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A Sedimentary Core Analysis of Late Pleistocene to Recent Sediments in a Portion of Bellingham Bay, Washington

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A SEDIMENTARY CORE ANALYSIS OF
LATE PLEISTOCENE TO RECENT SEDIMENTS
IN A PORTION OF BELLINGHAM BAY, WASHINGTON

by

James T. Niski

Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

Dean of Graduate School

Advisory Committee

Chairman

MASTER'S THESIS

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February 14, 2018

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A SEDIMENTARY CORE ANALYSIS OF LATE PLEISTOCENE TO RECENT SEDIMENTS IN A PORTION OF BELLINGHAM BAY, WASHINGTON

A Thesis
Presented to
The Faculty of
Western Washington State College

In Partial Fulfillment
of the Requirements for the Degree
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ABSTRACT

Sub-bottom profiles and core sampling indicate that a trough-like depression below the bay near South Bellingham is a Pleistocene erosional paleotopographic surface sloping bayward from the uplands to the east. A series of Late Pleistocene glacial till and glacio-marine deposits overlie the erosional surface and fill the depression. The glacial deposits are overlain by Recent sand and mud deposits which are rich in wood fragments and shell material.

Bellingham Bay is basin-shaped with a deep narrow trough to the west. The Pleistocene basement is generally structureless and conforms to the bay bottom. Several trough shaped depressions which are overlain by Pleistocene and Recent sediments are located near the perimeter of the bay.

ACKNOWLEDGMENTS

Dr. Maurice L. Schwartz, Associate Professor of Geology at Western Washington State College, served as advisor for this thesis. His helpful guidance, criticism, and technical assistance have been elemental to the successful completion of this study. The thesis committee members have provided helpful criticism and thought-provoking discussion throughout the course of this project.

I am indebted to the University of Washington Oceanography Department and Mr. Richard Sylwester for the use of the sub-bottom profiling equipment without which this study could not have been made. I am also grateful to Capt. Warren Hansen who provided the vessel and fuel for the sub-bottom profile survey. I would like to thank the Huxley College students who expressed interest in the project and acted as crew members on the survey vessel.

The bore hole drilling and sampling program was part of a project funded by the Port of Bellingham. I am deeply indebted to Mr. Tom Glenn, Port Manager, and the Port of Bellingham for the opportunity to work with the drilling project. The Port of Bellingham also assisted in the loading and unloading of the profiling equipment from the survey vessel. I am equally grateful to Dames and Moore Associates who took the core samples and made them available for this study.

The computer program for statistical analysis was designed with the help of Dr. Edwin H. Brown, Associate Professor of Geology, Western Washington State College. Mrs. Linda Wilcox typed the draft and final manuscripts.

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I. Introduction

Objectives

Geologic and oceanographic interest in Bellingham Bay has rapidly accelerated in the past decade. Increased public concern over man's role in contributing to the natural systems in which he lives has demanded a more thorough understanding of the history of these systems prior to his influence. This study is concerned with the geological history of a portion of the bay. The purpose is to investigate the geological structure and the Late Pleistocene to Recent sedimentological history of a portion of Bellingham Bay. This objective may be divided into the following specific endeavors:

1. to determine the geologic structure of Bellingham Bay.
2. to describe the Late Pleistocene to Recent sediments found in the bay near South Bellingham and their horizontal and vertical distributions.
3. to relate sediments to the geologic structure of the bay near South Bellingham and reconstruct its sedimentological history.

Previous Work

Previous geologic and oceanographic work in Bellingham Bay include mercury studies in Recent sediments in Bellingham Bay (Bothner, 1971); an oceanographic survey to determine the circulation and physical properties of the water in the bay, measuring temperature, salinity, dissolved oxygen, spent sulfite liquor, and currents, (Collias, et al, 1966); Recent sediment studies, (Sternberg, 1961); a surface current survey (O'Keefe, 1960); a biological investigation in Bellingham Bay (Tollefson, 1959); and a study of shingle spits on Pt. Frances

(Vonheeder, in progress). Sternberg's work is the only known prior study concerning deposition of sediments in Bellingham Bay. Sternberg carried out an extensive sampling program utilizing an 18.6 meter piston corer, a 1.83 meter gravity corer, and a 22.9 cm grab sampler to obtain Recent sediment samples. The two piston cores taken only recovered 11 meters of sediment sample owing to a malfunction in the coring device (Sternberg, 1961). Sternberg's study involved the areal extent of sediments in Bellingham Bay to the depth of two meters, excluding the piston cores and further, did not attempt to investigate any sediments older than Late Recent age.

Geographic and Geologic Setting

Bellingham Bay, Washington is located in the far northwestern corner of Washington (Fig.1). It is approximately 18 miles south of the Canadian Border and linked to the Pacific Ocean via the Strait of Juan De Fuca and the Strait of Georgia. The areas to the north, northwest, and northeast of the bay are made up of Pleistocene lowland deposits of glacial till, glaciomarine drift, and sand and gravel (Easterbrook, 1962). The eastern side of the bay is flanked by steep hillsides exceeding 1500 feet (457.2m) above sea level. These hillsides are composed of late Cretaceous to early Tertiary deposits of sandstone, shale, conglomerate and minor coal of the Chuckanut Formation. The western side of the bay is open water with several islands separating it from Hale passage. Lummi Island, the largest of these islands, is composed of Pre-Tertiary sediments on the northern side, and steep hillsides of graywacke, shale, and low rank metamorphic rocks on the southern end. The main entrance to the bay lies between Eliza and Samish Islands south of the map area. There is a deep narrow trough trending north from

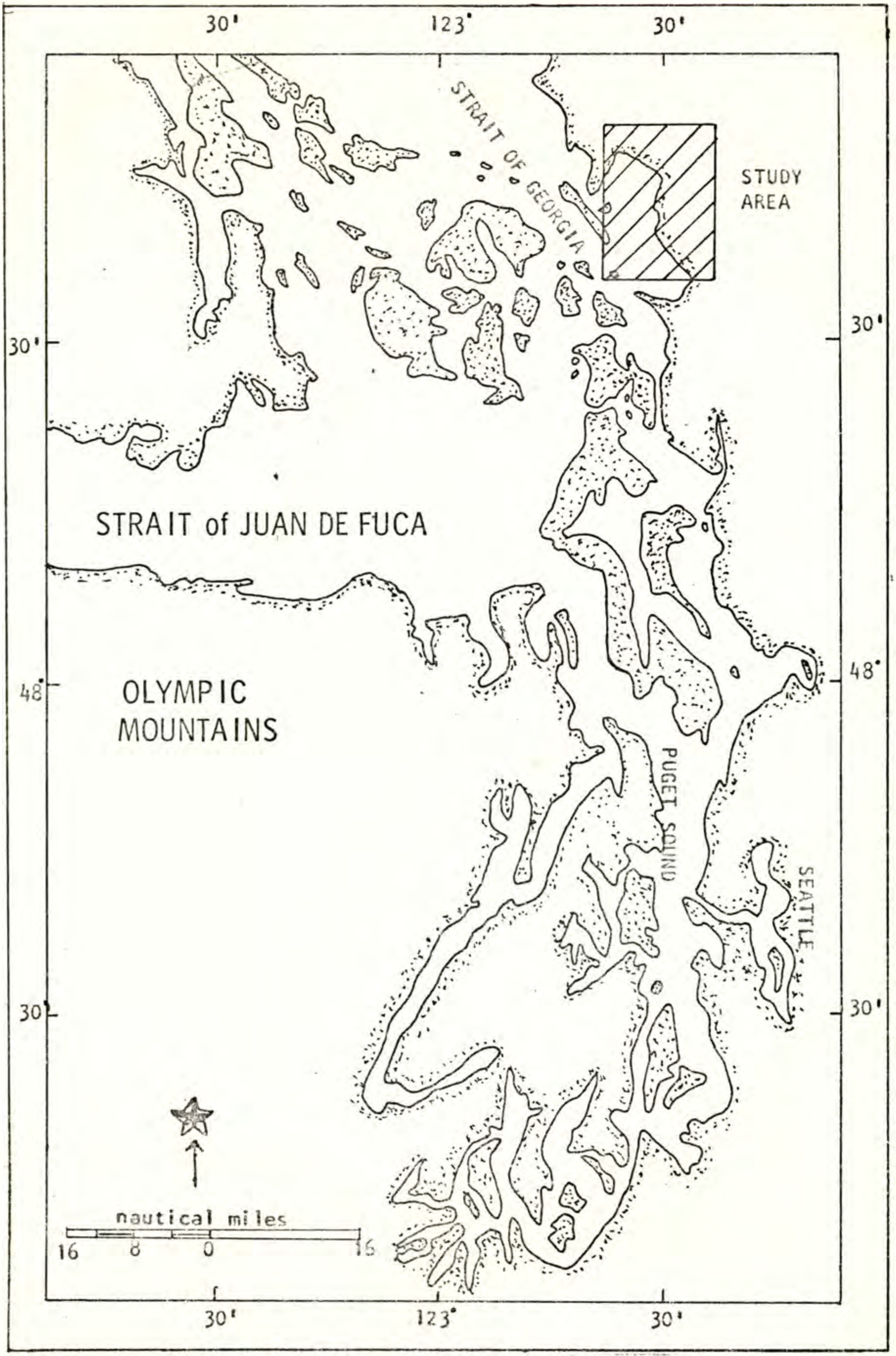


Fig.1 Index Map Showing Study Area

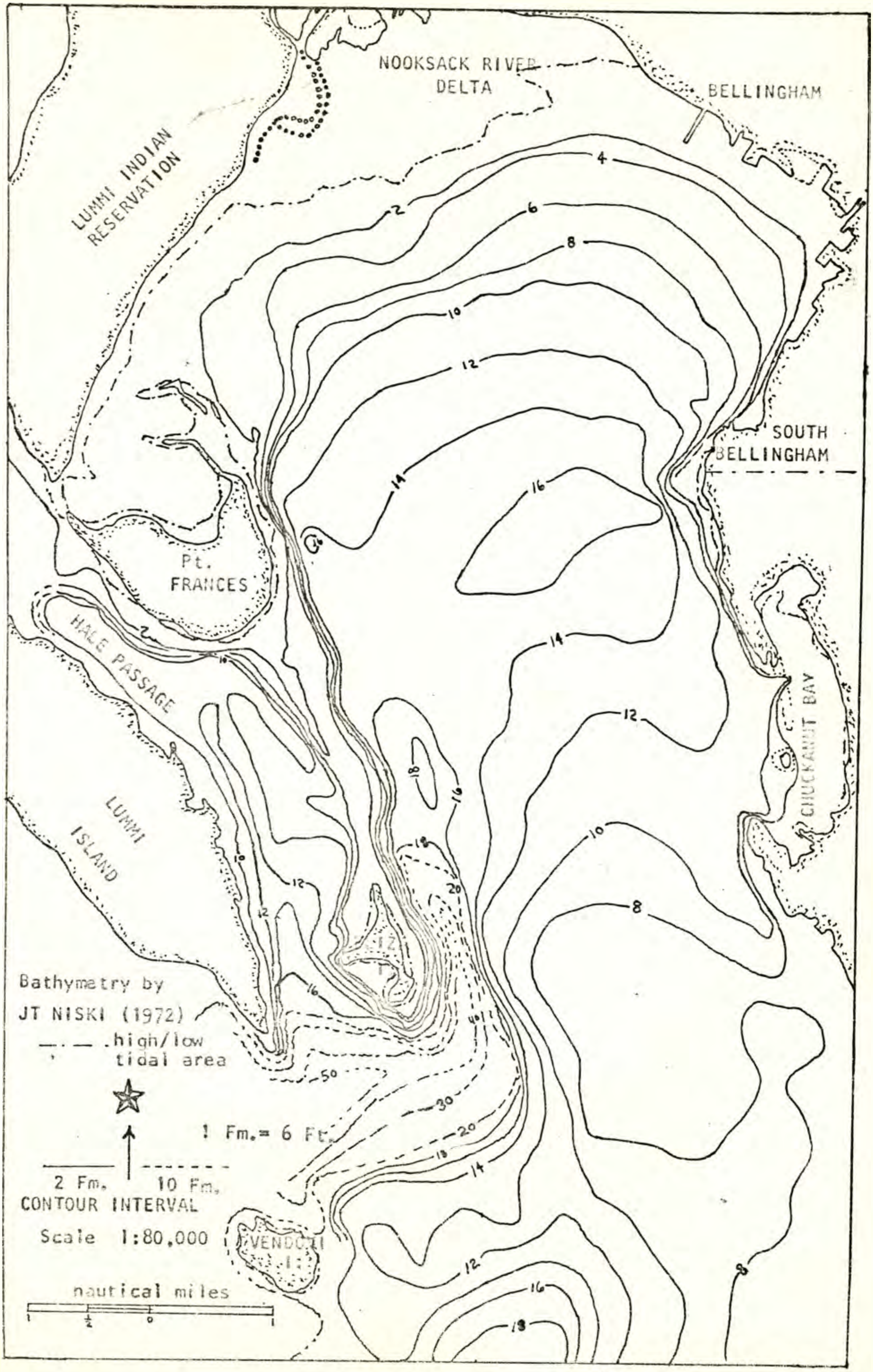


Fig.2 Bathymetric Contour Map of Bellingham Bay

Eliza Island to Pt. Frances. This trough shoals rapidly to the west and has depths to 350 feet (106.7m) (Fig.2). The bay is basin shaped with a rise in the far southern end. Depths in the center of the basin are approximately 90-100 feet (27.4-30.5m), while in the southern end, they rarely exceed 60 feet (18.3m) excluding the trough area.

Streams and Currents

The Nooksack River is the major stream contributing large amounts of sediment as evidenced by the building of a large delta at the mouth of the Nooksack River (Fig.2). In the past 70 years, the delta has been extended into Bellingham Bay approximately one mile (Sternberg, 1961). The mean annual discharge is approximately 3,700 cfs ranging from a maximum of 46,200 cfs to a minimum of 595 cfs (measured by the United States Geological Survey, 1959, at Lynden). Two small creeks, Whatcom and Squalicum Creeks, enter Bellingham Bay at the northern end. They constitute a total annual discharge of 200 cfs and drain the lowland area north of Bellingham including Lake Whatcom (Sternberg, 1961).

