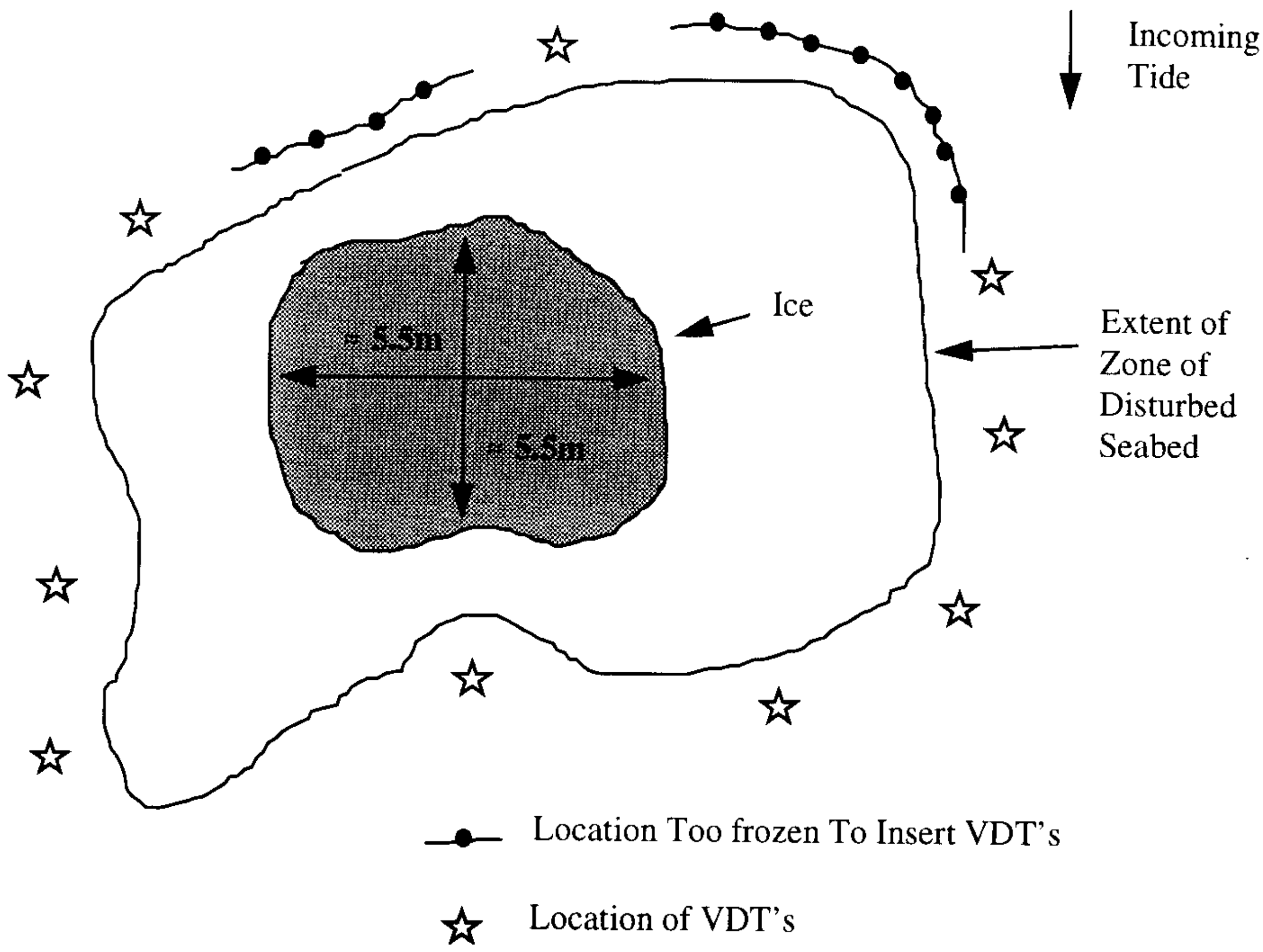
Figure # 7



C-CORE

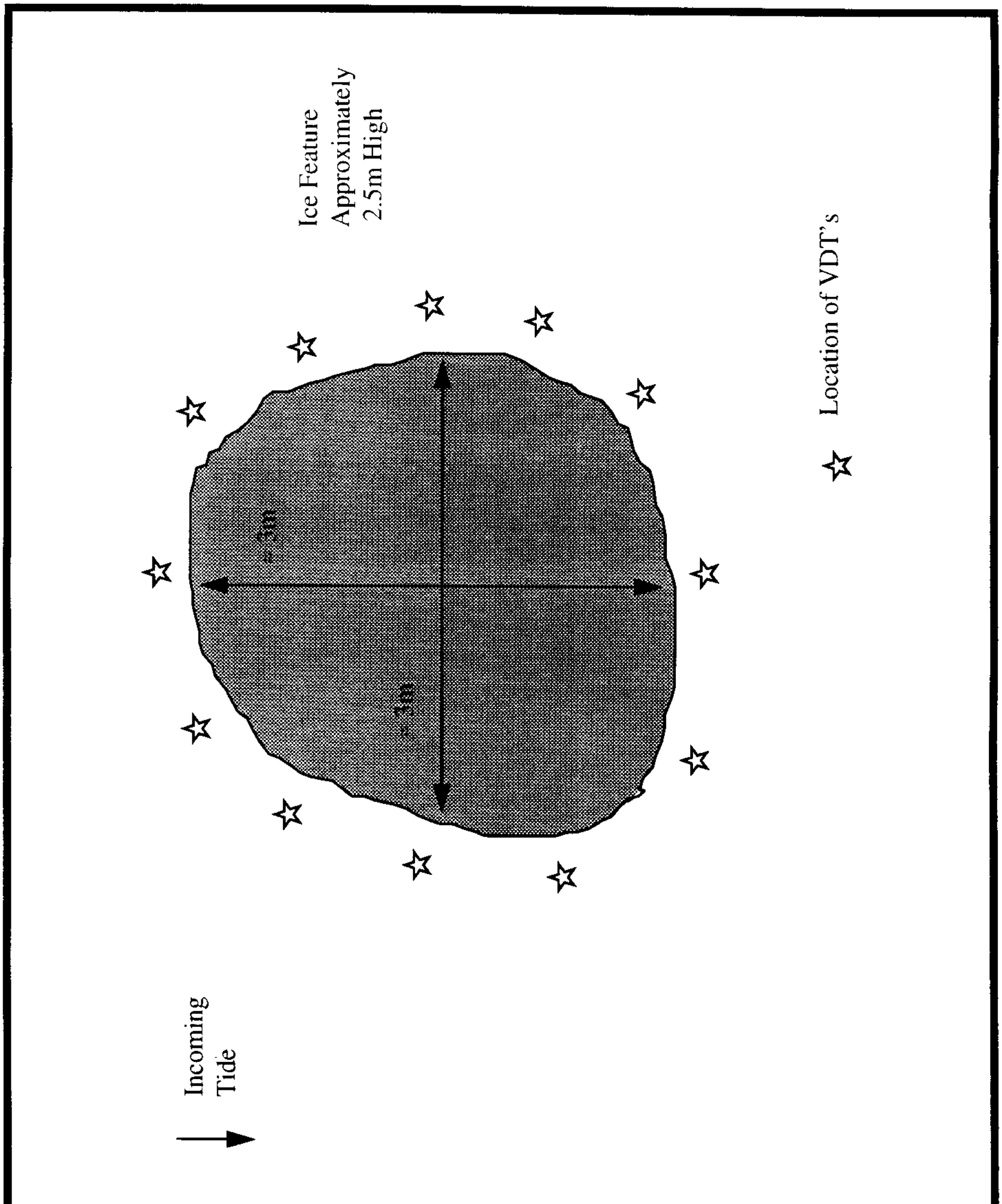
Iceberg #2 Area

Figure # 8



Iceberg #4 Area

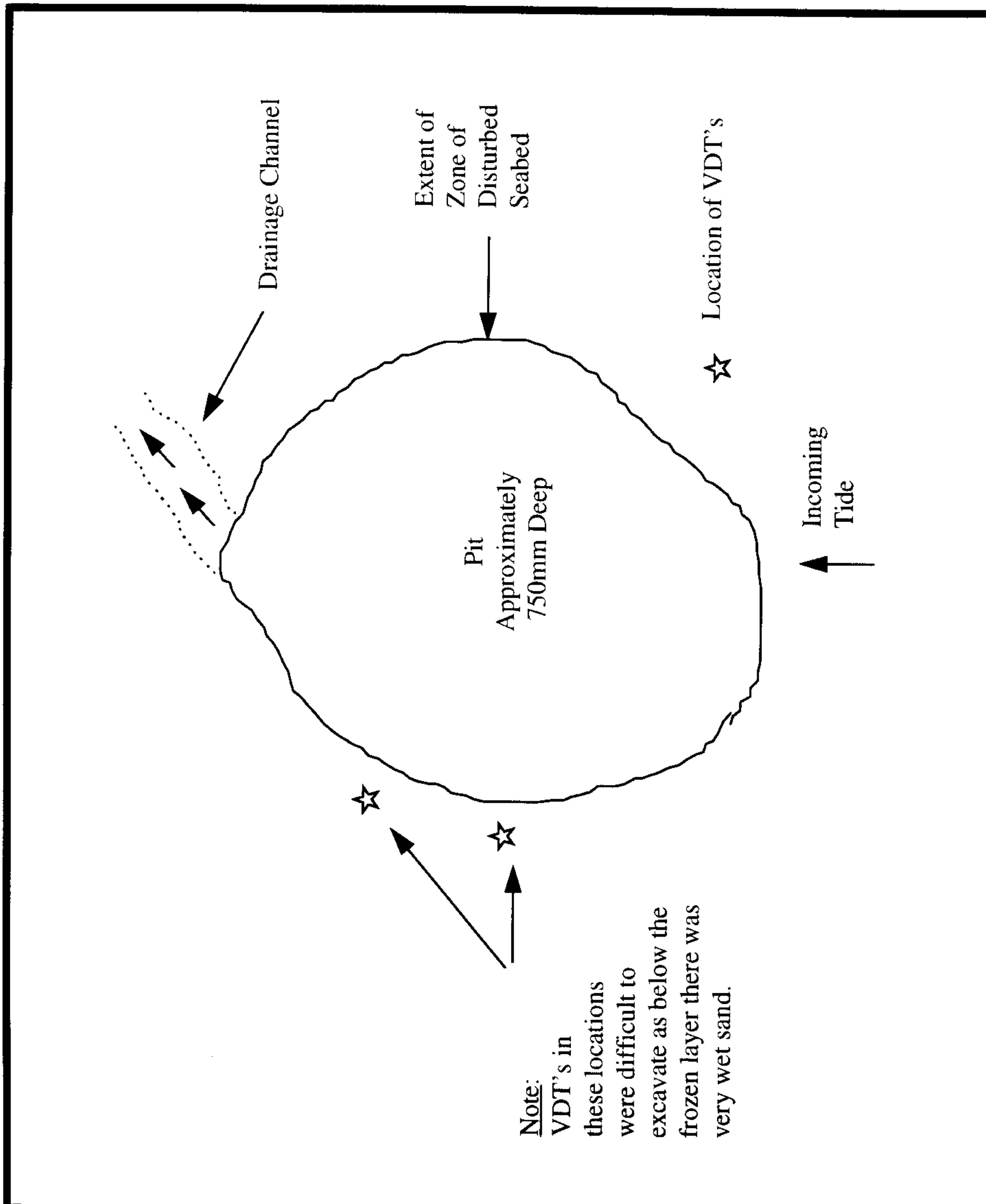
Figure #
9



C-CORE

Iceberg #5 Area

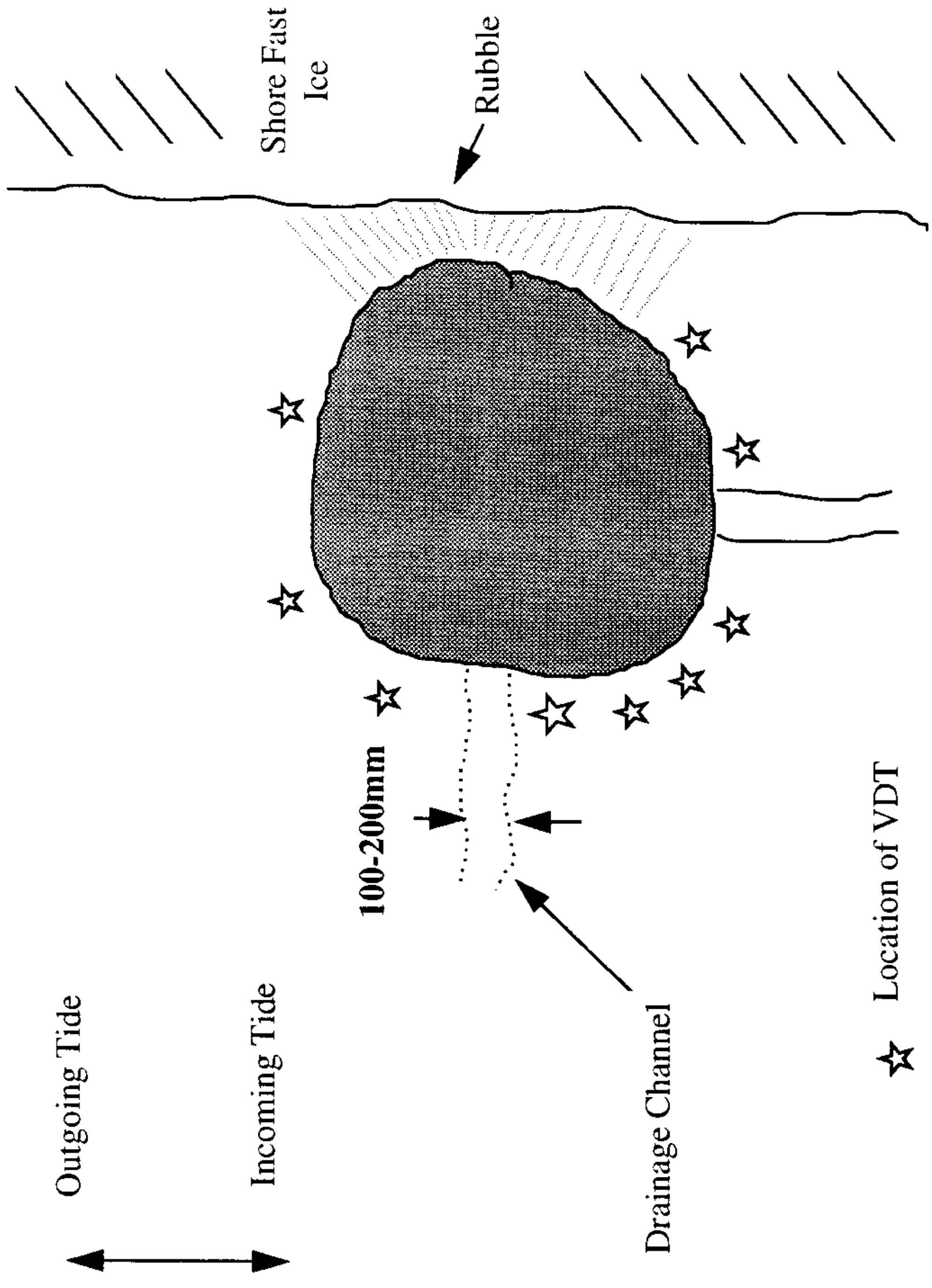
Figure #
10



C-CORE

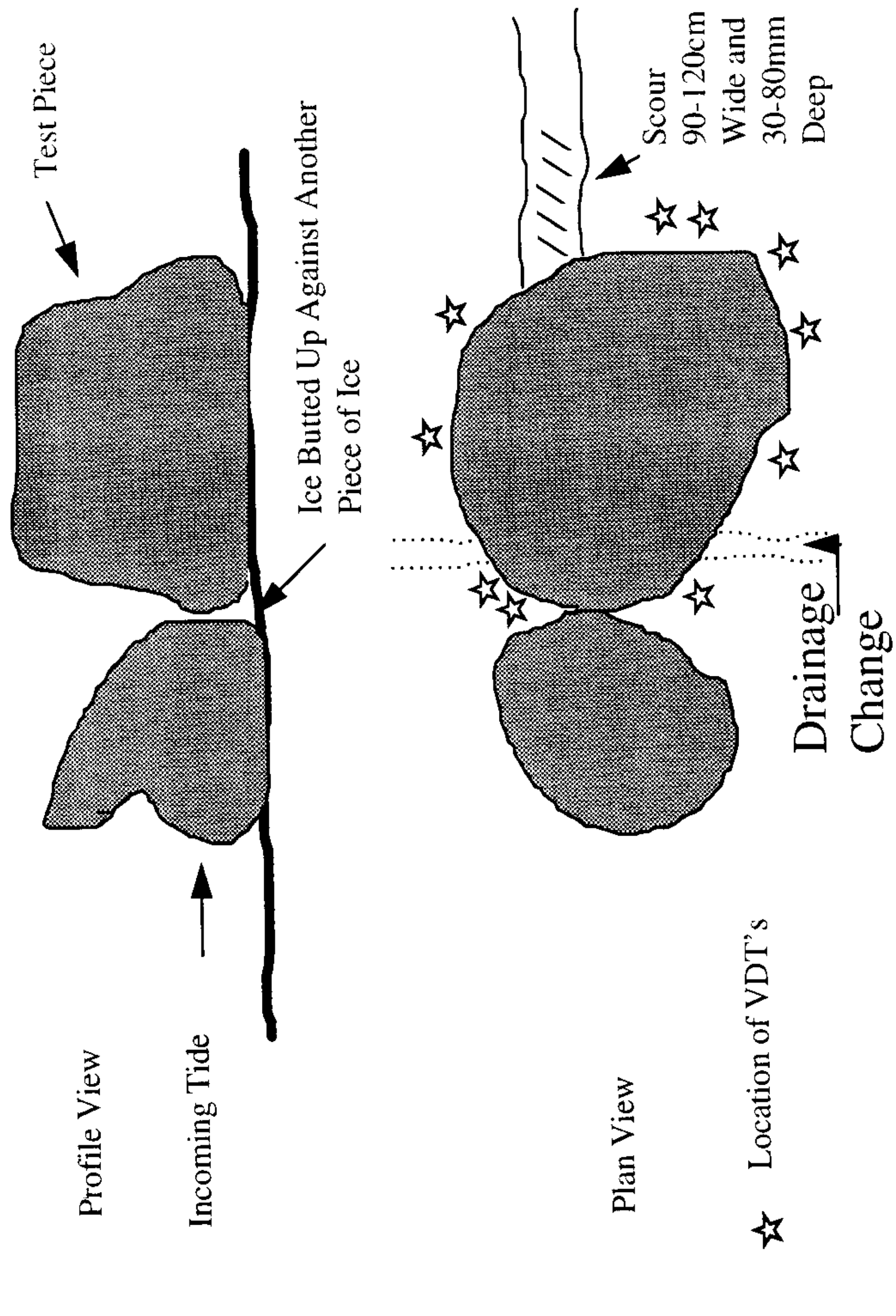
Iceberg #4 Area after Tidal Cycle and Departure of Iceberg