Surface current circulation in Bellingham Bay is generally in a counterclockwise direction. Water enters the bay near Vendovi Island and moves north along the eastern side of the bay, swinging westward near Bellingham. The water moves past the Nooksack Delta and then turns south, traveling along the deep north-south trending trough. Finally it exits the bay near Vendovi Island close to the entrance point (O'Keefe, 1960; Murty, 1960).

II. Field Work

General Statement

The field work, carried out in the spring of 1971, consisted of two parts: a sub-bottom seismic profile of Bellingham Bay and a bore hole drilling program. The purposes of the sub-bottom profile were to obtain the general geologic structure of Bellingham Bay and to locate possible areas for drilling. The bore hole drilling program was instituted to obtain sediment samples which would represent the sedimentological history of the bay.

The Sub-bottom Profile Survey

The profiling equipment was obtained from the Oceanography Department of the University of Washington. Liaison between the Oceanography Department of the University of Washington and the Geology Department of Western Washington State College resulted in obtaining the sub-bottom profiler manufactured by Alpine Geophysical Associates, an Ocean Sonics GDR-T recorder, associated electrical equipment, and a qualified technician to operate the equipment. The SS Liberty, a 55 foot (16.8m) commercial fishing boat commanded by Warren Hansen, was available for use and was large enough to accommodate the profiling equipment and crew. Crew members were: an equipment operator, a navigator, and two deck hands to handle rigging.

The sub-bottom profiler (Fig.3) contains a 25 kilowatt gasoline powered generator which supplies power to a sparker transformer unit. The transformer unit produces a high energy electrical pulse which is transmitted through an insulated cable to a pair of electrodes. The insulated cable and electrodes are towed behind the vessel. The electrodes are submerged 5 to 8 feet (1.5-2.5m) below the surface of the

Fig.3 Sub-bottom profile sparker unit (right) and generator (left) stowed on survey vessel.

Fig.4 Sub-bottom profile recorder in operation.

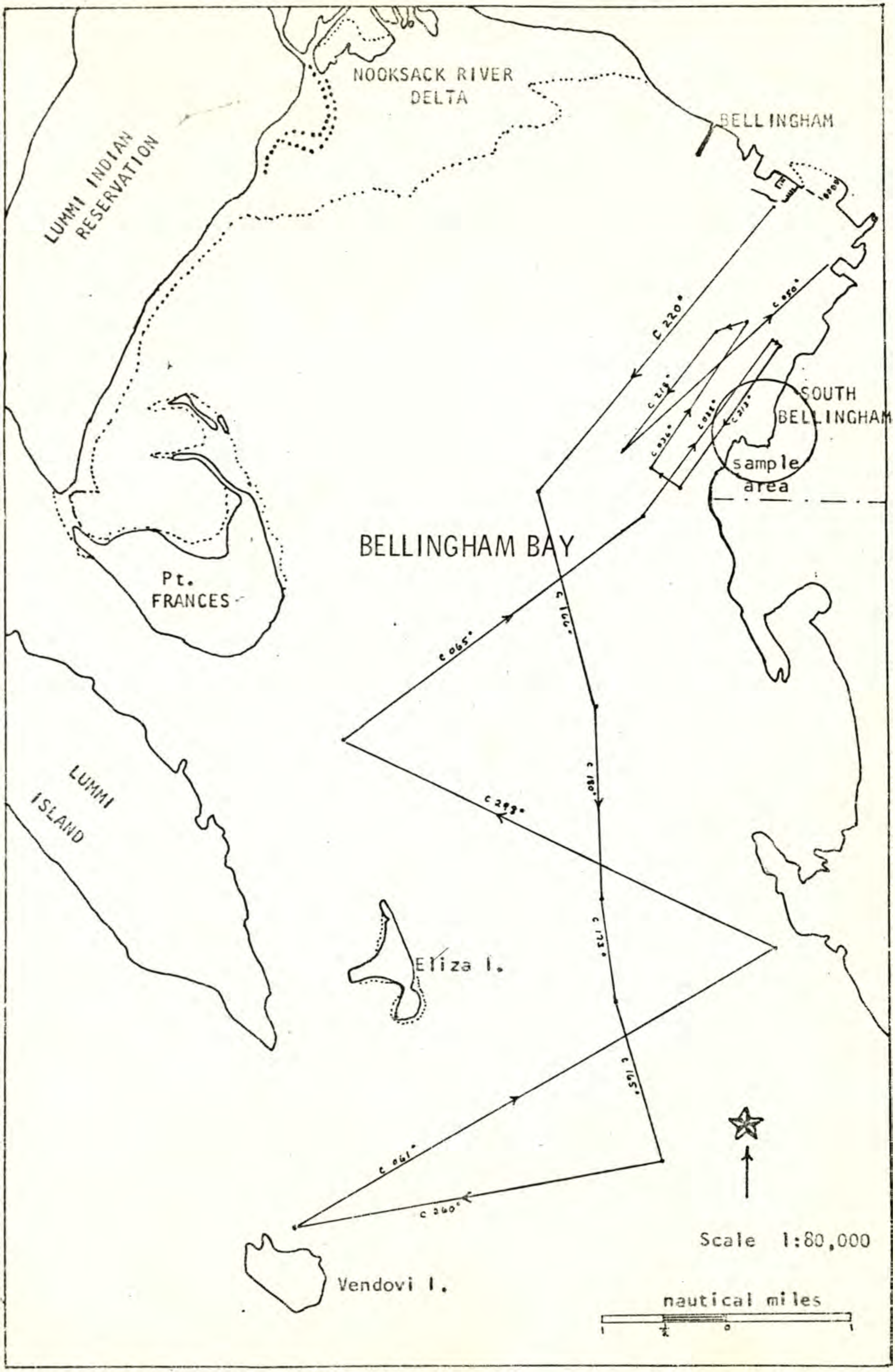


Fig.5 Sub-bottom Profile Survey Map

water. When the pulse reaches the electrodes, the resulting electrical spark generates a high energy sound wave which is transmitted through the water and is reflected by sediment interfaces below the bay bottom. The transmitted and reflected sound waves are picked up by a hydrophone towed on the surface. These waves are amplified and sorted chronologically by an electronic computer. The resultant electrical signals are then relayed to a wet paper recorder (Fig.4) which burns marks on the recording paper. Thus a continuous trace of the bottom and sub-bottom may be immediately obtained and evaluated. Profiles of particular interest or those resulting from equipment malfunction can be re-recorded without delay.

The sub-bottom profile survey (Fig.5) was carried out on March 4, 1971. The recording scale which ranged from 100 to 600 fathoms (183-540m) was set at 100 fathoms to receive the greatest detail. The survey was run at speeds of 3 to 4 knots in a light sea with waves no greater than 1.5 feet (0.46m). The ship's position was determined by taking radar and visual fixes every fifteen minutes. Radar ranges and visual bearings to navigational aids were used when possible. Courses and visual bearings were taken from a magnetic compass on the vessel. A portion of the sub-bottom profile is shown as Appendix D. Its geologic significance and interpretation are fully discussed in Sections V and VI.

Bore Hole Drilling Program

Feasibility studies for obtaining sediment core samples of Bellingham Bay began in mid-March 1971. Initially, the core sampling program called for nine drilling sites on a grid system which would cover the entire profile area, but the original drilling program later proved to be infeasible because of insufficient financial support.

However, it was discovered that the Port of Bellingham was investigating its South Terminal Piers for possible expansion. This investigation required a drill sampling program and soils analysis in order to obtain information on structural support for the pilings. The sub-bottom profile of the bay area near South Bellingham was reviewed, and it showed an anomalous sloping structure beneath the bay bottom (Fig.12 and Appendix D). This buried feature appeared to lie partially beneath the South Terminal area. It also appeared to be overlain by an extensive amount of sediment. Therefore the South Terminal area was an excellent drilling site for obtaining sedimentary core samples and a drilling program was carried out in cooperation with the Port of Bellingham.

In May 1971, the Port of Bellingham contracted Dames and Moore, Consulting Engineers in the Applied Earth Sciences, to undertake the soils investigation program for the South Terminal expansion. Liaison between the Port of Bellingham, Dames and Moore, and the Geology Department of Western Washington State College resulted in a cooperative core sampling program which was undertaken in June 1971. Dames and Moore did a soils investigation of the South Terminal area for the Port of Bellingham in July, 1969. Therefore the 1971 investigation supplemented the 1969 report. Bore sampling commenced on June 3, 1971 and was completed on July 9, 1971.

Dames and Moore subcontracted the bore hole drilling to Axelsen Drilling Company, Seattle. A Dames and Moore soils engineer supervised the drilling operation and logged the core samples. Eleven borings were drilled offshore with cable tool drilling equipment (Fig.6) mounted on a barge owned by the Port of Bellingham. The barge was anchored with a four point mooring to stabilize the drilling platform. Each boring was lined with casing to prevent sidewall collapse. The borings are numbered

Fig.6 Drilling equipment rig mounted on Port of Bellingham barge for offshore drilling.

9 through 18. Boring 19 was drilled onshore near the west edge of the tidal inlet pond. The boring locations are shown in Figure 7.

Undisturbed samples of the sediments were obtained from each boring at frequent intervals as noted in the boring logs which are shown as Plates A-1 to A-7 (Appendix A). The samples were taken with a Dames and Moore Type U Sampler (Fig.8). The sampler was driven into the sediment with a weight of 400 pounds falling a distance of 24 inches (La Mont, 1971), obtaining a 1 foot, 2½ inch diameter core sample. Only the central 6 inches of the core sample was needed for Dames and Moore's soils investigation. The rest of the core samples were sealed in plastic containers (Fig.9) and made available for analysis.

Elevations of the mud line at the offshore boring locations were established by depth measurement from the water surface. Readings from a tide guage located nearby, determined the tide levels at the times of measurement (La Mont, 1971). Elevations refer to Mean Lower Low Water Datum. The boring locations were determined by sighting on range markers which were set by surveyors for the Port of Bellingham (La Mont, 1971).

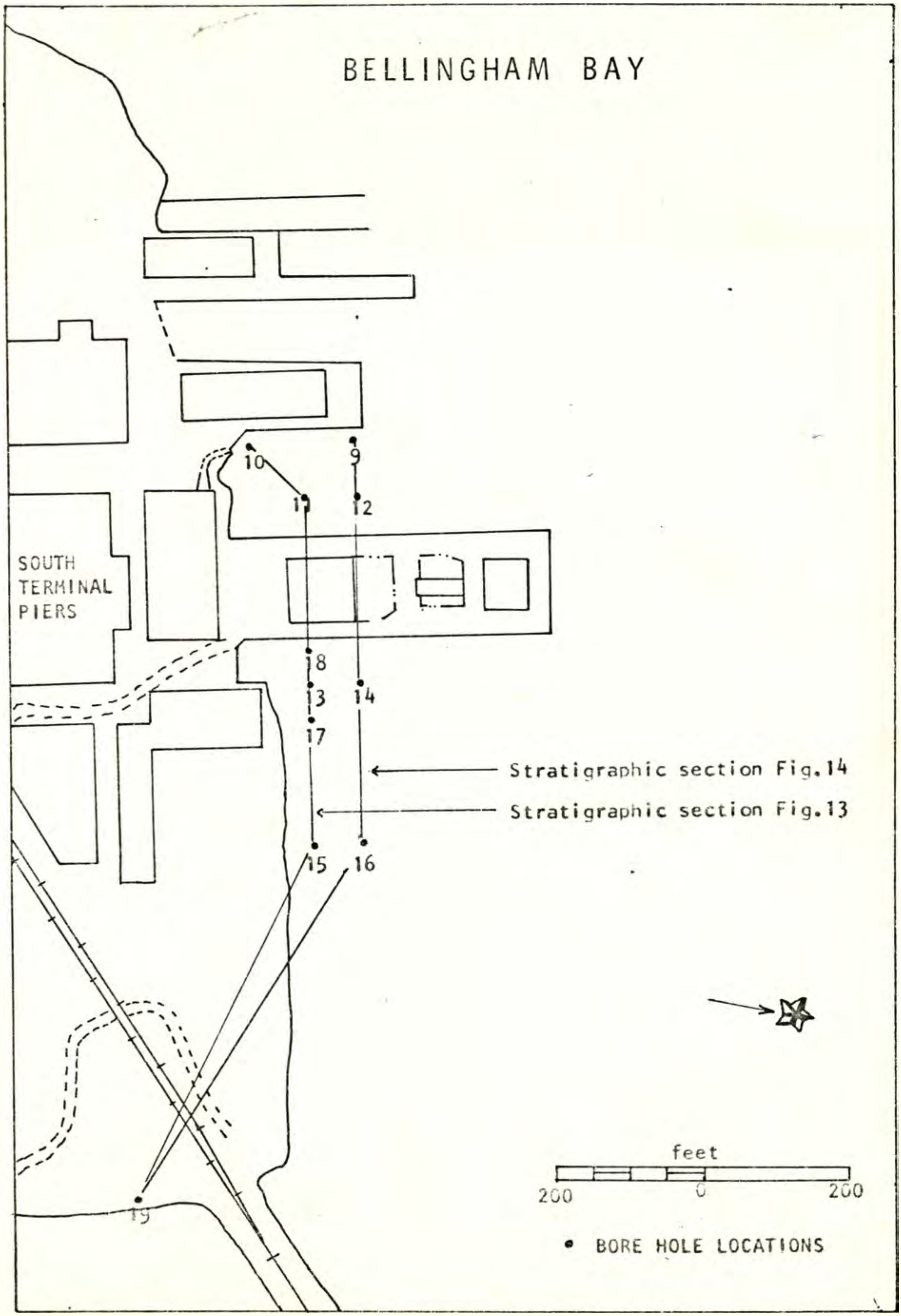
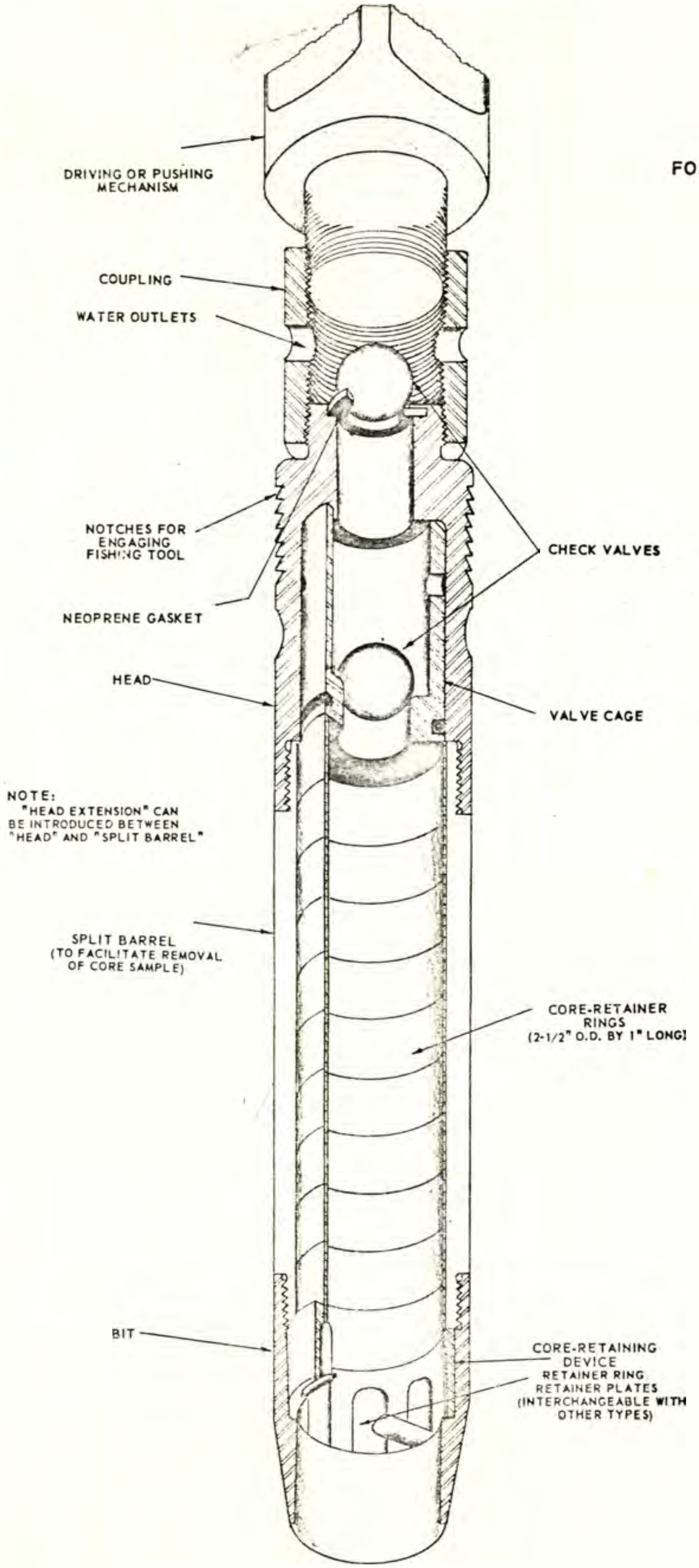