Figure # 11

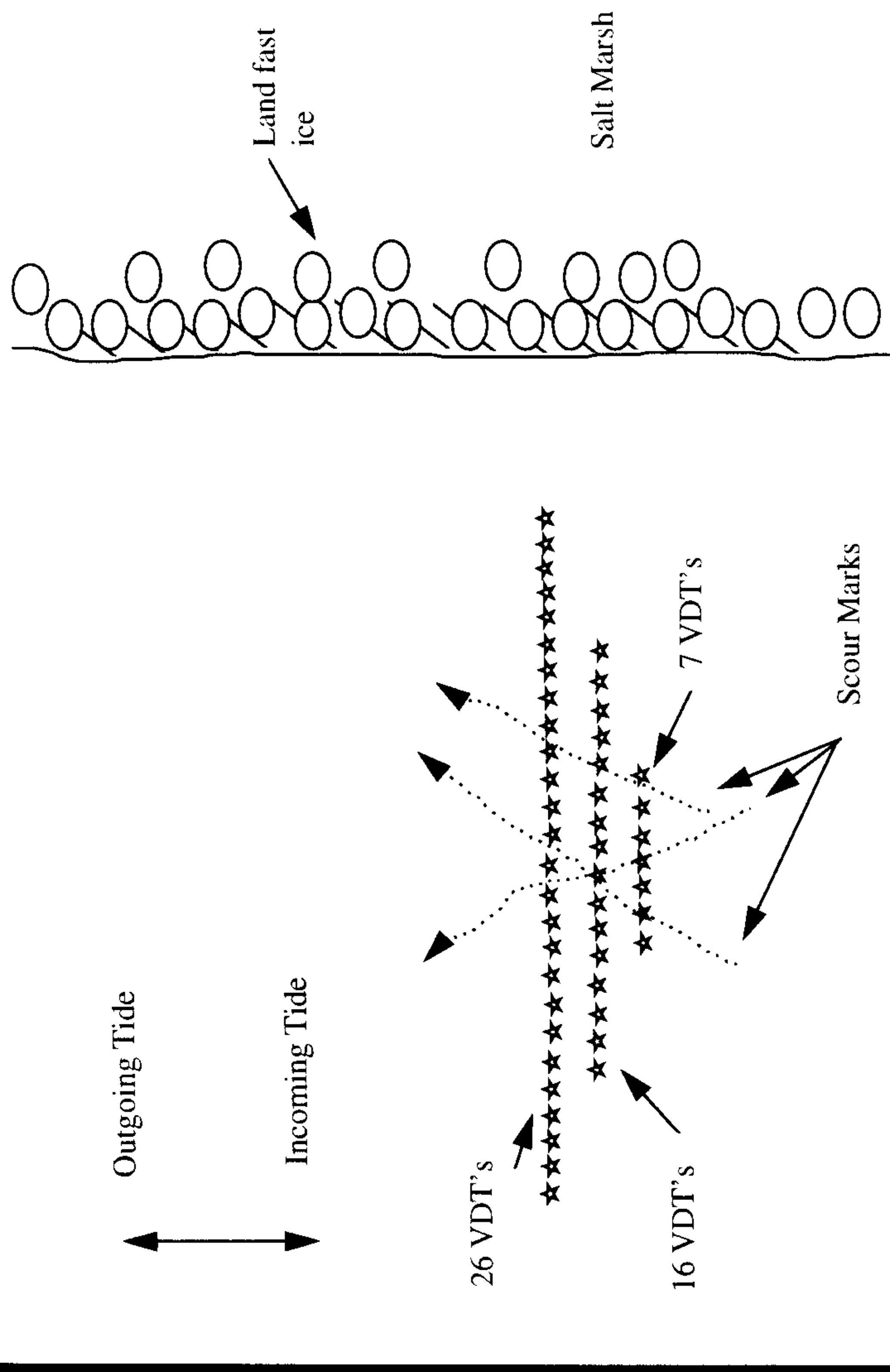


Iceberg #6 Area

Figure # 12



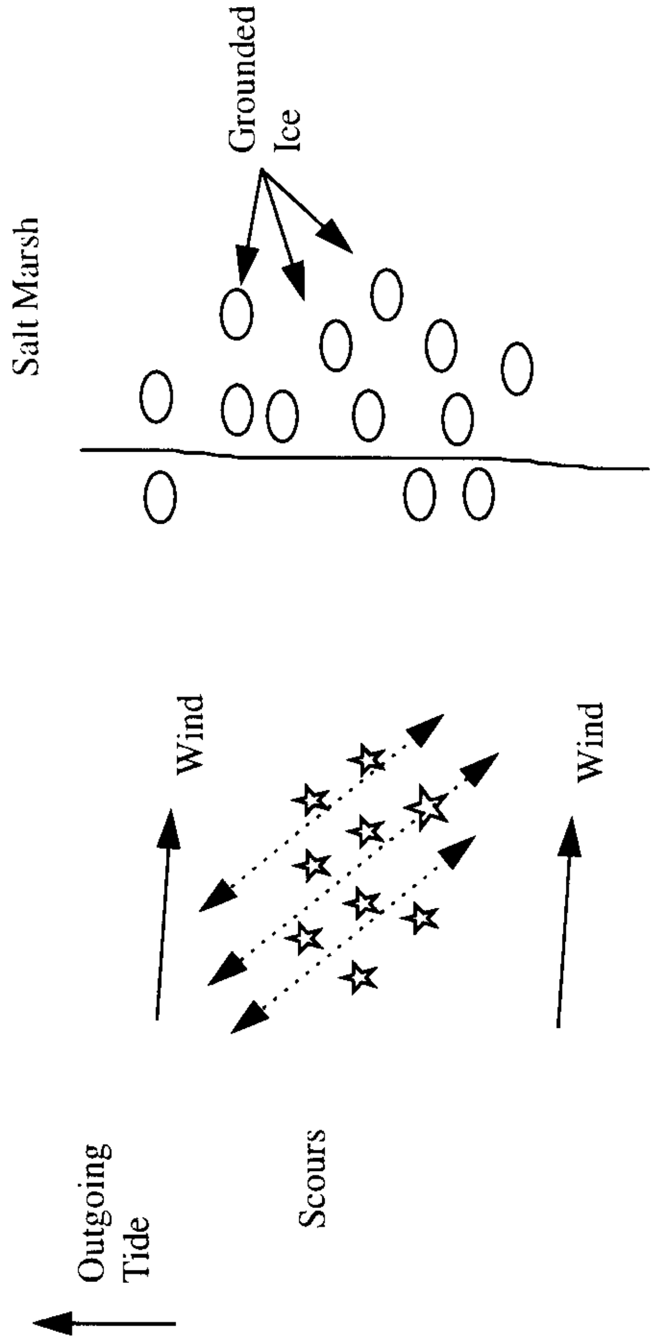
C-CORE	**Iceberg #7 Area**	**Figure # 13**



C-CORE

VDT Lines

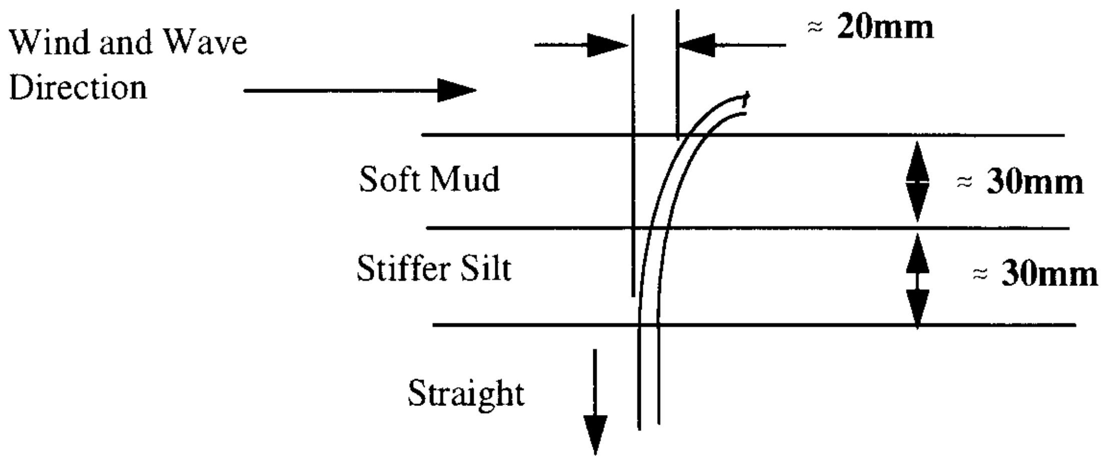
Figure # 14



C-CORE

Orientation of Scours over VDT Lines

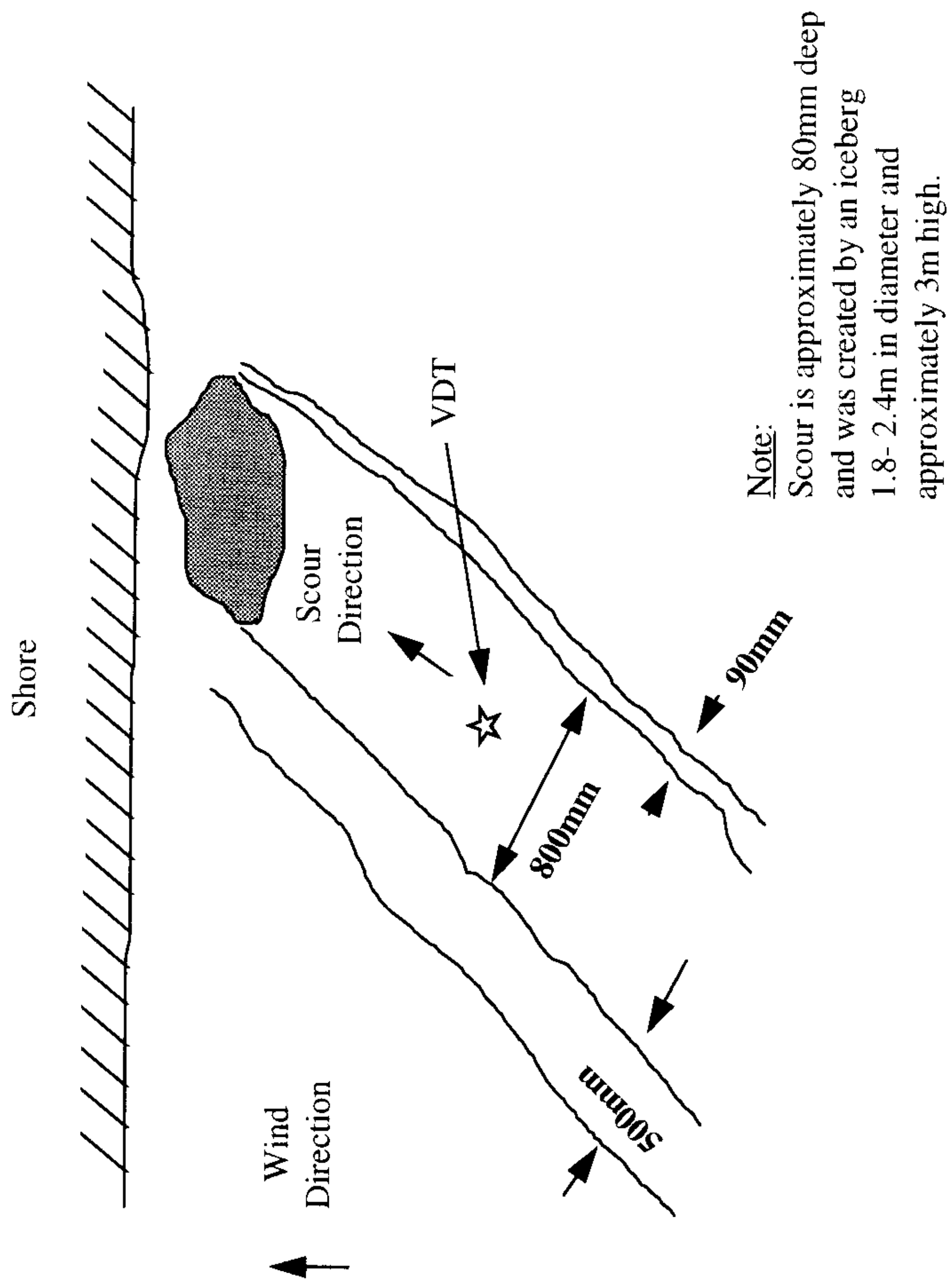
Figure # 15



C-CORE

Excavated Profile of VDT #1

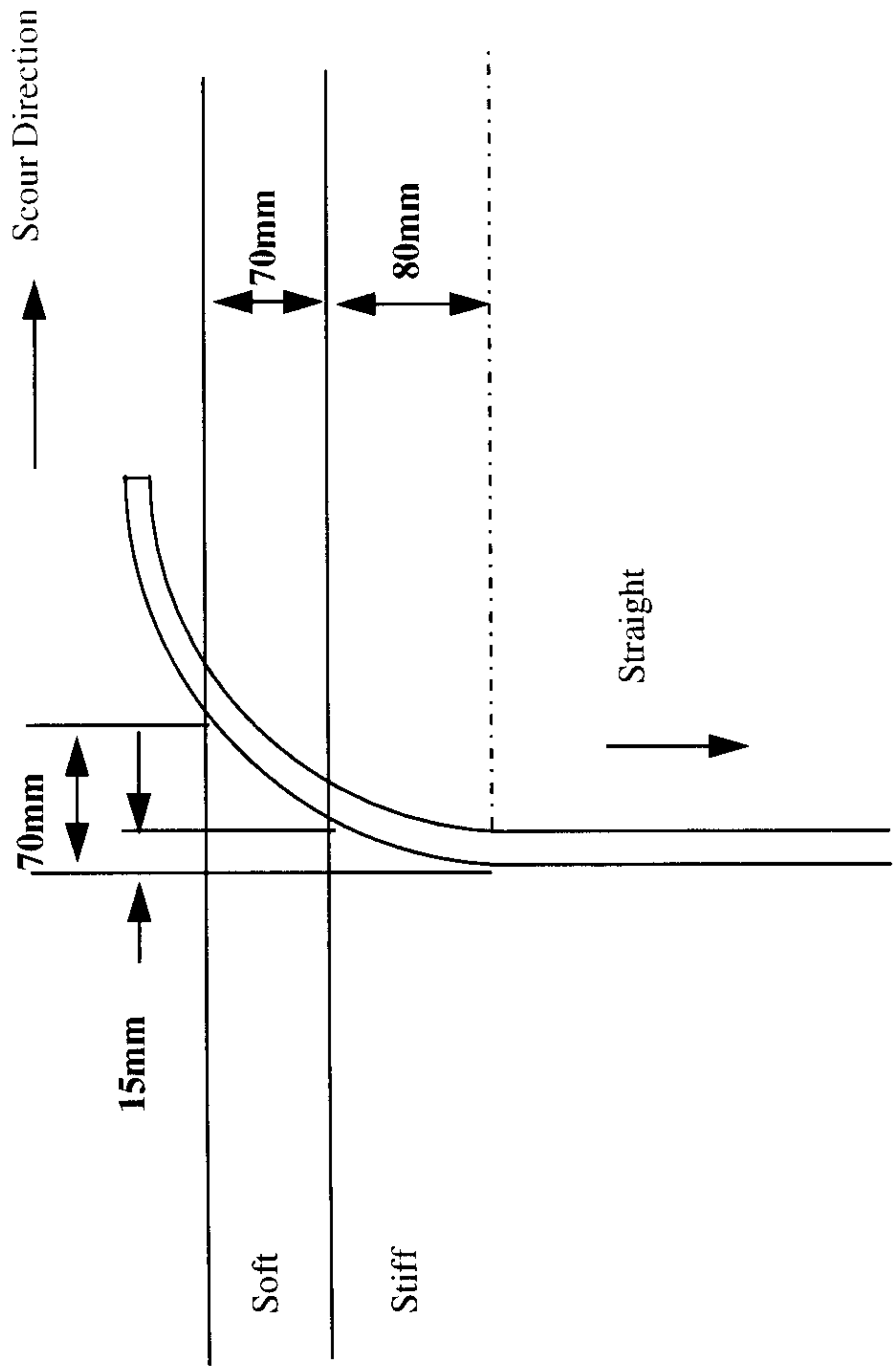
Figure # 16



C-CORE

Scour Layout in Relation to VDT #2