Fig.7 Bore Hole Location Map

SOIL SAMPLER TYPE U

FOR SOILS DIFFICULT TO RETAIN IN SAMPLER



ALTERNATE ATTACHMENTS

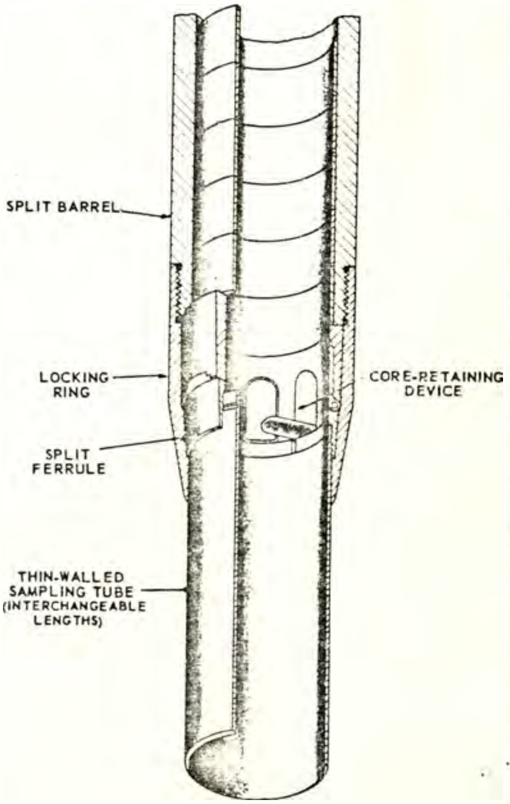


Fig.8 Type U Sampler

DAMES & MOORE

Fig.9 Core Sampler and Sample Storage. Split barrel corer has been separated and sample rings (held by gloved hands) are being packaged in plastic cylinders at right.

III. Sedimentary Core Sample Analysis

Preliminary Analysis

A preliminary physical analysis of all sedimentary core samples was conducted in order to gain an overall knowledge of the sediment types. The core samples had been stored in plastic containers which were not sealed properly and were in various stages of desiccation Therefore, in order to maintain consistent sample description, the samples were allowed to reach uniform dryness at room temperature. Sample color was determined by comparison with the Geological Society of America Rock Color Chart. The core samples were split lengthwise to note possible sedimentary structures. A few of the cores showed small sand lenses, 0.5 cm to 1.0 cm in thickness, in silty clay units. No other sedimentary structures were evident. A Bausch and Lomb 40 X binocular stereo microscope was used to initially describe grain size and composition in order to obtain an overall sedimentary description of the eleven bore holes. Certain core samples representing the major sedimentary units in each of the borings were selected for grain size analysis.

Grain Size Analysis

Selected samples were analyzed for amounts of gravel, sand, silt and clay. Thirty to one-hundred grams of sediment sample was used, depending on the relative amounts of gravel, sand, silt and clay. Royse (1970) has cautioned against use of sonic disaggregators to disaggregate sediment samples for grain size analysis as platy or fragile minerals and fossils are liable to be split apart, influencing the distribution of particle sizes. Prior to analysis, experimentation with a Bronwill Biosonik III disaggregator showed little or no mineral and fossil breakup of sediment samples. Therefore it was found suitable for disaggregation. The samples were weighed to 0.001 gram on a triple beam balance and wet sieved through a 62 micron (230 mesh) standard 10" sieve to separate the clay-silt size particles from the sand and gravel. Grain-size analysis followed procedures outlined by Folk (1968).

The sand and gravel fractions of the wet sieve separation were dried in an oven having a temperature of 90°C for 24 hours. They were allowed to cool for three hours at room temperature and weighed on a triple beam balance. The samples were then placed in a series of standard sieves at 1/2 phi intervals which ranged from -2 Ø (4.0mm) to +4 Ø (0.0625mm). The nest of sieves was placed in a Braun-Porter Sand Shaker and shaken for 10 minutes. The size fractions were then weighed to 0.001 gram on a triple beam balance and sealed in envelopes for future studies.

The clay and silt fractions were placed in 1000 ml graduates filled with distilled water for pipette analysis. All of the clay-silt fractions showed some degree of flocculation in the graduates. Electrical charges developed on the surface of the clay size particles caused the particles to attract one another and the samples settled rapidly to the bottom of the graduates. Pipette analysis demands that particles settle individually without any attraction to each other. Therefore 0.5 gm by dry weight of Calgon, a commercial water softener, was added to each of the samples as a dispersant to break the electrical bonds between the particles. The samples were pipetted in accordance with the procedure outlined by Folk (1968). Pipette samples were taken at 1/2 phi intervals from 4 Ø to 6 Ø and at one phi intervals from then on to 10 Ø. Further size analysis beyond 10 Ø was neither necessary nor feasible, and smaller size fractions were extrapolated from a cumulative frequency curve. The samples were weighed to 0.0001 gm on a Mettler analytical balance. Since the samples contained both a certain grade size material plus all material finer, sample weights were successively subtracted from each other, resulting in an individual grade size weight. These weights, when combined with the weights of the sieved fractions of each sample, constituted the grain size analysis of the samples. Individual weight percents in each grade and cumulative weight percents of each size fraction were calculated for each sample. The pipette data were utilized in the statistical analysis and in determination of sediment classification (Fig.10).

GRAIN SIZE CLASSIFICATION
(FOLK, 1968)

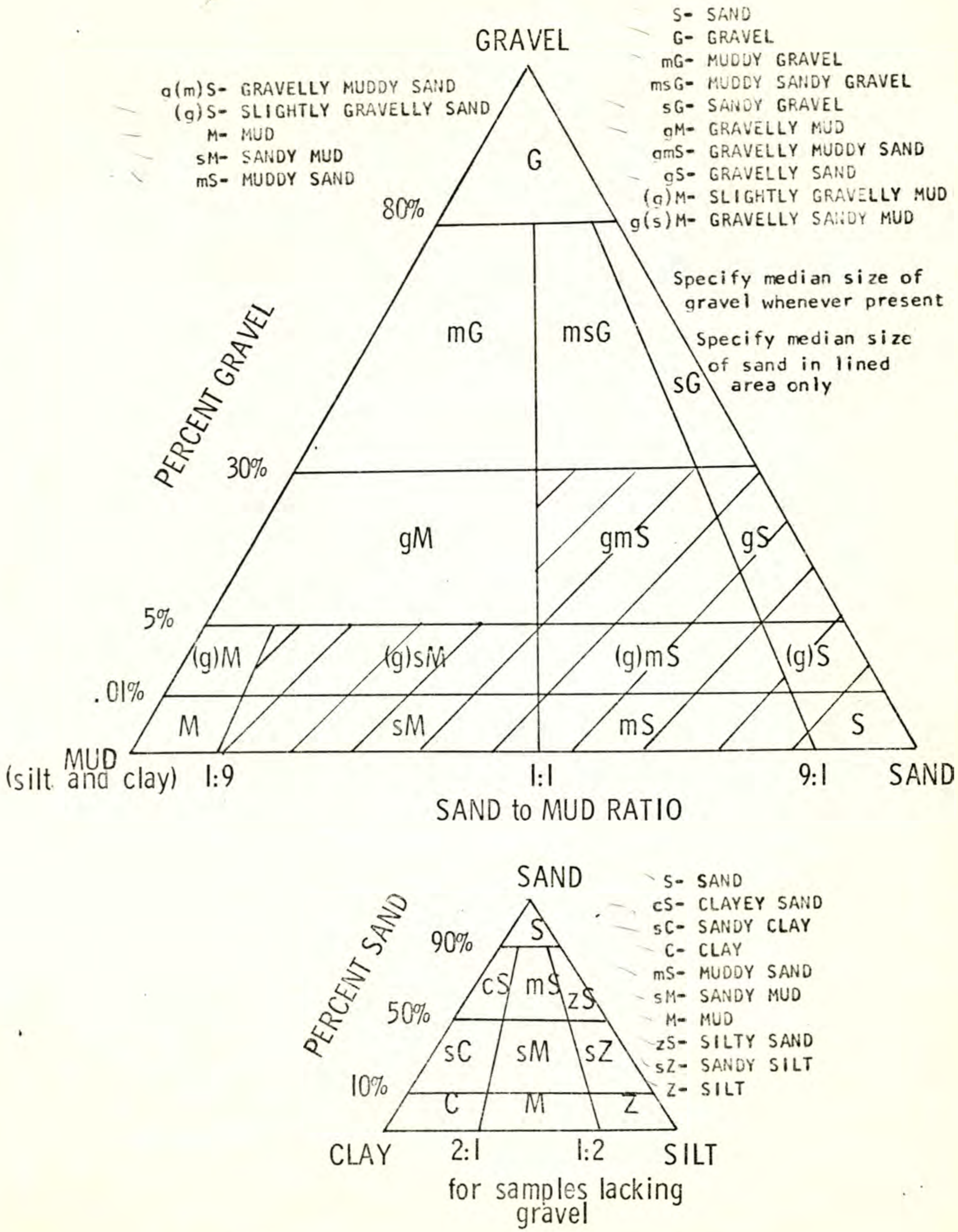


Fig.10 Folk (1968) Grain Size Classification

IV. Statistical Analysis of Sedimentary Samples

The results of the size fraction analyses provided data for statistical analyses from which parameters indicative of different sedimentary environments could be obtained. There are various statistical parameters and methods of obtaining them which can be used to achieve the desired result. It was decided to adopt the Folk (1968) graphic statistical parameters for the statistical analysis.

Frequency curves

The cumulative percent data from the size fraction analysis were plotted against the grade sizes of each sample on probability graph paper. The resultant curves represent cumulative frequency distributions of all grade sizes, -2 Ø to +14 Ø. The probability scale was also valuable for studying the departure of sediments from normal probability size distributions.

The results of the size analyses were graphed in smooth continuous curves passing through all data points. The cumulative curves were extrapolated in straight lines from the last data points (10 Ø) to 14 Ø at 99.99 percent, under the assumption that all clay particles were larger than 14 Ø (0.06 micron). Grain size data were obtained from the extrapolated curves when necessary. The lower ends of the curves approached -8 Ø at 0.01 percent because the largest particle observed in the preliminary analysis of the sediments was cobble size. The curves were utilized to obtain values for computation of Folk's statistical measures.

Statistical Parameters of Grain Size

The best graphic measure for determining overall size is the

Graphic Mean (M_Z) (Folk) given by the formula $M_Z = (\phi_{16} + \phi_{50} + \phi_{84})/3$. It is superior to the median because it is based on three points and gives a better overall picture (Folk, 1968).