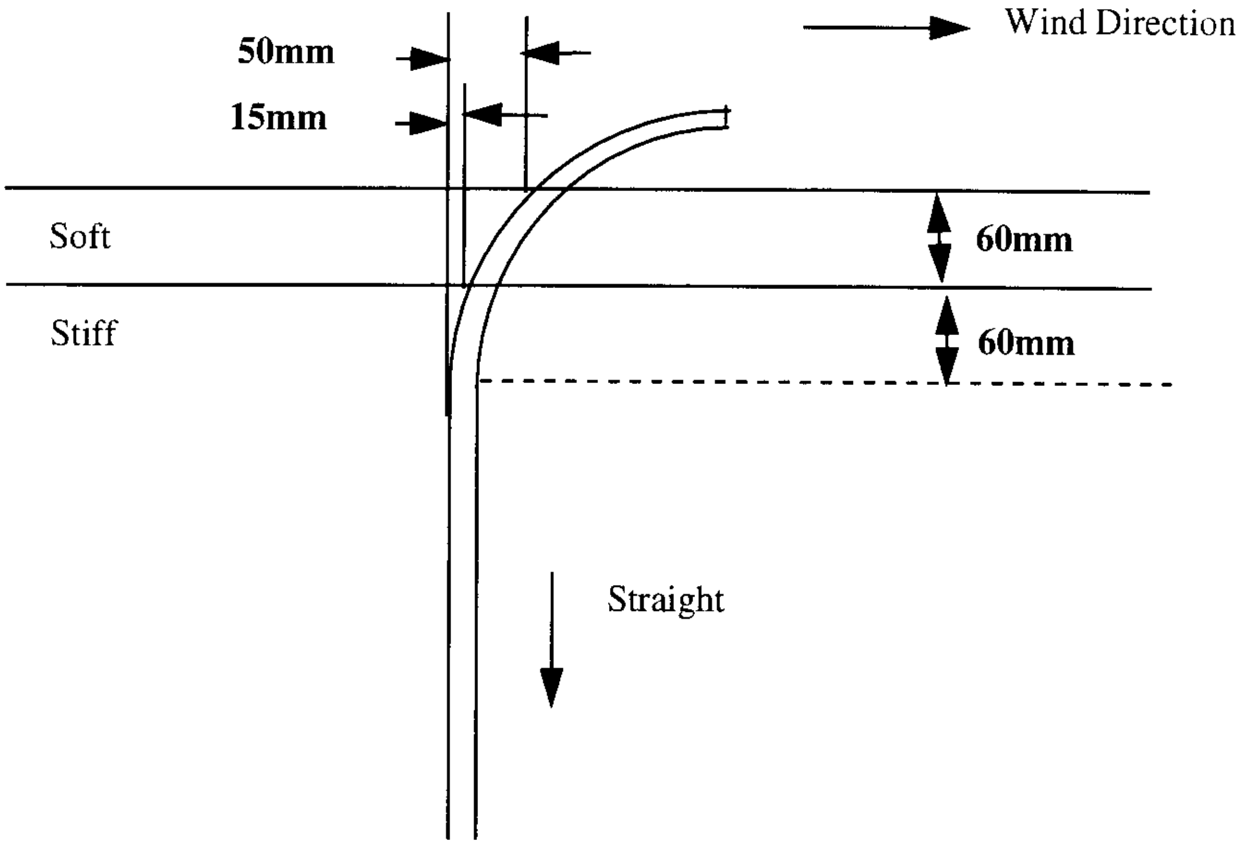
Figure # 17



C-CORE

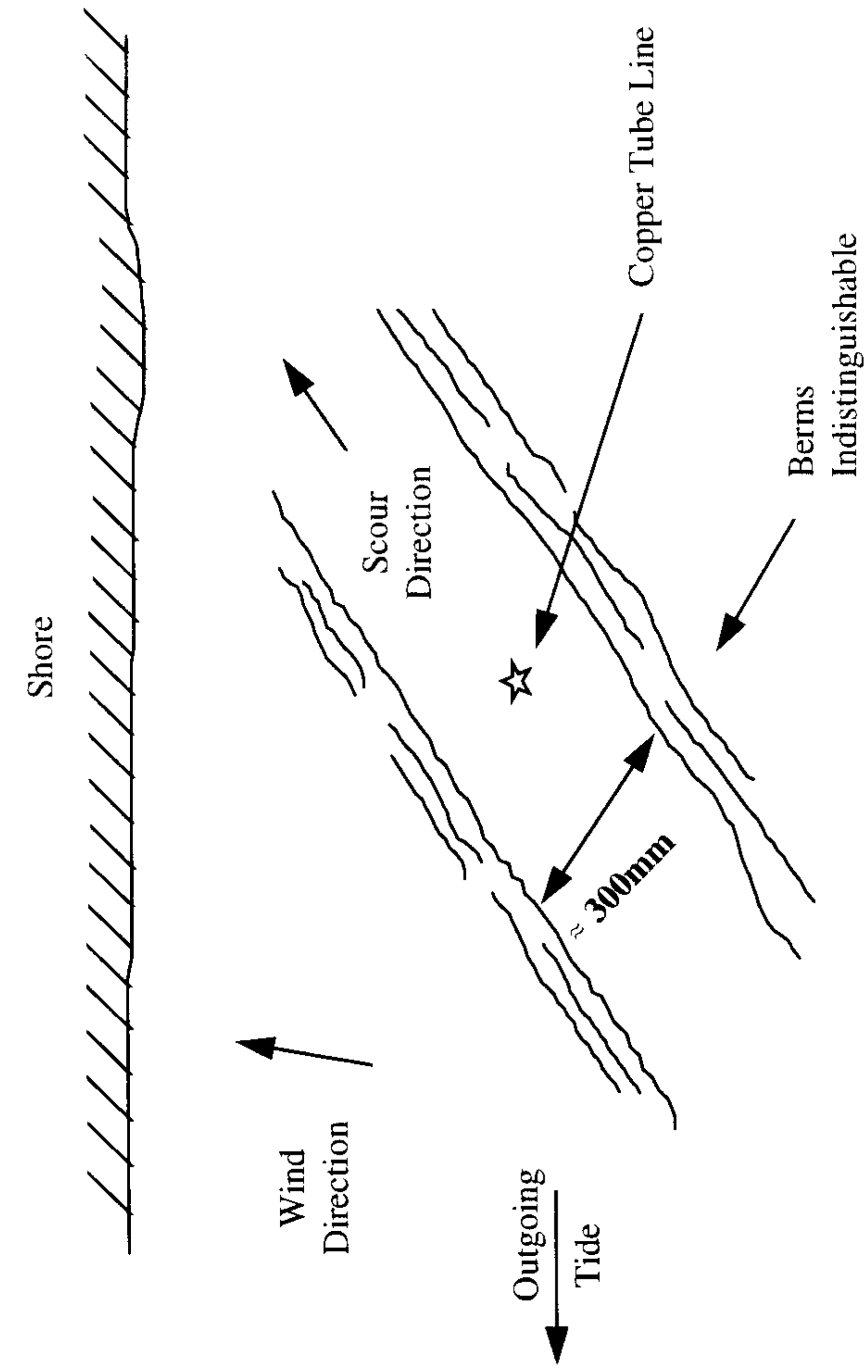
Excavated Profile of VDT #2

Figure #
18



Excavated Profile of Control VDT

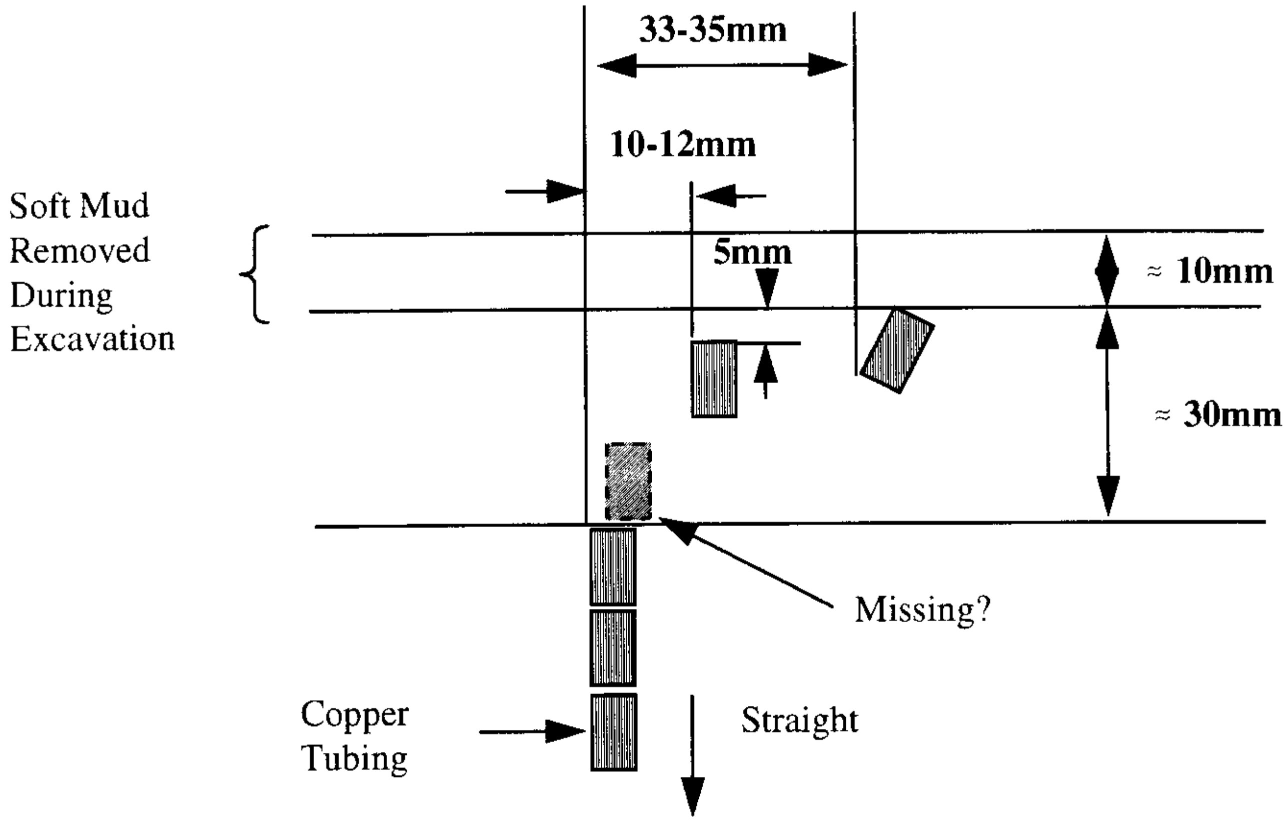
Figure #
19



C-CORE

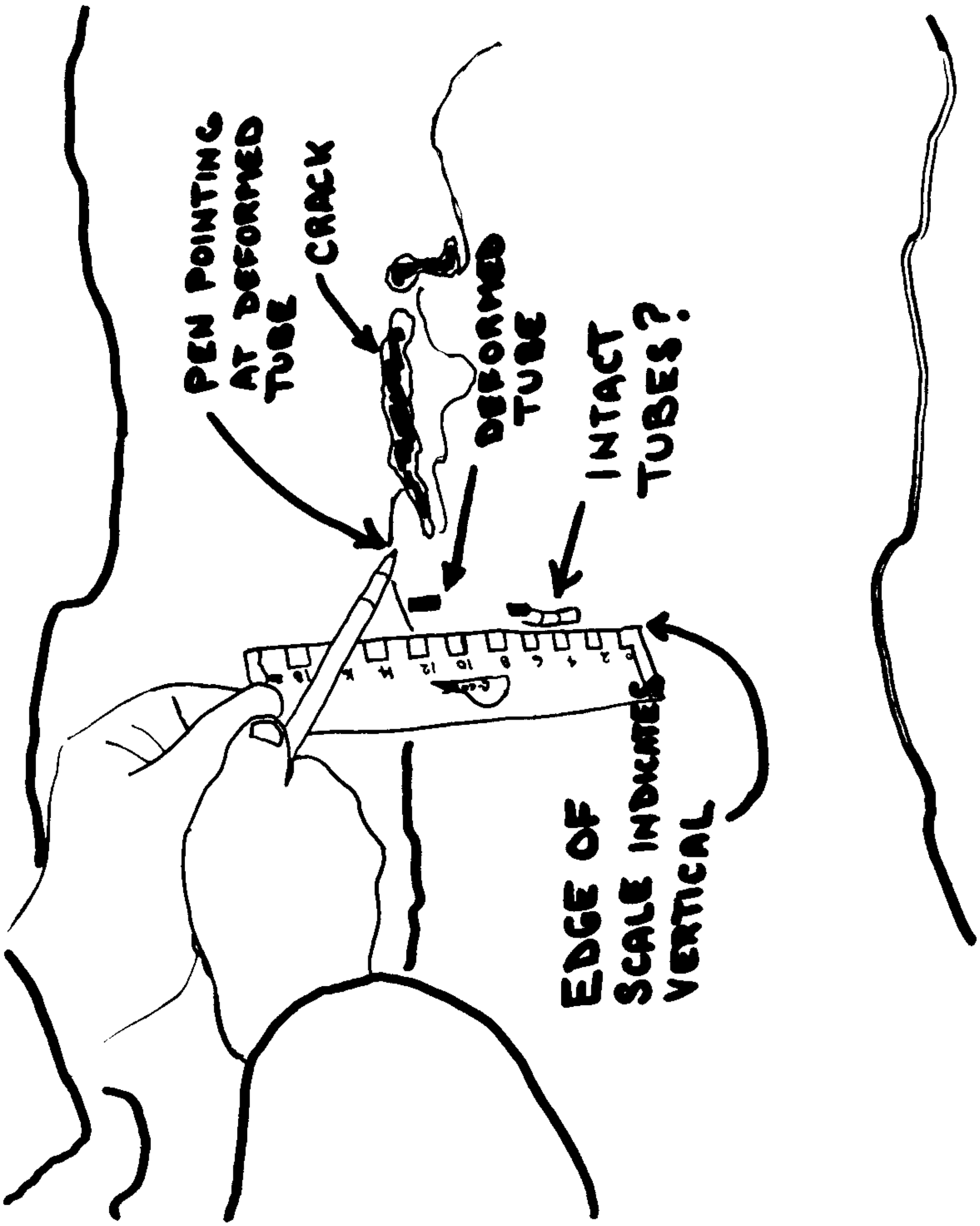
Scour Layout in Relation to Copper Tube Line

Figure # 20



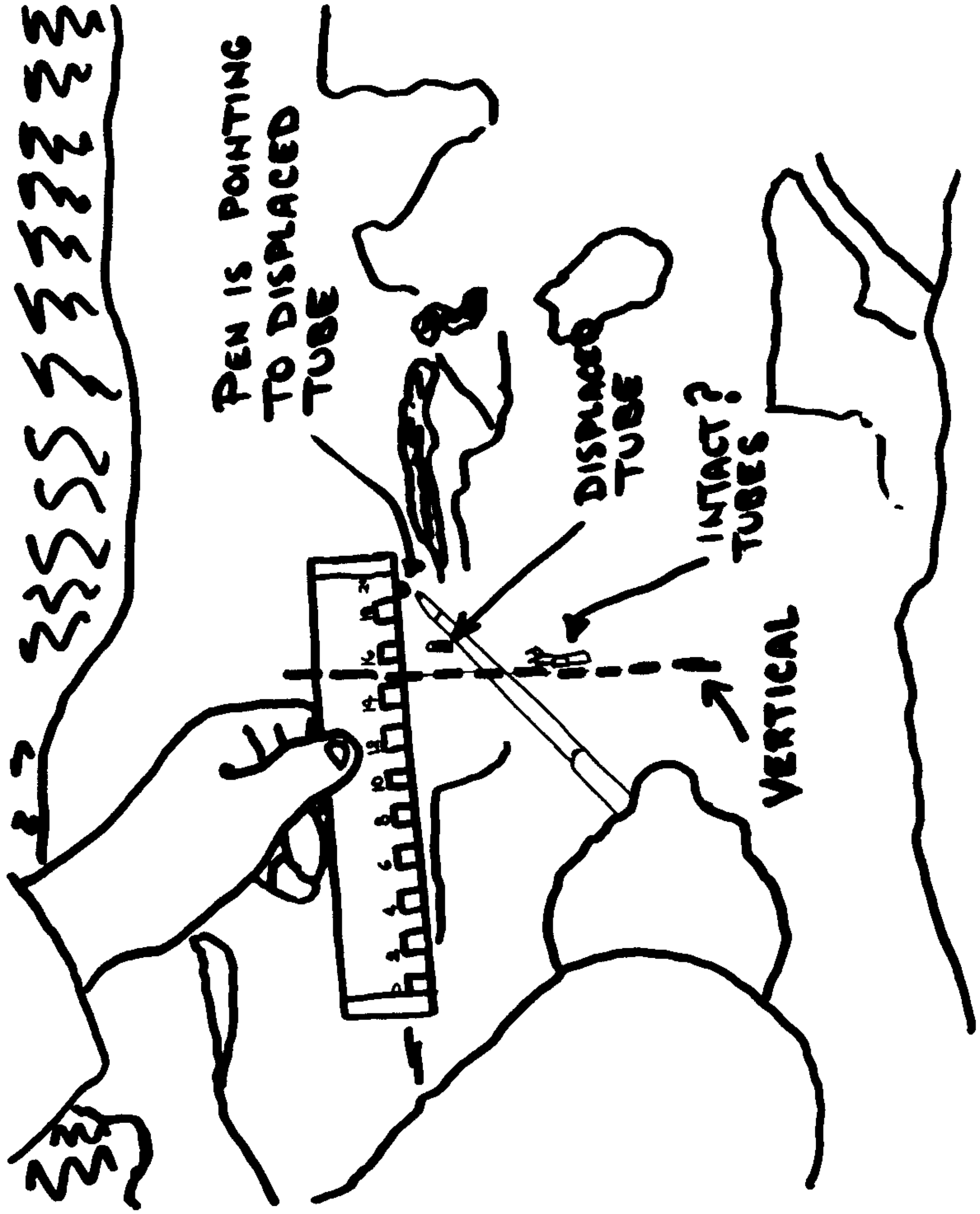
Excavated Profile of Copper Tube Line

Figure # 21



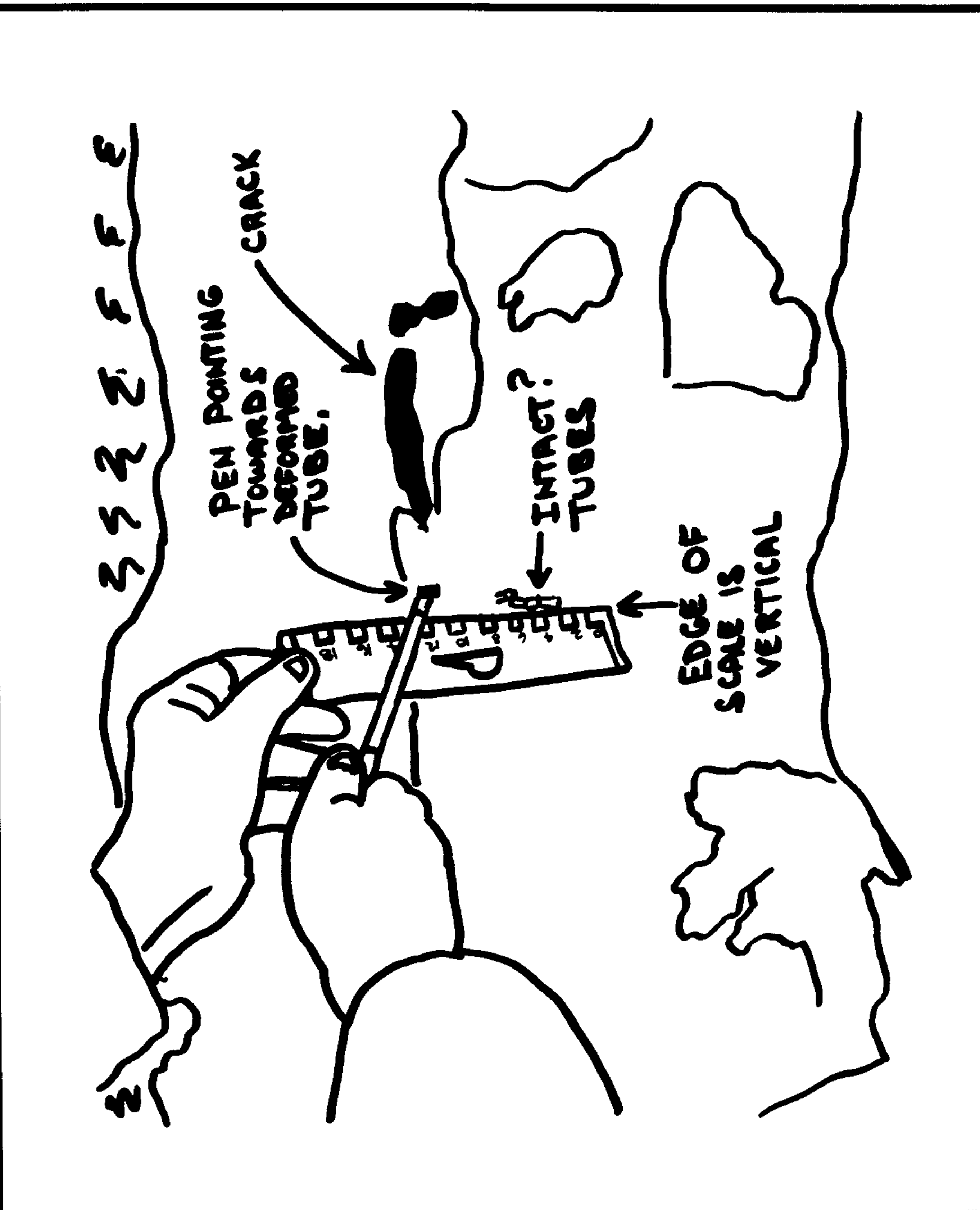
Annotated Sketch of Photo 60a

Figure # 22a



Annotated Sketch of Photo 60b

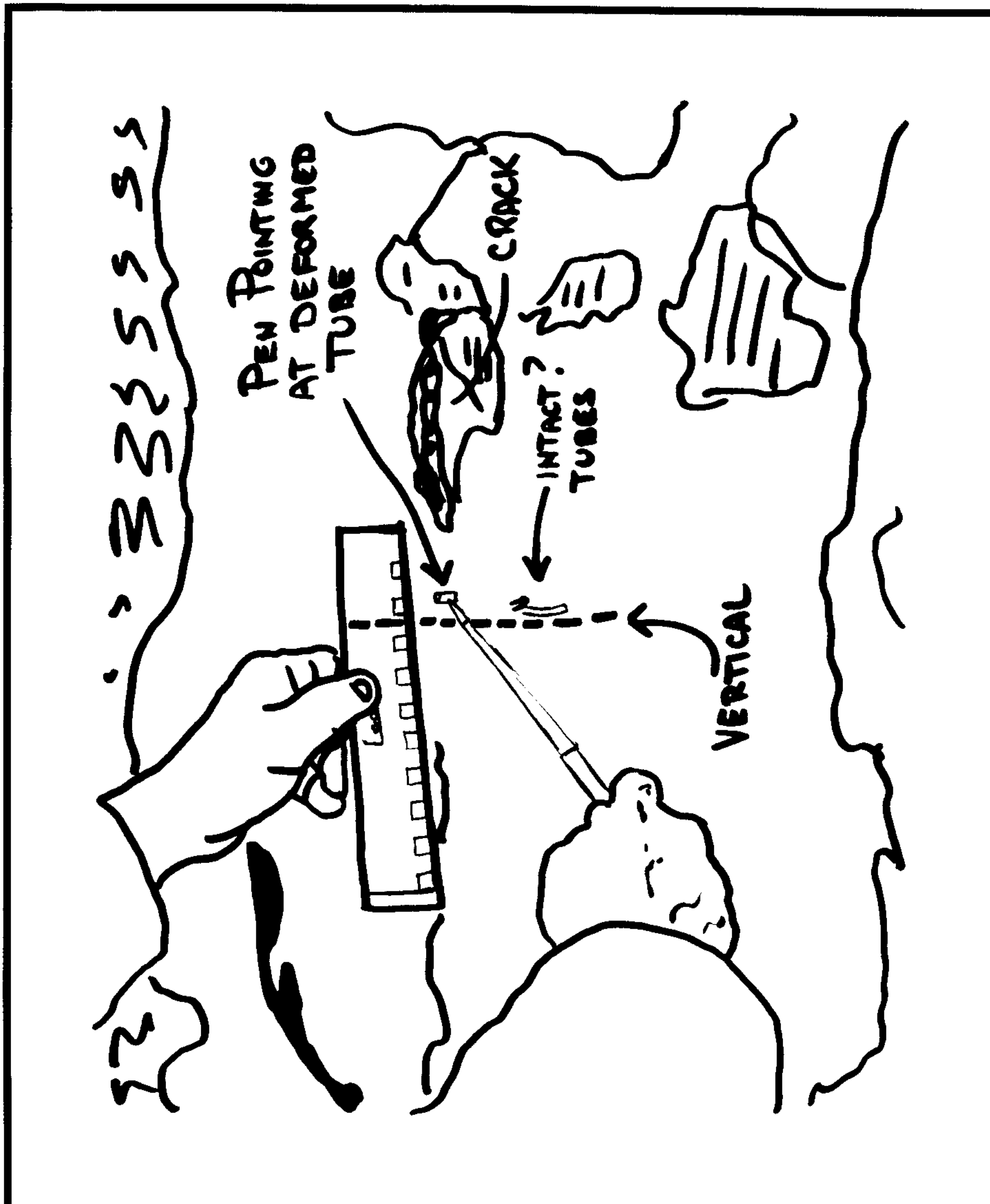
Figure # 22b



C-CORE

Annotated Sketch of Photo 61a

Figure # 23a



C-CORE

Annotated Sketch of Photo 61b

Figure #
23b

Appendix B

Laboratory Testing of Mudflat Material from Black Rock

Field Sampling

During the field program, three soil samples were taken from the Black Rock mudflats. At each sample location, the upper, softer sediment (50-75 mm thick) was collected separate from the lower, more competent material. In the sample designation, the number refers to the sample number while the U or L designation indicates whether the sample was collected from the upper or lower sediment.

Water Content

Water content testing was performed according to the ASTM D2216-92 (ASTM, 1996a) standard. The water contents of the samples are provided in Table B.1.

Specific Gravity

Specific gravity testing was performed according to the procedure outlined by Bowles (1986). The testing was performed on samples oven dried at a temperature of 110°C. A sample size ranging between 95 and 110 g was used for samples S1L, S1U, and S2U. A sample size ranging between 30 and 70 g was used for samples S2L, S3L, and S3U. A 500 ml volumetric flask was used and deairing was accomplished by use of an applied vacuum of 20 psi. A calibration curve for the volumetric flask was not used. The temperature at which the mass readings were taken were within 1°C of each other. The test was repeated until the specific gravity values obtained for two tests were within two percent of each other. The two specific gravity values obtained were averaged to obtain the specific gravity of the soil. The specific gravity of the samples are presented in Table B.1.

Liquid Limit

Liquid limit testing was attempted using the ASTM D4318-95 (ASTM, 1996b) standard; however, the soil would not adhere to the cup and the method could not be used. Liquid limit testing was performed using the fall cone method outlined by Bowles (1986). A 60 degree, 60 g cone was used with the liquid limit defined as the water content at a cone penetration of 10 mm (Leroueil and Le Bihan, 1996). The testing was performed on samples oven dried at a temperature of 110°C. There was not always enough soil to completely fill the cup during testing; however, the cup was usually almost full. The liquid limits of the samples are summarized in Table B.1.

Plastic Limit

Plastic limit testing was performed according to the ASTM D4318-95 (ASTM, 1996b) standard. The testing was performed on samples oven dried at a temperature of 110°C. The plastic limits of the samples are summarized in Table B.1.

Grain Size Analysis

Grain size analyses were performed as outlined by Bowles (1986). The testing was performed on samples oven dried at a temperature of 110°C. A set of sieves containing a No. 40, No. 60, No. 100, No. 140, and No. 200 sieve was used for the mechanical sieve analysis. The sample sizes ranged between 60 and 250 g. The sieves were placed in a mechanical sieve shaker for 6 minutes. An hydrometer analysis, using a 152H type hydrometer, was performed on the soil passing the No. 200 sieve. The sample sizes generally ranged between 37 and 50 g; only soils S2L and S3L had less than 50 g. The samples were mixed with 125 ml of 4% sodium metaphosphate solution and left overnight prior to hydrometer testing. The specific gravity of the soils obtained from the test outlined above was used for the hydrometer analysis.