The Inclusive Graphic Standard Deviation, σ_I (Folk), given by the formula $\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$ includes 90% of the distribution and is the best overall measure of sorting because of its close approach to the standard deviation. Measurement of sorting values for a large number of sediments has suggested the following verbal classification scale for sorting (Folk, 1968):

σ_I under 0.35 ϕ very well sorted
0.35 - 0.50 ϕ well sorted
0.50 - 0.71 ϕ moderately well sorted
0.71 - 1.00 ϕ moderately sorted
1.00 - 2.00 ϕ poorly sorted
2.00 - 4.00 ϕ very poorly sorted
over 4.00 ϕ extremely poorly sorted

Skewness measures the degree of asymmetry of the cumulative curve, especially at the "tails". The Inclusive Graphic Skewness, SK_I (Folk), covers 90% of the curve and therefore is the best measure of skewness since the "tails" are where the most critical difference between samples lie (Folk, 1968). Inclusive Graphic Skewness (SK_I) is given by the formula:

$$SK_I = \frac{\phi_{16} + \phi_{84} - 2\,\phi_{50}}{2\,(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\,\phi_{50}}{2(\phi_{95} - \phi_5)}$$

Symmetrical curves have $SK_I = .00$; those with excess fine material have positive skewness and those with excess coarse material have negative skewness (Folk, 1968).

The following verbal limits on skewness apply (Folk, 1968):

SK_I + 1.00 to + .30 strongly fine skewed
+ 0.30 to + 0.10 fine skewed
+ 0.10 to - 0.10 near symmetrical
- 0.10 to - 0.30 coarse skewed
- 0.30 to - 1.00 strongly coarse skewed

In the normal probability curve, the diameter interval between the ϕ_5 and ϕ_{95} percentiles should be exactly 2.44 times the phi diameter between the ϕ_{25} and ϕ_{75} points. A normal straight line curve obeys this ratio, and it is said to have a normal kurtosis (1.00). Departure from a straight line will alter this ratio, and kurtosis is the quantative measure used to describe this departure from normality (Folk, 1968). If the central portion is better sorted than the tails, the curve is said to be excessively peaked or leptokurtic; if the tails are better sorted than the central portion, the curve is flat peaked or platykurtic. Graphic Kurtosis, K_g (Folk), is given by the formula $K_g = \dfrac{\phi_{95} - \phi_5}{2.44\ (\phi_{75} - \phi_{25})}$

The following verbal limits apply (Folk, 1968):

K_g under 0.67 very platykurtic
0.67 - 0.90 platykurtic
0.90 - 1.11 mesokurtic
1.11 - 1.50 leptokurtic
1.50 - 3.00 very leptokurtic
over 3.00 extremely leptokurtic

The foregoing statistical parameters were calculated for each sample analyzed, and the appropriate verbal limits were applied

(Appendix B).

A computer program (Appendix C) was designed to calculate Folk's (1968) graphic statistical parameters. An IBM 360/40 computer utilizing language PL/1 was used to run the program.

Grain Size Nomenclature for Sediments

The end result of the grain size and statistical analyses provided parameters by which the sedimentary samples could be classified. Folk's (1968) classification system of sediments (Fig.10) was used to determine descriptive nomenclature by plotting the proportions of gravel (material coarser than 2mm), sand (0.625 - 2mm), and mud (less than .0625mm - silt plus clay) on the triangular diagram. For samples lacking gravel, proportions of sand, silt (.0039 - .0625mm), and clay (less than .0039mm) were plotted on the smaller triangular diagram (Fig.10). A summary of the sediment nomenclature for the 75 samples is shown in Appendix B.

V. Interpretation of Analyses

Preliminary Analysis

Preliminary analysis of the core samples proved to be useful in interpreting and evaluating the sediment samples. The samples were grouped into series, representing all eleven borings. The first series of samples, taken approximately five feet (1.5m) below the bay bottom, have significant volumes of wood and shell material. The wood material consists of reddish brown wood fragments 5 - 10mm long. The shell remains, 1 - 15mm in diameter, are mostly barnacle and pelecypod fragments with a few whole unfractured pelecypod shells. The wood and shell fragments are present in clay, sand, and gravel sediments and show no affinity for a particular type of sediment. Therefore the fragmental material may have been allogenic and deposited by current or wave action. The presence of whole pelecypod shells indicates that pelecypods may have lived in the particular environment in which they were found. The wood fragments are absent from the second series of sediment samples, mostly silt and clay, taken at a depth of 8 - 10 feet (2.4-3.0m) below the bay bottom. The shell material gradually diminishes to a minor volume percent in relation to the amounts of shell material of samples above. This significant decrease indicates a change in depositional environment. There is also an associated color index change, notably a loss of yellow-brown iron staining between the second and third series of samples. The third and fourth series of samples, taken 25 to 35 feet (7.6-10.7m) below bay bottom, are mainly muds (silts and clays) intermixed with sand and pebbly gravel. The sand grains appear angular to sub-angular (0.2-0.3 Powers Roundness) whereas the pebbles were subrounded (0.4 Powers Roundness). The muds are poorly sorted and indicate a significant change in depositional environment. The series of gravelly muds continue to a depth of approximately 50 feet (15.2m) below sea level. At 50 feet (15.2m), a 5 - 15 foot (1.5-4.5m) muddy sand unit is present in each boring locality. This unit is much better sorted than the muds and consists of angular to subround (0.2-0.4 Powers Roundness) sand grains. The abrupt change in sediment types suggests another change in depositional environment. The next series of samples taken at depths of 60 - 75 feet (18.3-22.9m), consists of pebbly muds, and suggests a return to an environment similar to that above the sand unit. Very fine coal fragments in the gravelly muds might be used to differentiate them from similar units above the sand unit. Some of the larger pebbles appear to be faceted and one large cobble is faceted and striated. These observations indicate a possible glacial environment for deposition of the pebbly muds. The lowest series of samples 70 - 120 feet (21.3-31.2m) below the bottom, are mainly composed of muddy gravels. These gravels were in a matrix of fine silty clay and were extremely poorly sorted. Some of the pebbles are faceted, and there are several large well rounded (0.85 Powers Roundness) granitic cobbles. Some minor coal fragments are also present in the gravels. The shape and surface texture of the pebbles and cobbles indicate a glacial origin.

La Mont (1971) established the moisture content of selected core samples and recorded the blow count of each core sample. The blow count is the number of blows required to drive the core sampler one foot into the sediment. It was discovered that the moisture content (8-10%) of most sediment samples decreased rapidly at depths greater than 45 feet (13.7m) below sea level. Moisture contents of sediments above this depth vary from 25 to 50%. An associated increase in the number of blows required to drive the sampler into the sediments at depths below 50 feet showed a significant change in sediment compaction below 50 feet (15.2m). There also was a considerable increase in blow count of the muddy pebble gravels in the lowest series of samples. The blow count went from 25 to 200, indicating a change in material and degree of compaction. The association of the gravel and its blow count constituted a major sedimentary horizon and a change in depositional environment.

Statistical Analysis

The descriptive names given to the sedimentary samples fell into four main categories: gravels, sands, muds, and gravelly muds. These categories, when associated with their respective statistical parameters, reflected certain sedimentary characteristics. These characteristics were applied in determining the depositional environments of the sediments and were used as an aid in stratigraphic correlation.

The gravels are extremely poorly sorted. Their mean grade size ranges from -1 Ø to +2 Ø but their skewness shows an excess of fine material (sand and mud). The gravels are better sorted at their coarse and fine ends than at their central portions as indicated by the platykurtic to mesokurtic nature of their cumulative frequency curves. Some of the platykurtic nature of the curves was caused by using extrapolated values of extended frequency curves.

The sands are described as poorly sorted but are better sorted than any other group by comparison. They appear to be very fine grained, ranging from 2 Ø to 4 Ø in mean size. The sands have a near symmetrical distribution of grade sizes but sometimes have excessive fine material in the form of silt and clay. The central portions of their frequency curves are much better sorted than the end members as shown by the leptokurtic nature of their kurtosis.

The mean grade size of the muds is 8 Ø, the dividing value between silt and clay size particles. They are described as being very poorly sorted and are near symmetrical in skewness. The ends of the frequency curve are better sorted than the central area. Therefore, they are more poorly sorted than the sands. Sorting commonly becomes poorer with both increasing and decreasing size from the fine-sand range (2 - 3 Ø) (Griffiths, 1951).

The gravelly muds have a mean grade size of 4 Ø to 5 Ø and are extremely poorly sorted. Their frequency curves show excess coarse material owing to the fact that a few pebbles in a muddy matrix skew the sediment when cumulative weight frequency curves are plotted. As in the gravels, the gravelly muds are better sorted at the end members than in the central portion. This is also partly due to the fact that the ends of the curves were sometimes extended in order to extrapolate statistical values.

The values of each statistical parameter were placed alongside their respective sample numbers in a stratigraphic column. A correlation between borings was attempted based only on the statistical values. When one significant figure to the right of the decimal was used, a first order approximation was made, which correlated one unit to the other between bore holes. This statistical correlation aided the determination of stratigraphic relationships of the sediments discussed in Section VI.

VI. Structure and Stratigraphy of Bellingham Bay

Interpretation of Sub-bottom Profile

The geologic structure of Bellingham Bay was determined from the sub-bottom profile. The profile interpretation was confirmed by the eleven borings (Figs.12, 13, and 14). The floor of the bay is basin shaped near the city of Bellingham with a slight rise in the southern area between Eliza Island and the eastern shore. A deep narrow trough extends northward from Eliza Island to Pt. Frances (Fig.2). The profile of the first survey leg, course 220°T, was interpreted as an area underlain by irregular discontinuous sediments to a depth of 90 feet (27.4m) below the bay bottom. These sediments are underlain by a relatively more compacted unit as indicated by a strongly reflective profile trace. The sediments terminate abruptly in a lateral discontinuity with sediments on the second leg of the survey, course 166°T. This portion of the bay is much less distinct in that the profile shows a strong reflective surface approximately 20 feet (6.1m) below the bottom, underlain by a homogeneous unit showing no apparent structures to a depth of 600 feet (182.5m), the maximum depth of the profile. This characteristic profile continued throughout the survey track until the track neared Vendovi Island, course 260°T. The profile indicated that the deep narrow trough that extends east and then northward toward Eliza Island continues as a structural feature to a depth of 67 feet (20.4m) below the bottom of the bay and is partially filled with sediments. Some of these sediments appear to be lens shaped and others appear to be conformable upon the irregular buried surface of the trough. The profile to the northeast of the trough, course 061°T, shows the structureless homogeneous unit as described on the second leg, However, a vertical displacement of the reflective horizon 20 feet (6.1m) below the bay bottom was apparent 1.8 miles from Vendovi Island on course 061°T. The displacement of the reflecting horizon was interpreted as being a fault or slump structure with an approximate vertical displacement of 15 feet (4.6m). The southern portion of the bay indicated by the slight rise (Fig.2) appears to have irregular V-shaped notches 1 to 5 feet (0.3-1.5m) deep and 1 to 5 feet (0.3-1.5m) across incised upon the bay bottom. These incisions are located along course 298°T. If the bay bottom restricts submarine water movements to particular troughs or channels, these V-shaped channels may be cut by tidal scour. The surface current pattern described by O'Keefe (1960) may cause submarine currents to parallel its flow. The area between the left margin and the 1340 time line of the sub-bottom profile (Appendix D) shows a trace typical of the bay, three heavy dark traces near or at the bay bottom underlain by a structureless homogeneous unit which is continuous to the bottom of the profile. The two sets of lighter contrast traces parallel to the first dark set are second and third multiple reflections of the same profile trace and are not to be interpreted as structural horizons.

The area near South Bellingham was profiled extensively and the resultant profile (Appendix D) revealed a seismically unconformable horizon buried beneath the bay bottom. A detailed portion of the survey (Fig.11) indicates the location of the unconformity, its extent, and positions of the profile shown in Figure 12 and Appendix D. Figure 12 was constructed to show the horizontal and vertical relationship between the three profile lines. Specifically, the profile is interpreted as being a trough-like unconformity extending 160 feet (48.8m) below the bay bottom and overlain by rela-

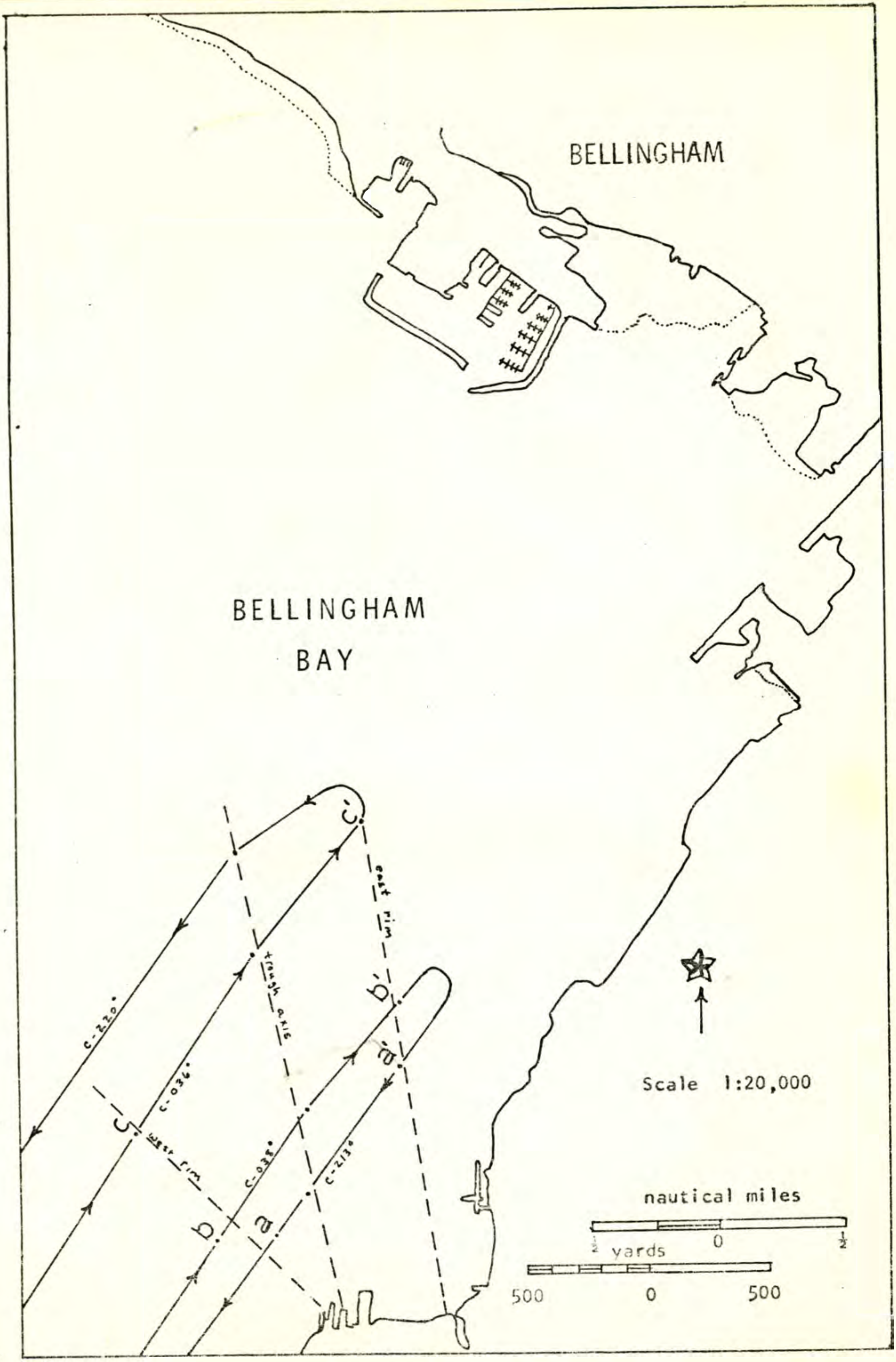


Fig.11 Sub-bottom Profile Location Map in Sample Area Showing Projections of Trough Extent