References

ASTM (1996a). "Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock". ASTM Standard D2216-92, 1996 Annual Book of ASTM Standards, ASTM, West Conshohocken, PA, Vol. 04.08, pp. 185-188.

ASTM (1996b). "Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils". ASTM Standard D4318-95, 1996 Annual Book of ASTM Standards, ASTM, West Conshohocken, PA, Vol. 04.08, pp. 560-570.

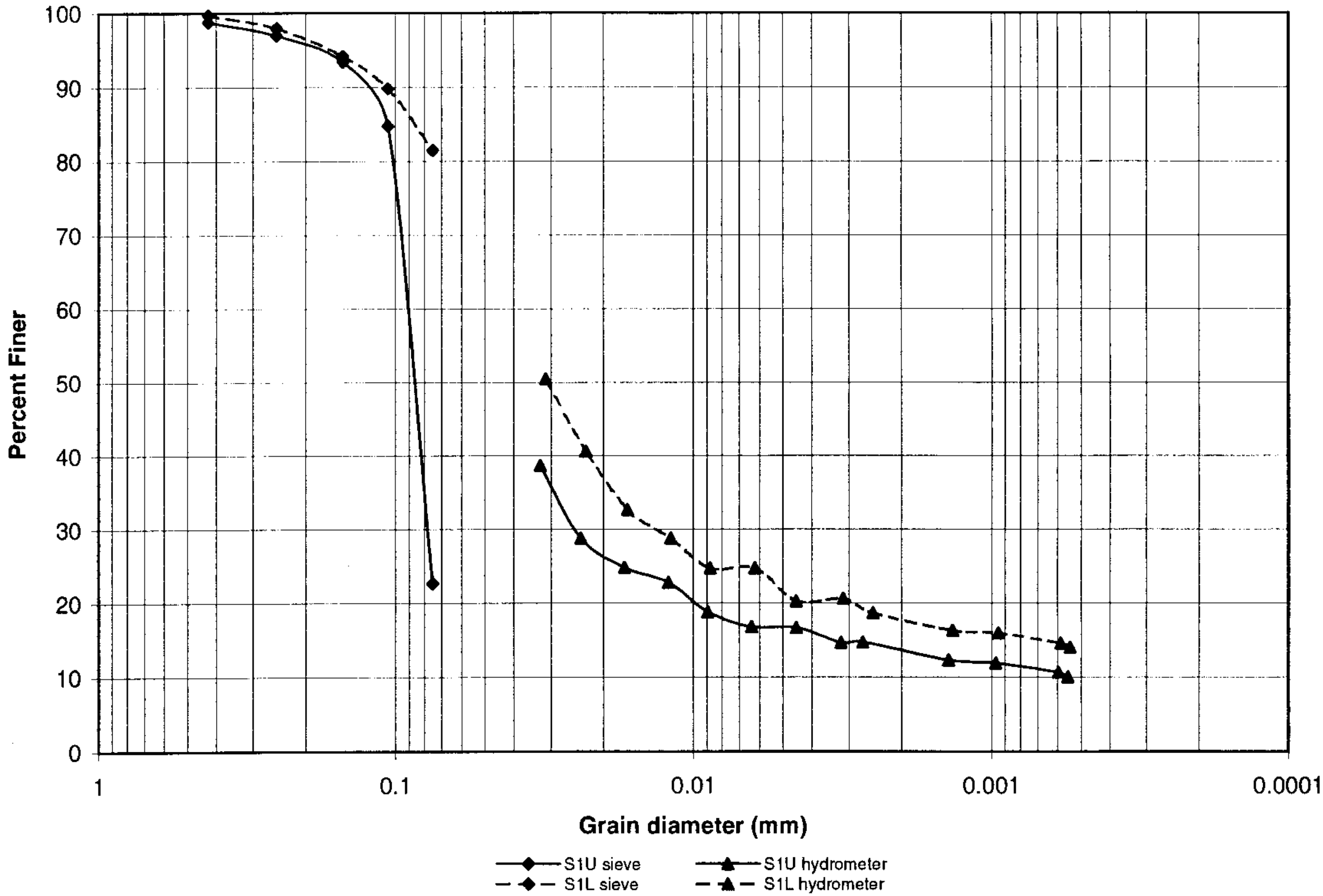
Bowles, J.E. (1986). "Engineering Properties of Soils and their Measurement Third Edition". McGraw-Hill, Inc., New York, pp. 15-64.

Leroueil, S., and Le Bihan, J-P. (1996). "Liquid Limits and Fall Cones". Canadian Geotechnical Journal, Vol. 33, pp. 793-798.

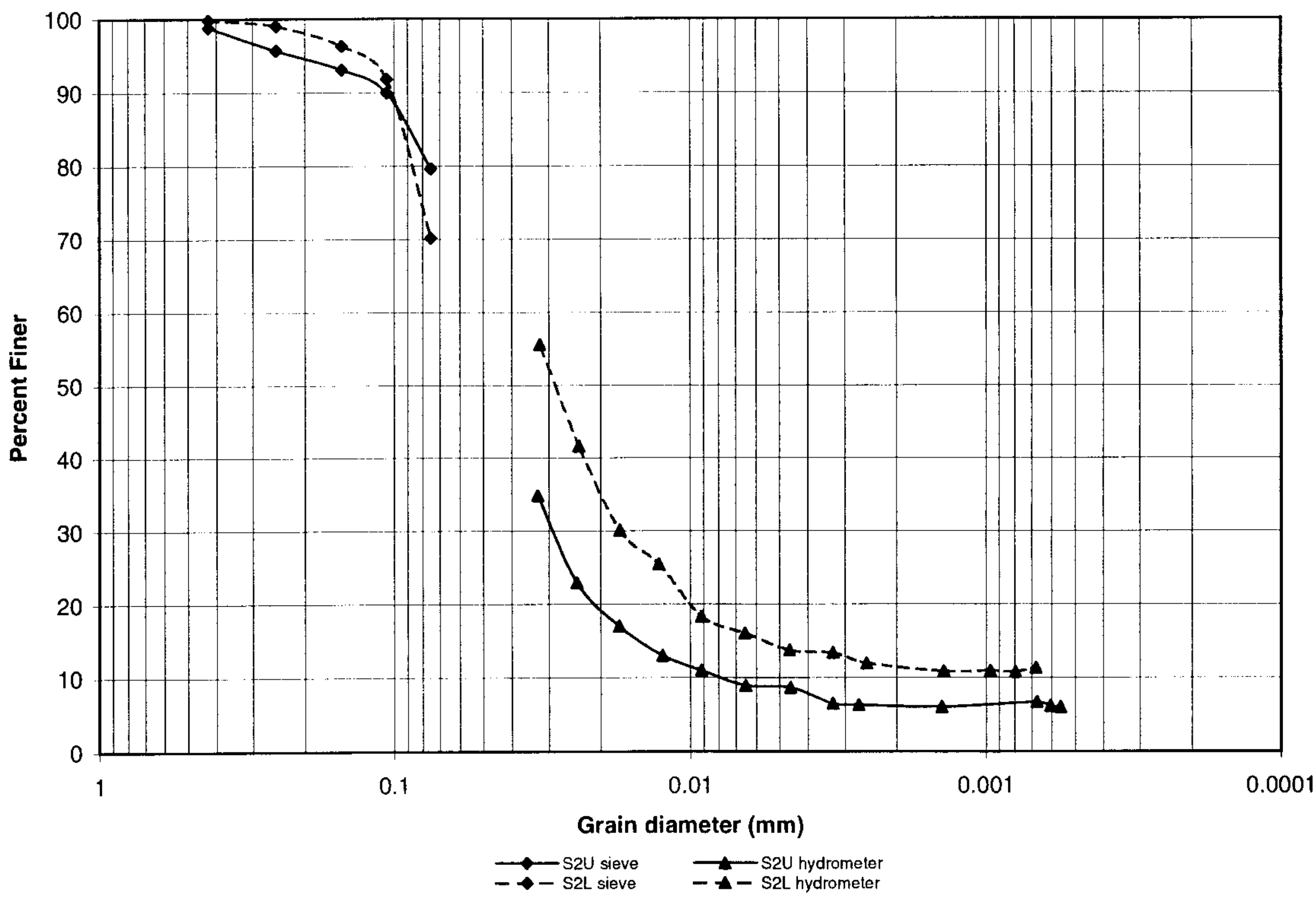
Table B.1 - Summary of Laboratory Test Results