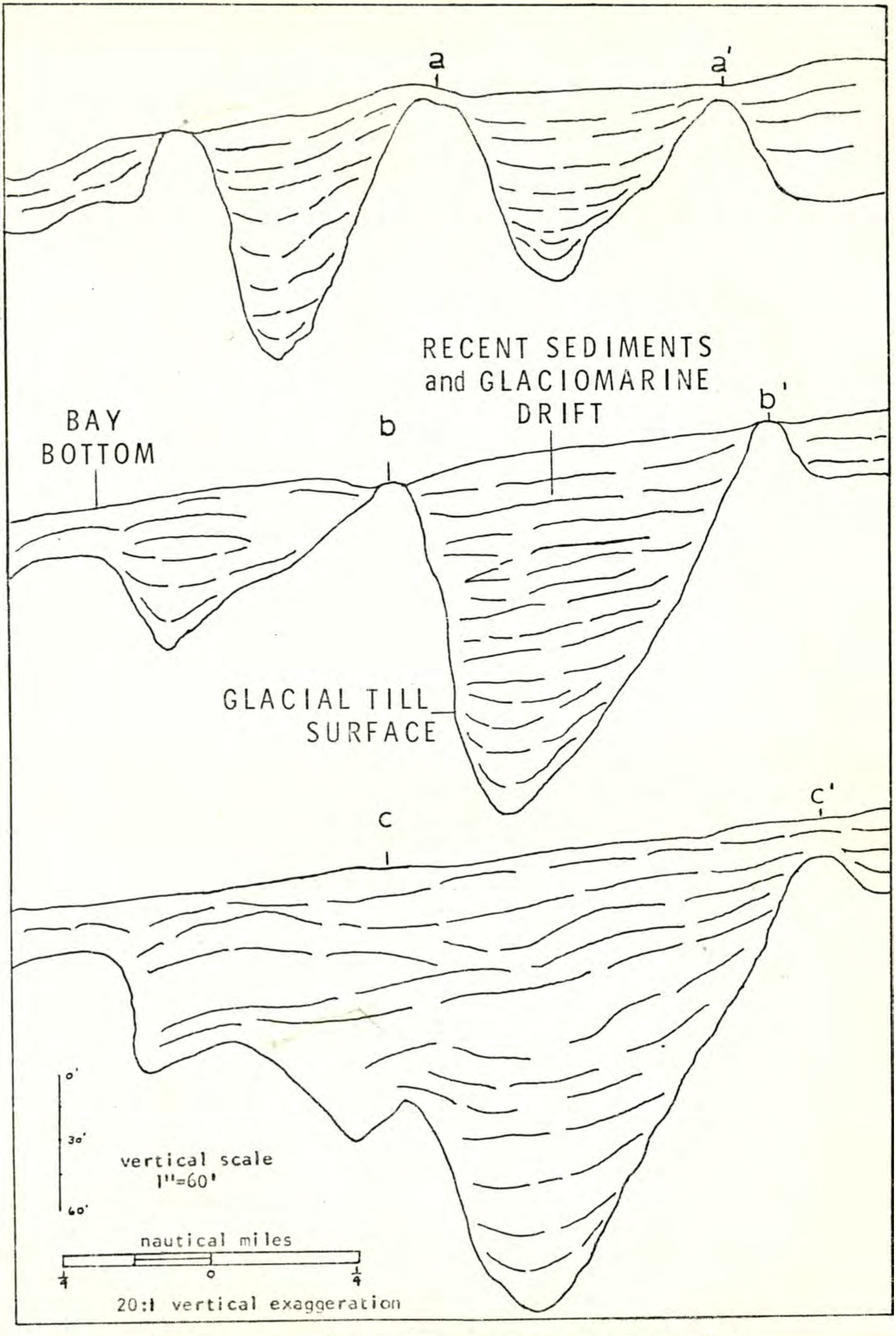


Fig. 12 Profile Interpretation of Survey Lines in Sample Area

tively horizontal and lens shaped sedimentary deposits which extend upwards to the present bay bottom. The vertical and lateral extent of the buried unconformity changes rapidly toward the center of the bay. The trough broadens as it approaches the center of the bay. Projections of its central trough axis and its rims (Fig.11) indicate that the trough continues beneath the shoreline and should crop out nearby. However, the shoreline area was completely covered by soil or landfill and no significant outcrops were visible. The far right side of the profile (Appendix D) shows the broad extent of the trough into the bay. The irregular, discontinuous sedimentary deposits continue laterally toward the northwest as evidenced by their presence in the profile on course 220°T.

Stratigraphy

The stratigraphy and sedimentological history of the portion of Bellingham Bay near South Bellingham was interpreted from the combined results of the sub-bottom profile and the analyses of the 75 core samples of the eleven bore holes. Borings of the trough near the profile area are representative of the sedimentary units below the profile area. The boring logs (plates A-1 to A-7, Appendix A) summarize the sample descriptions which were used to interpret the stratigraphy of the sample and profile areas shown as Figures 13 and 14. The sedimentological characteristics of the core samples such as grain size, grain shape, sorting and texture, discussed in Section V, constitute strong evidence of glacial origin for many of the sedimentary units in the bore holes. Easterbrook (1962, 1963) provided further insight into the glacial origin of the sediments and consequently became a guide to the interpretation of the stratigraphy and sedimentological history of the sample area. The stratigraphic sequence of Upper Pleistocene

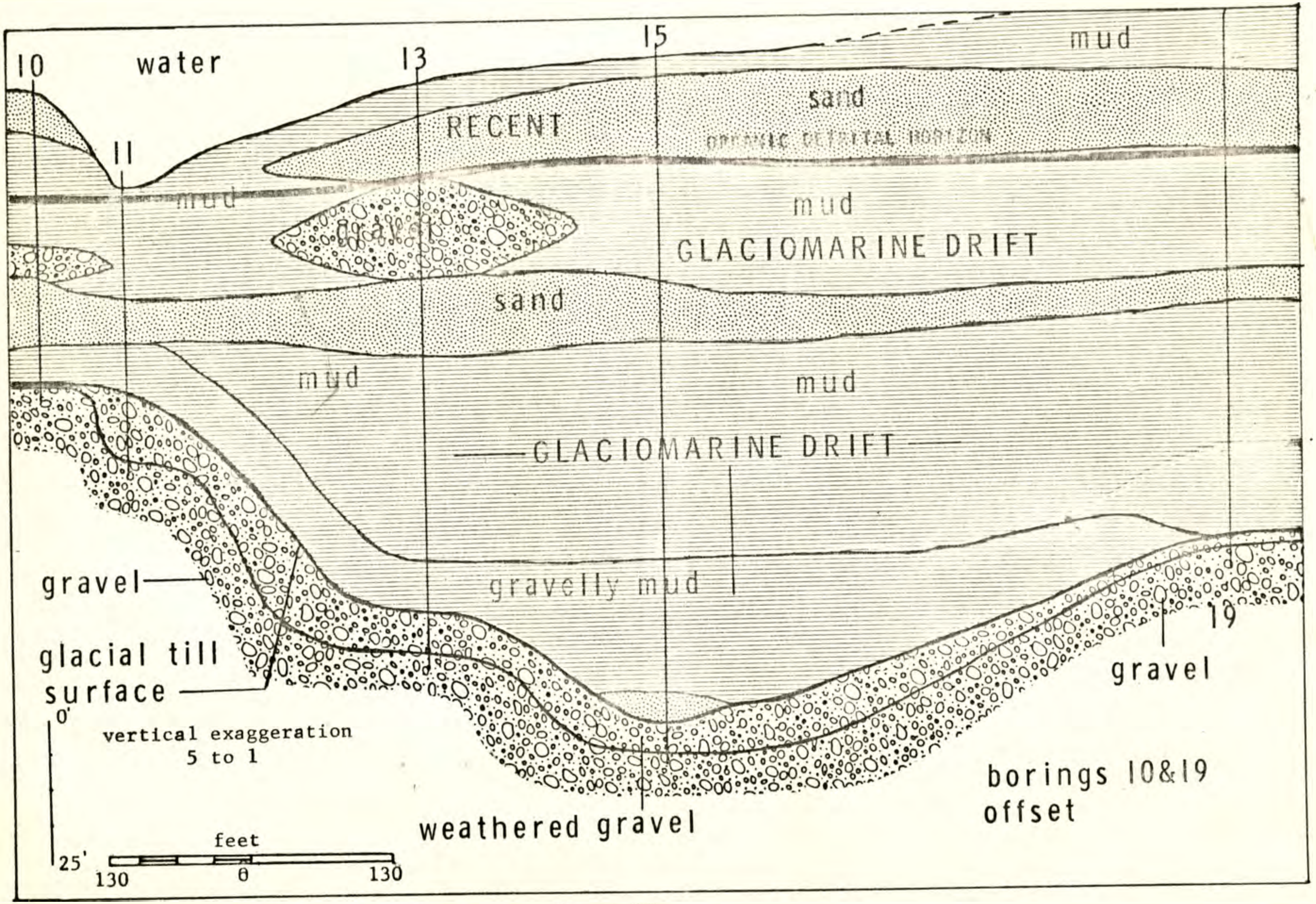


Fig.13 Stratigraphic Cross Section through Borings 10, 11, 13, 15, and 19

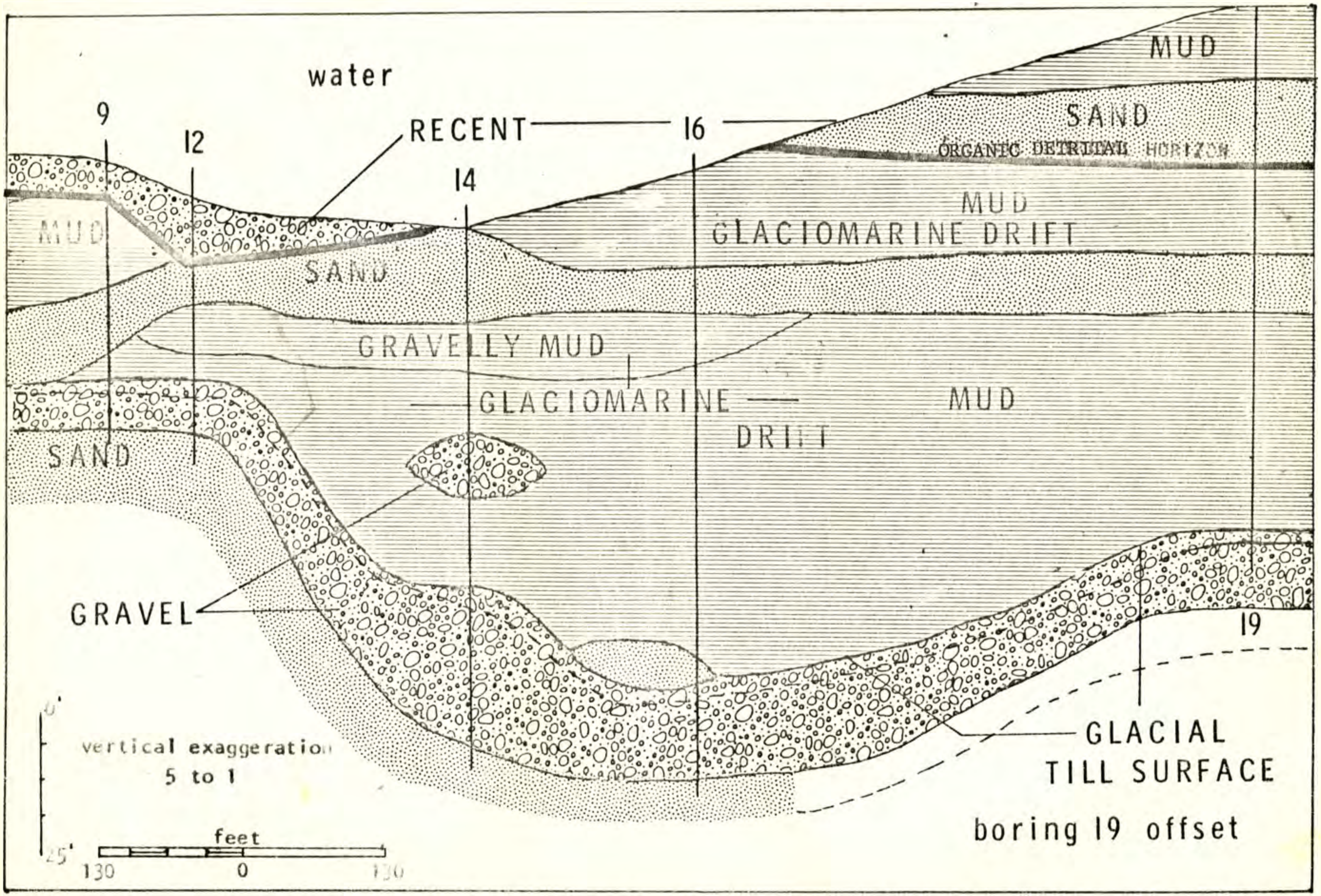


Fig.14 Stratigraphic Cross Section through Borings 9, 12, 14, 16, and 19

deposits in the northern Puget lowland (Easterbrook, 1963) is shown in Figure 15.

The lowest distinguishable sedimentary deposit in the bore holes is the compact unsorted deposit of gravel (Figs.13 and 14). Its compact nature is noted by the great increase in blow count of the drill bit and seismic reflectivity of the profile, and its sorting, grain size and texture indicate a possible glacial origin. The compact gravel appears to be unconformably deposited on an irregular eroded surface indicated by the profile trace (Fig.12 and Appendix D) and the stratigraphic cross sections (Figs.13 and 14). The sand unit below the glacial till deposit (Fig.14) is considered to be part of the glacial till sedimentary sequence.

According to Easterbrook (1963) an unconformity exists between the Cherry Point Silt, the oldest known Pleistocene unit in the Northern Puget lowland area, and the Vashon Till. This unconformity is erosional with several hundred feet of relief, and dating indicates a time break of at least 12,000 years between the deposition of Cherry Point Silt and Vashon Till (Easterbrook, 1963). The Vashon Till, a compact unsorted mixture of pebbles, cobbles and boulders in a sandy silty matrix, is a lodgment till deposited beneath a glacier which had incorporated rounded to subrounded pebbles from a stream gravel (Easterbrook, 1962). There is great similarity between the depositional environments and sedimentary characteristics of the lowest stratigraphic units of the sample area and those of the Cherry Point-Vashon sequence. Therefore these units are considered to be equivalent and define the lower limit of the sub-bottom profile and bore hole correlation.

A series of gravelly sands and muds with gravel and sand lenses

	Stades	Radiocarbon Dates	Rock Stratigraphic Units	Relative Sea Level
RECENT			Recent alluvium	As present
			Older alluvium alluvial deposits above present drainage; marine terrace deposits; dune sand	
LATE PLEISTOCENE	Sumas	9,920±760y. 9,300±250y. BP	Sumas Drift till and ice-contact deposits; outwash sand and gravel; silt, clay, and peat	About 40-80 feet higher than present
	Everson	11,800±400y. 12,090±350y. 10,370±300y. 11,640±275y. BP	Bellingham Glaciomarine Drift pebbly clay till-like drift; pebbly clay; contains marine fossils	500-700 feet higher than present
		11,640±275y. BP	Deming Sand sand, interbeds of clay, silt, gravel, and peat.	About 40-60 feet higher than present
		11,660±350y, BP	Kulshan Glaciomarine Drift pebbly clay till-like drift; pebbly clay, contains marine fossils	
	Vashon	18,000±400y. BP	Vashon till till; minor lenses of sand and gravel	
			Mountain View sand and gravel sand, sandy gravel, and gravel	
		38,000y. BP	Cherry Point silt stratified marine silt and clay; minor sand, contains marine fossils	About 250 feet higher

Fig.15 Upper Pleistocene Stratigraphic Sequence in the Northern Puget Lowland, Washington (Easterbrook, 1969).

conformably overlie the glacial till in the sample and profile areas. These units are characteristically less compacted than the till and represent a change in depositional environment. Easterbrook (1963) describes the Kulshan Glaciomarine Drift, which overlies the Vashon Till, as a series of massive blue-gray unsorted, unstratified till-like sediments having faceted, striated cobbles and pebbles scattered randomly throughout a matrix of clay, silt and sand. The till-like material grades into silty clay with few pebbles and has a composition of about 48% silt and clay, 33% fine sand and 12% pebbles (Easterbrook, 1963). The series of gravelly muds, muds, and gravel immediately above the glacial till are similar in sedimentary characteristics and depositional environment to the Kulshan Glaciomarine Drift and are considered to be equivalent. There is a 5 to 10 foot (1.5-3.0m) sand lens in the lower central portion of the stratigraphic cross sections (Figs.13 and 14) which lies on the till surface. It is a very fine grained granular sand and may be an outwash channel deposit. The theories of origin of the glaciomarine drift are discussed by Easterbrook (1963), and it is thought to have been deposited by a combination of marine environment with floating berg of shelf ice. Melting at the base of floating ice causes entrapped clay, silt, sand, pebbles and cobbles to be released from the ice, and the rain of material settles to the sea floor forming till-like deposits and pebbly clay. The till-like deposits represent times when debris-charged floating ice was extensive, whereas the pebbly clays represent times when the floating ice was less abundant or was without large quantities of debris (Easterbrook, 1963). The sand and gravel lenses in the glaciomarine units (Figs.13 and 14) may indicate large ejections from debris-laden ice.

A continuous fine grained muddy sand deposit overlies the glaciomarine drift, separating it from the succeeding glaciomarine deposit. This sand deposit, a fine-grained muddy sand with some gravel, indicates a change in glacial environment. The sand was possibly in a marine or estuarine environment receiving material from the upland to the east. The sand deposit varies in thickness from bore hole to bore hole indicating possible variations in channel current velocity and direction in the depositional area. The Deming Sand, consisting of stratified sand clay and gravel, lies between the Kulshan Glaciomarine Drift and the Bellingham Glaciomarine Drift as described by Easterbrook (1963). The Deming Sand at its type locality is partly nonmarine, but it becomes associated with marine beach deposits near Bellingham (Easterbrook, 1963). The sand unit in the sample area was deposited in a trough and is, therefore, possibly a portion of the Deming Sand in a marine environment.

A 15 to 25 foot (4.5-7.6m) sedimentary unit consisting of pebbly muds and gravel lenses lies above the fine sand deposit. This unit is similar in sedimentary characteristics to the glaciomarine drift below the sand deposit and is considered to be of the same origin. The return to a glaciomarine environment suggests an advance of the ice coincident with submergence of the lowland (Easterbrook, 1963). If the sand unit is not evidence of a relative emergent phase of the lowland but rather just a large sand lens deposited from a sand laden ice shelf, the two glaciomarine units can not be differentiated. Easterbrook (1963) discussed the deposition of the Bellingham Glaciomarine Drift, which lies above the Deming Sand, and concluded that the Kulshan and Bellingham glaciomarine drifts can not be distinguished from each other when juxtaposed, but regional distinctions can be made after considering relative sea level changes. Since the area of investigation is localized, the distinction between the two glaciomarine units has little value in this study.

The stratigraphic cross sections (Figs.13 and 14) were constructed from information obtained from the bore holes. The stratigraphic relationships are only accurate at the bore hole locations. Areas between are correlations based on those relationships. The heavy black line (Figs.13 and 14) approximates the lower limit of the post-glacial sediments, separating them from the Pleistocene glaciomarine drift. Gradation of the units into one another indicates a transitional environmental change from glaciomarine to post-glacial sediments. The post-glacial depositional horizon is marked by a significant increase in organic detrital material.

The Recent or post-glacial sediments overlie the glaciomarine deposits and have a thickness ranging from 5 to 15 feet (1.5-4.5m). They are composed of muds and sands with a considerable volume of organic detritus. The deposits represent sedimentation since the glaciomarine environment and therefore are transitional from Pleistocene to Recent. There is no distinct break in sedimentation but rather a marked change in the nature of the detrital material. The wood and shell fragments represent a major change in depositional environment. The wood fragments obtained from samples taken at depths of 5 to 15 feet (1.5-4.5m) below the bay floor were transported in a fluvial environment and were distributed in a marine environment by current and tidal actions. Sternberg (1967) attributed most of the wood fragments found in the outer bay to a depth of 20 cm to the fragmenting of the log rafts set up by the pulp mills on the bay. The horizontal and vertical distribution of the wood fragments in the bay rapidly decreases away from the location of the pulp mills (Sternberg, 1967). The shell material in the upper units was fragmented and therefore difficult to identify. It was noted that some barnacle fragments were identifiable but they were too recent in age for use in age determination. The wood and shell fragments are found in sandy, muddy gravels and sandy silts. The sediments do not have the fine rock flour silt of the glaciomarine sediments and are less compact. They have a yellowish iron stain indicating that they are oxidized to some extent. Easterbrook (1963) reported a radiocarbon date of the Bellingham Glaciomarine Drift of 11,800±400 years BP. Therefore, if the glaciomarine unit in the sample area is considered to be of approximately the same age, the sediments above would represent approximately 11,000 years of sedimentation.

Summary and Conclusions

The combined results of the sub-bottom profile and core sampling indicate that the trough-like depression below the bay near South Bellingham is a Pleistocene erosional paleotopographic surface sloping bayward from the uplands to the east. The trough appears to have been cut by sub-aerial stream erosion which drained into the lowland of the bay. The upper surface of the trough is plastered with a deposit of lodgment till by a Late Pleistocene (Vashon) glacier which later deposited a series of glaciomarine drifts from floating shelf ice. The last 11,000 years of sedimentation deposited muds, sands and gravels in a marine environment rich in marine organisms. The trough proved to be unique in studying the stratigraphy and structure of Bellingham Bay in that the sediments which were deposited in the troughs were protected from subsequent erosion. The sub-bottom profile revealed that the bay is relatively featureless in bottom and sub-bottom topography as only 20 to 30 feet (6.1-9.1m) of material above the Vashon till deposit remains. Trough areas reveal the most complete stratigraphic history of the bay as indicated by the thick deposits of sediments in the troughs. These deposits are localized because of their containing structures but their sedimentological history reflects the history of Bellingham Bay, since the Late Pleistocene sedimentary deposits are regional in extent (Easterbrook, 1963). If the paleotopographic erosional surface of the profile is considered to be the unconformity on Cherry Point Silt as described by Easterbrook (1963), then the entire bay is underlain by Cherry Point Silt as shown on the sub-bottom profile as a thick 550 feet (167.6m) or more uniform unit overlain by a mantle of glacial till, glaciomarine drift, and Recent marine deposits. The thickness of the glaciomarine drift varies in accordance with the topography of the Cherry Point Silt and subsequent erosion.

Future studies concerning the stratigraphy of Bellingham Bay might include a heavy mineral analysis and a detailed stratigraphic correlation of the sedimentary units described in this study with Late Pleistocene deposits of the northern part of the Puget Lowland of Washington described by Easterbrook (1963). Therefore the sub-bottom profile and core sample remains from this study are contributed to the Geology Department of Western Washington State College for future studies concerning Bellingham Bay.