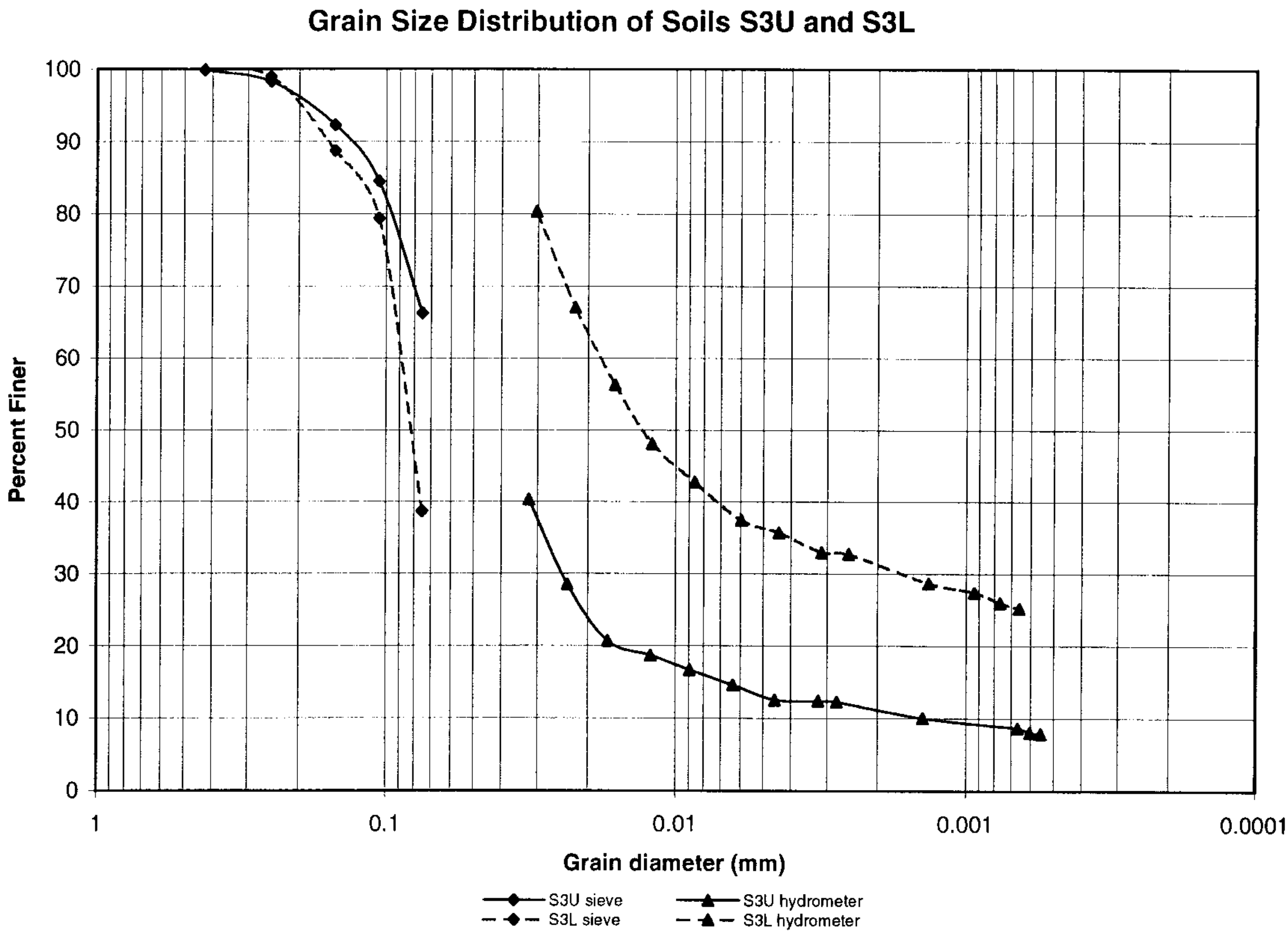
Parameter	S1U	S1L	S2U	S2L	S3U	S3L
Water content (%)	49.0	38.7	41.4	41.8	37.2	44.1
Specific gravity	2.70	2.70	2.70	2.61	2.72	2.65
Liquid limit (fall cone)	26.6	25.7	26.9	32.4	27.5	25.9
Plastic limit	23.8	21.8	21.9	19.5	22.6	17.3

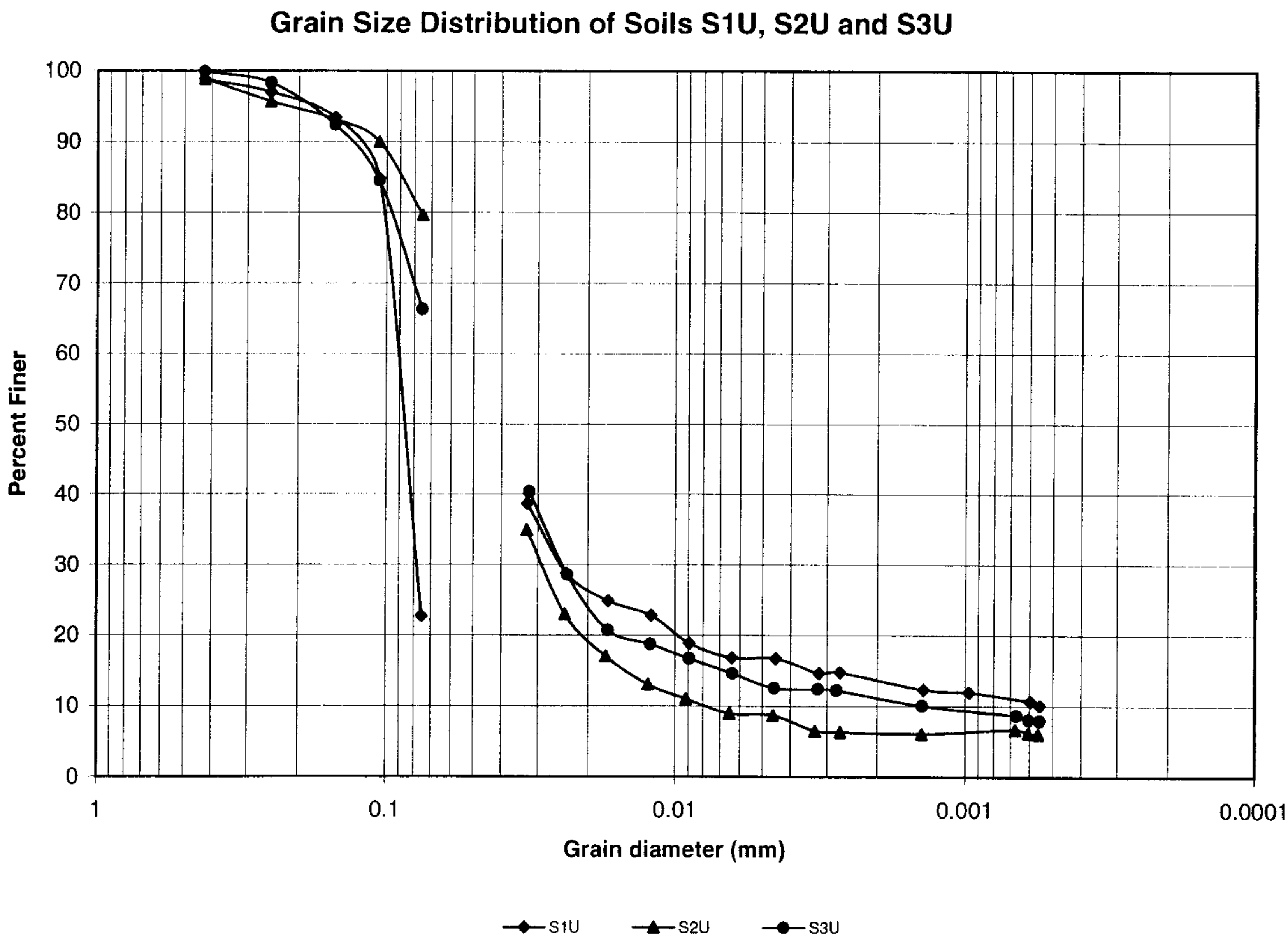
Grain Size Distribution of Soils S1U and S1L

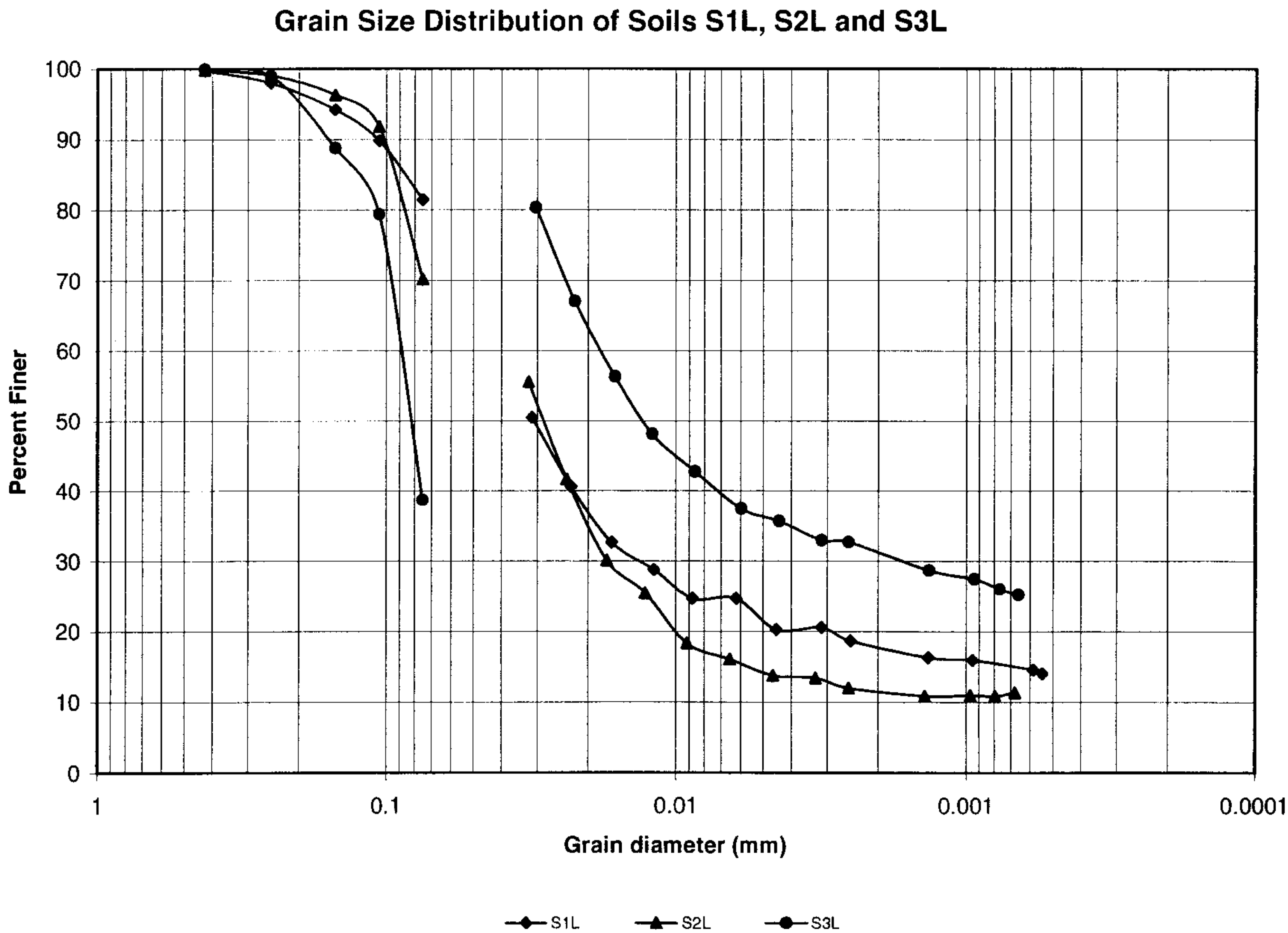


Grain Size Distribution of Soils S2U and S2L




Grain Size Distribution of Soils S3U and S3L
Percent Finer
100
90
80
70
60
50
40
30
20
10
0
1
0.1
0.01
0.001
0.0001
Grain diameter (mm)
S3U sieve
S3L sieve
S3U hydrometer
S3L hydrometer


Grain Size Distribution of Soils S1U, S2U and S3U
Percent Finer
100
90
80
70
60
50
40
30
20
10
0
1
0.1
0.01
0.001
0.0001
Grain diameter (mm)
S1U
S2U
S3U


Grain Size Distribution of Soils S1L, S2L and S3L
Percent Finer
100
90
80
70
60
50
40
30
20
10
0
1
0.1
0.01
0.001
0.0001
Grain diameter (mm)
S1L
S2L
S3L

Grain Size Distribution of Soil Samples