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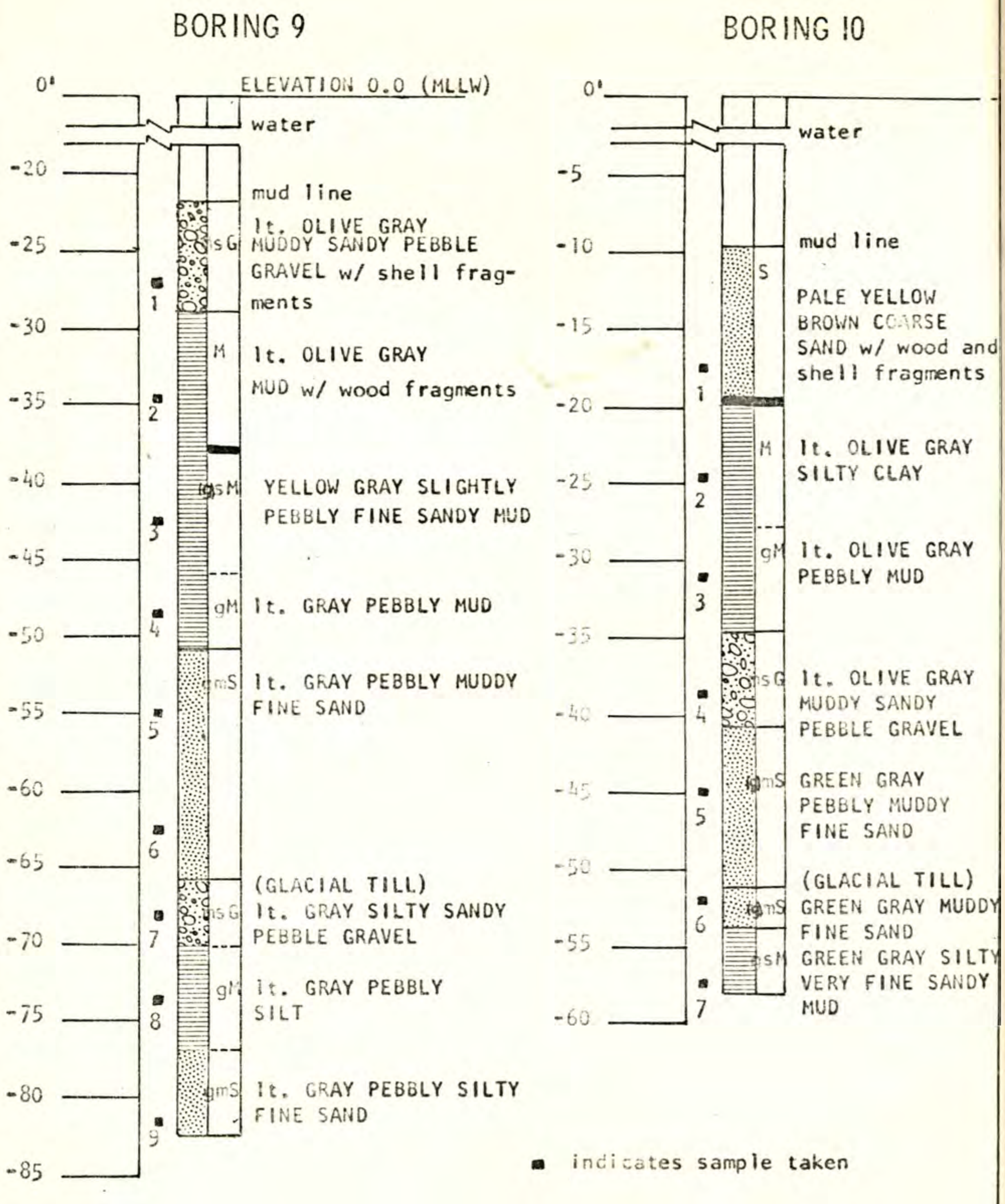
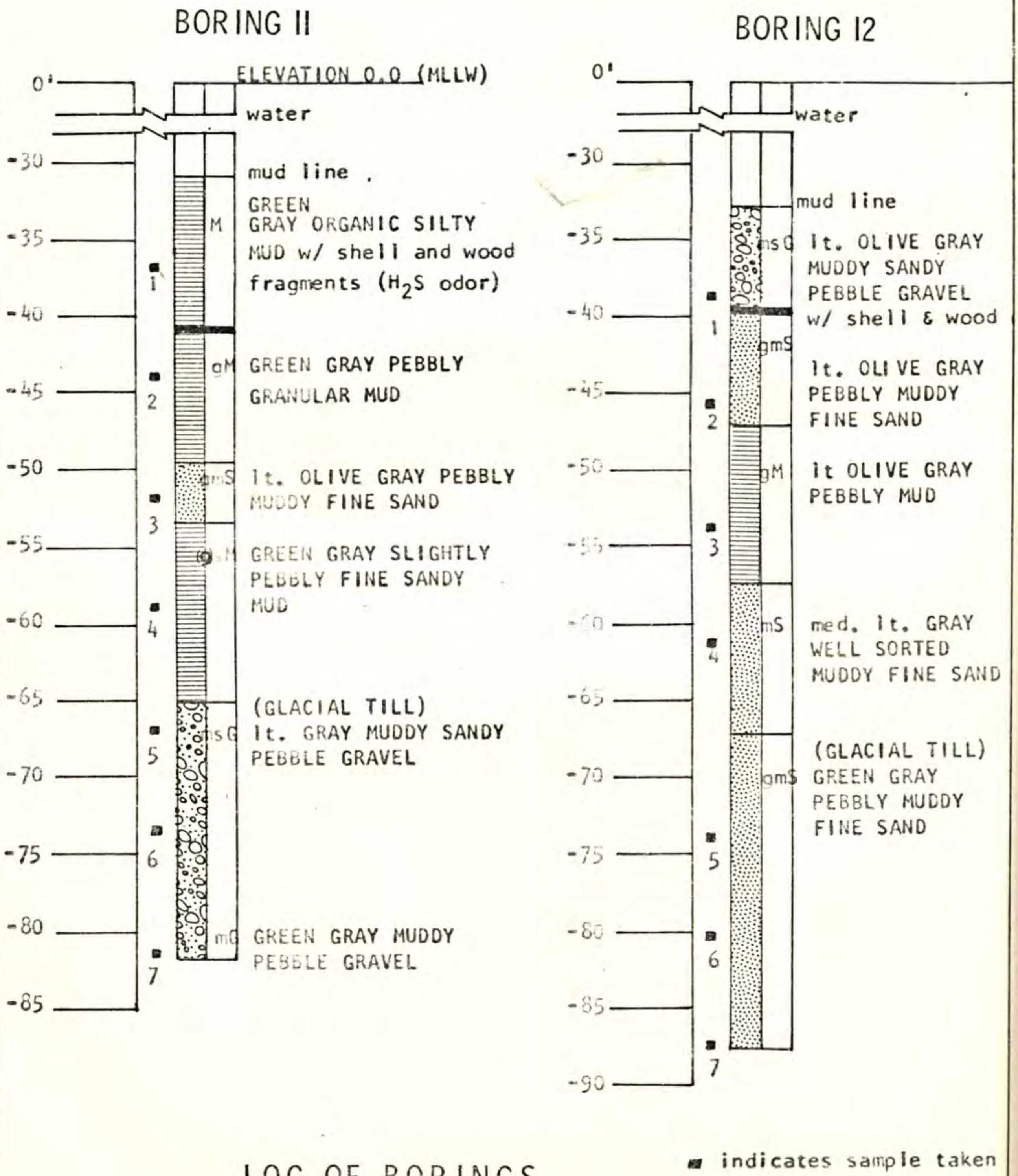
Appendix A

Log of Borings Plates A-1 to A-7



LOG OF BORINGS

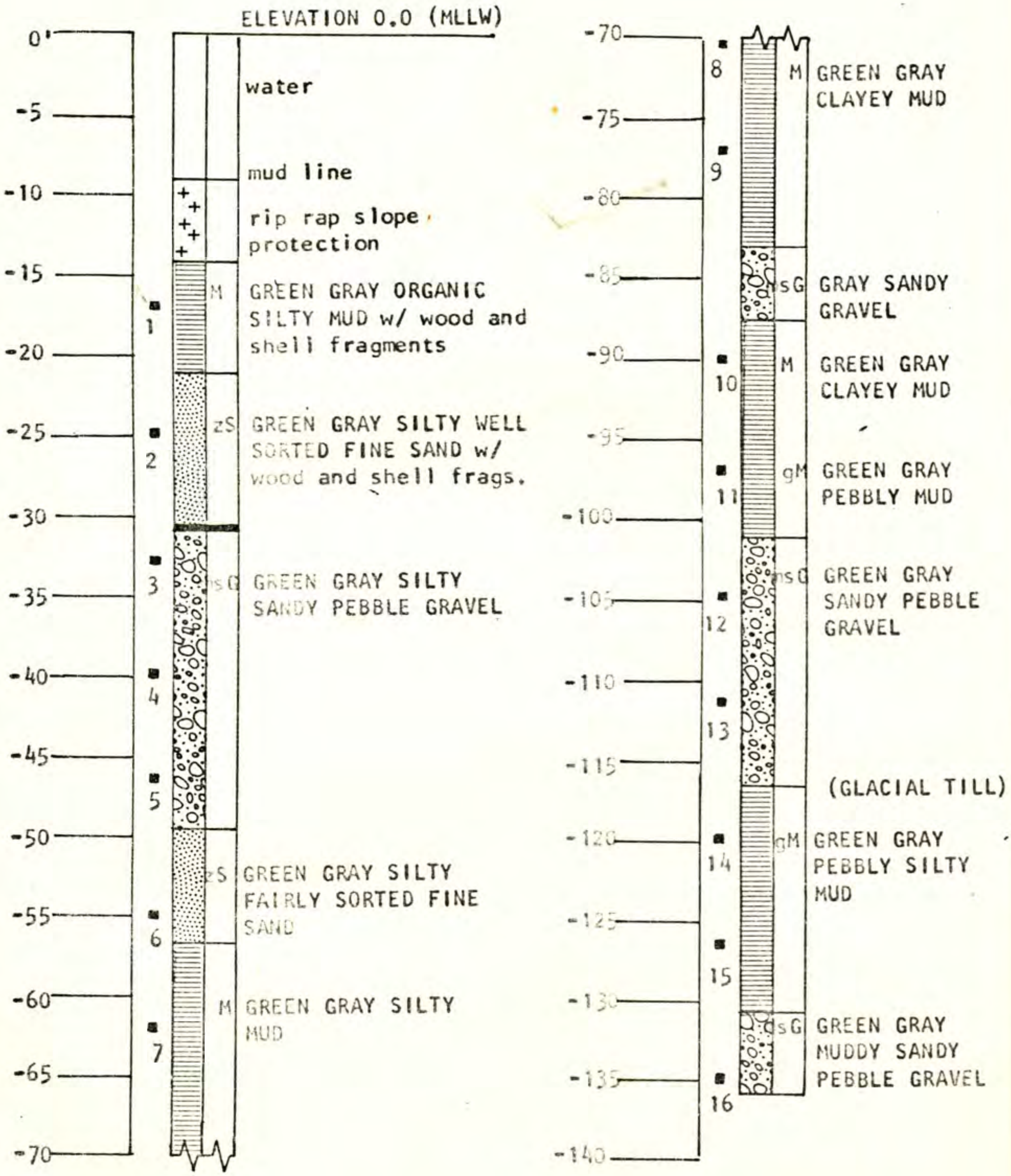
PLATE A-1



LOG OF BORINGS

PLATE A-2

BORING 13

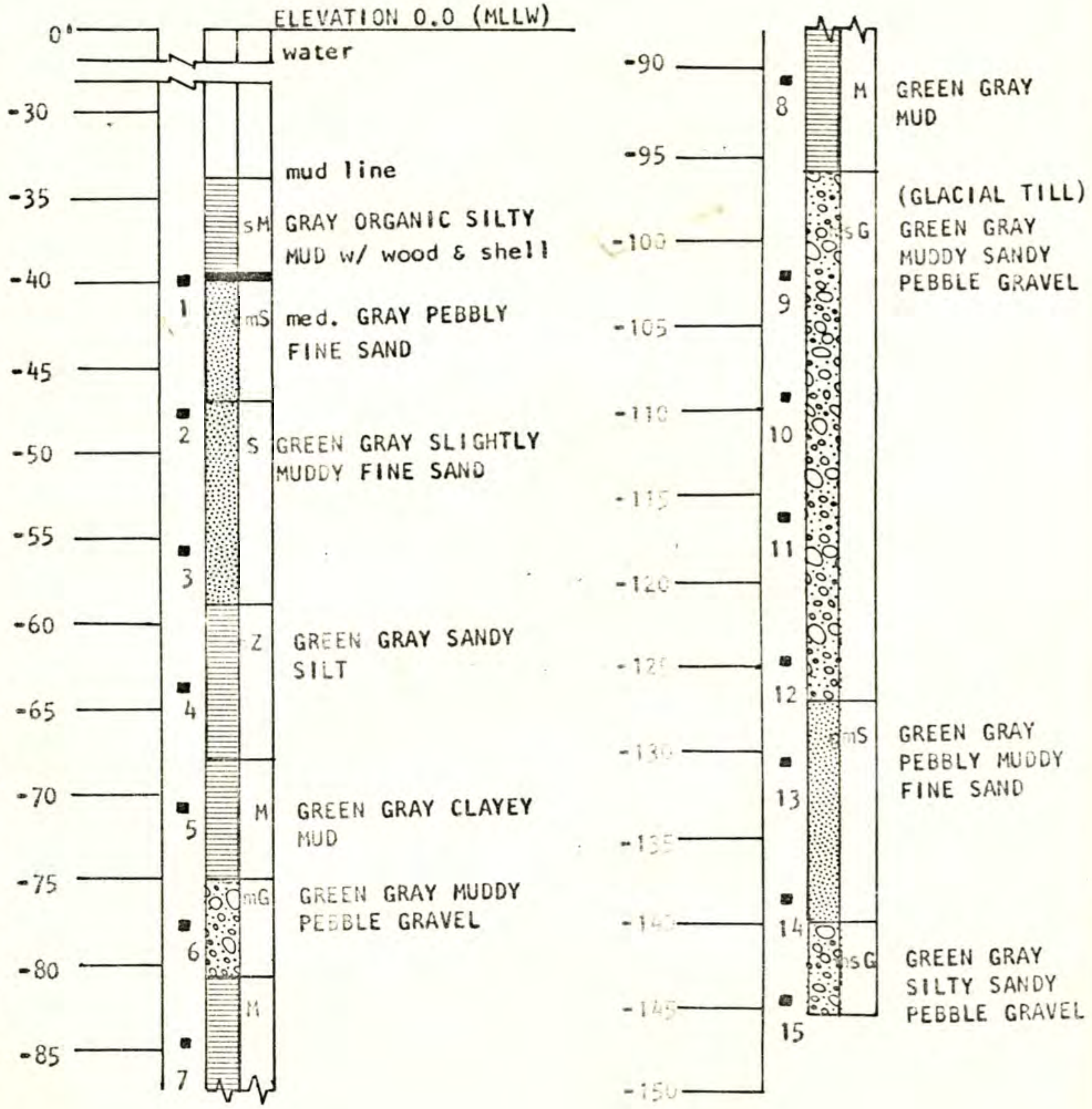


■ indicates sample taken

LOG OF BORINGS

PLATE A-3

BORING 14

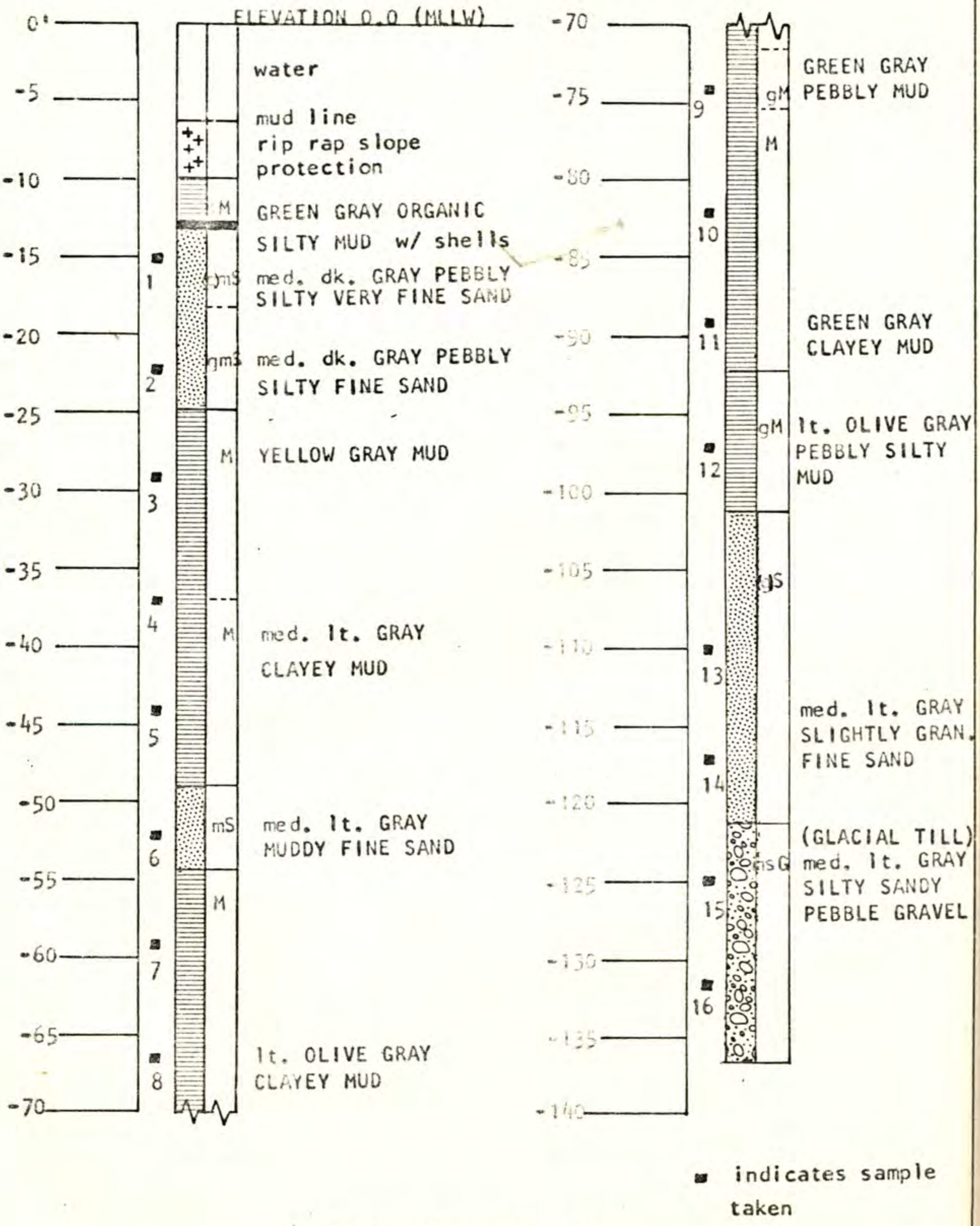


LOG OF BORINGS

■ indicates sample taken

PLATE A-4

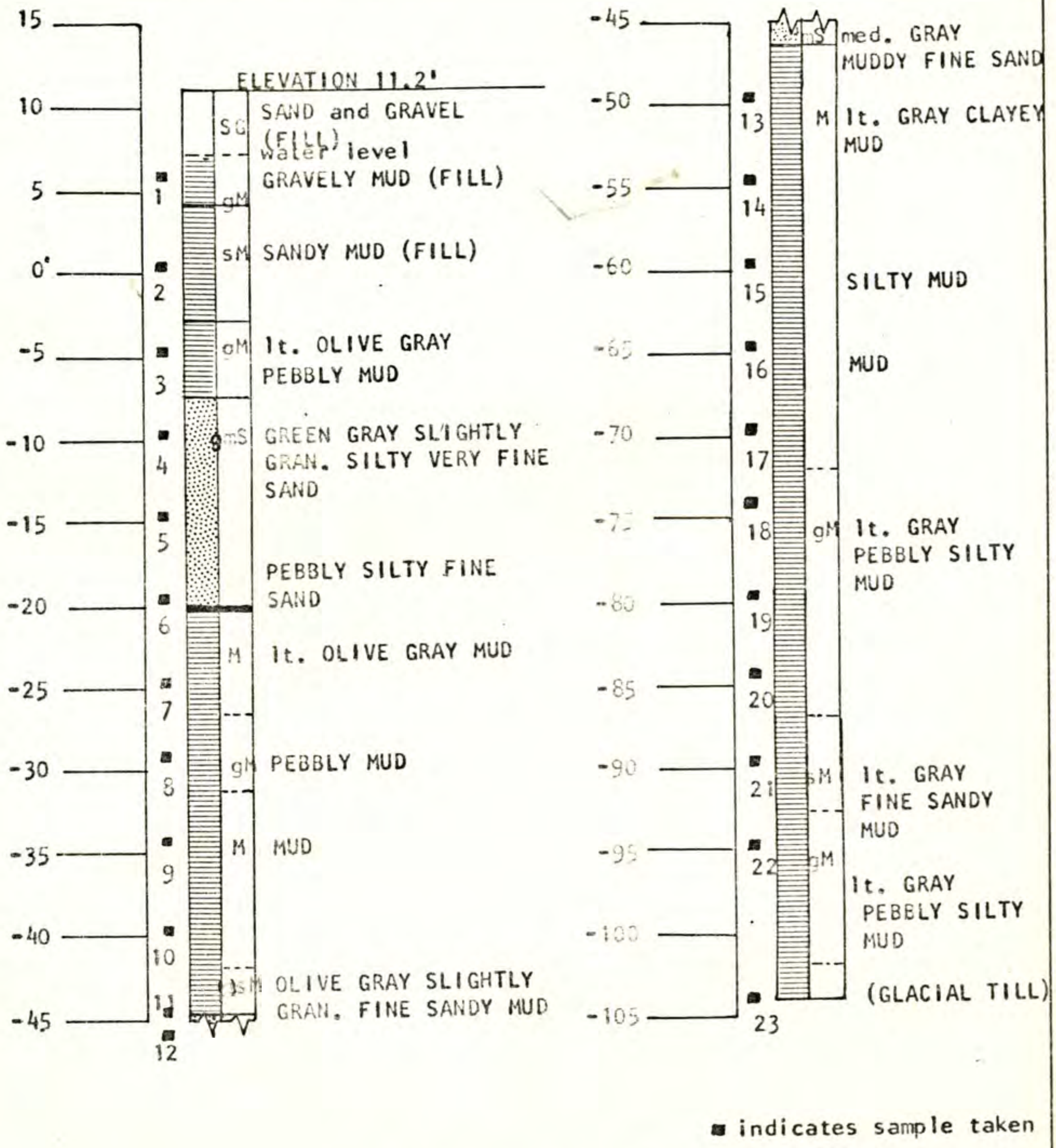
BORING 15



LOG OF BORINGS

PLATE A-5

BORING 19



LOG OF BORINGS

PLATE A-7

Appendix B

Statistical Analysis Data Summary

Sample Nomenclature Summary

Statistical Analysis Data Summary

Sample Number	M_z (ϕ)	σ_I (ϕ)	SK_I	K_G	Descriptive Limits Applied to Parameters
9-1	-0.850	2.950	0.353	1.034	vps, sfs, m
9-2	8.023	2.222	0.153	0.637	vps, fs, vp
9-3	6.546	3.793	-0.133	0.683	vps, cs, p
9-4	5.083	4.271	0.040	1.061	eps, ns, m
9-5	3.066	4.446	0.099	1.024	eps, ns, m
9-7	0.443	3.453	0.167	0.853	vps, fs, p
9-8	3.066	4.570	-0.148	0.916	eps, cs, m
9-9	2.066	4.145	-0.020	0.953	eps, ns, m
10-2	8.463	2.157	-0.088	0.735	vps, ns, p
10-3	6.086	4.331	-0.177	0.911	eps, cs, m
10-4	-0.026	2.849	-0.194	0.972	vps, cs, m
10-5	2.583	4.637	-0.040	1.133	eps, ns, l
10-6	2.056	1.534	-0.171	1.639	ps, fs, vl
10-7	4.546	2.087	0.297	1.555	vps, fs, vl
11-2	6.310	4.071	-0.224	0.899	eps, cs, m
11-3	4.810	3.726	0.402	1.191	vps, sfs, l
11-4	7.560	3.429	-0.228	0.852	vps, cs, p
11-5	1.806	4.602	0.156	0.878	eps, fs, p
11-7	1.890	4.689	0.114	0.833	eps, fs, p
12-1	2.383	4.735	0.162	0.670	eps, fs, p
12-2	6.226	3.915	-0.100	0.827	vps, ns, p
12-3	4.973	4.276	-0.159	0.989	eps, cs, m
12-4	3.393	1.904	0.729	2.800	ps, sfs, vl
12-5	3.876	4.112	0.154	1.113	eps, fs, l
13-2	3.230	2.023	0.578	2.073	vps, sfs, vl
13-4	1.073	4.142	-0.095	0.880	eps, ns, p
13-6	4.516	2.819	0.434	1.262	vps, sfs, l
13-7	7.183	2.493	0.316	0.692	vps, sfs, p
13-8	8.600	2.071	-0.077	0.711	vps, ns, p
13-10	8.596	2.257	-0.214	0.840	vps, cs, p
13-11	3.663	4.954	-0.041	0.921	eps, ns, m
13-12	-1.266	2.446	0.225	1.048	vps, fs, m
13-14	3.410	4.505	-0.075	0.943	eps, ns, m
13-16	0.226	4.251	0.429	0.956	eps, sfs, m
14-1	2.233	4.188	-0.033	1.246	eps, ns, l
14-2	3.093	1.023	0.391	1.725	ps, sfs, vl
14-4	4.950	2.139	0.669	2.943	vps, sfs, vl
14-5	8.726	1.972	-0.091	0.755	ps, ns, p
14-6	0.666	4.821	0.551	0.839	eps, sfs, p
14-8	8.316	2.328	-0.138	0.791	vps, cs, p
14-9	1.283	4.333	0.321	1.000	eps, sfs, m
14-13	3.050	4.621	0.090	1.056	eps, ns, m
14-15	1.963	4.273	-0.096	0.886	eps, ns, p

Statistical Analysis Data Summary

Sample Number	M_z (ϕ)	σ_i (ϕ)	SK_i	K_g	Descriptive Limits Applied to Parameters
15-1	3.540	2.003	0.352	2.121	ps, sfs, vl
15-2	1.960	3.756	0.081	1.581	vps, ns, vl
15-3	8.086	2.348	0.015	0.732	vps, ns, p
15-5	8.633	2.074	-0.098	0.752	vps, ns, vl
15-6	4.316	2.291	0.753	2.938	vps, sfs, p
15-8	8.233	2.322	-0.137	0.862	vps, cs, p
15-9	5.000	4.293	-0.014	0.848	eps, ns, p
15-11	8.250	2.743	-0.318	0.816	vps, scs, p
15-12	4.176	4.150	-0.071	0.990	eps, ns, m
15-14	2.270	1.355	-0.048	1.779	ps, ns, vl
15-16	0.533	3.562	0.100	0.823	vps, ns, p
16-1	7.453	1.557	0.171	1.010	ps, fs, m
16-3	3.290	1.626	0.522	2.847	ps, sfs, vl
16-4	7.053	3.015	0.061	0.661	vps, ns, vl
16-6	5.523	4.216	-0.145	1.037	eps, cs, m
16-8	7.983	2.450	-0.063	0.730	vps, ns, p
16-11	3.043	1.255	0.232	1.808	ps, fs, vl
16-13	1.916	4.501	0.193	0.987	eps, fs, m
19-3	2.750	4.855	0.155	0.807	eps, fs, p
19-4	5.100	3.020	0.447	1.275	vps, sfs, l
19-6	2.733	3.281	-0.013	1.837	vps, ns, vl
19-7	8.193	2.385	-0.059	0.715	vps, ns, p
19-8	3.816	5.101	-0.101	0.768	eps, cs, p
19-9	8.173	2.178	-0.022	0.687	vps, ns, p
19-11	7.650	2.826	-0.112	0.825	vps, cs, p
19-12	4.700	2.848	0.735	1.001	vps, sfs, m
19-13	8.516	2.512	-0.353	0.859	vps, scs, p
19-15	7.523	2.217	0.166	0.728	vps, fs, p
19-16	5.770	3.207	0.516	0.821	vps, sfs, p
19-19	3.556	4.443	-0.027	0.794	eps, sfs, p
19-21	6.903	3.186	-0.062	0.710	vps, sfs, p
19-22	5.550	3.414	0.147	1.222	vps, fs, l

ABBREVIATIONS

ps - poorly sorted
vps - very poorly sorted
eps - extremely poorly sorted
fs - fine skewed
sfs - strongly fine skewed
ns - near symmetrical
cs - coarse skewed
scs - strongly coarse skewed
m - mesokurtic
l - leptokurtic
vl - very leptokurtic
p - platykurtic
vp - very platykurtic

Sample Number	Folk (1968) Sediment Nomenclature Obtained From Figure 10	
9-1	MsG	muddy sandy pebbly gravel
9-2	M	mud
9-3	(g)sM	slightly pebbly fine sandy mud
9-4	gM	pebbly mud
9-5	gmS	pebbly muddy fine sand
9-7	msG	silty sandy pebble gravel
9-8	gM	pebbly silt
9-9	gmS	pebbly silty fine sand
10-2	M	silty clay
10-3	gM	pebbly mud
10-4	msG	muddy sandy pebble gravel
10-5	gmS	pebbly muddy fine sand
10-6	(g)mS	slightly granular muddy fine sand
10-7	(g)sM	slightly pebbly silty very fine sandy mud
11-2	gM	pebbly granular mud
11-3	gmS	pebbly muddy fine sand
11-4	(g)sM	slightly pebbly fine sandy mud
11-5	msG	muddy sandy pebble gravel
11-7	mG	muddy pebble gravel
12-1	msG	muddy sandy pebble gravel
12-2	gmS	pebbly muddy fine sand
12-3	gM	pebbly mud
12-4	mS	well sorted muddy fine sand
12-5	gmS	pebbly muddy fine sand
13-2	zS	silty well sorted fine sand
13-4	msG	silty sandy pebble gravel
13-6	zS	silty fair sorted fine sand
13-7	M	silty mud
13-8	M	clayey mud
13-10	M	clayey mud
13-11	gM	pebbly mud
13-12	msG	muddy sandy pebble gravel
13-14	gM	pebbly silty mud
13-16	msG	muddy sandy pebble gravel
14-1	gmS	pebbly muddy fine sand
14-2	S	slightly muddy fine sand
14-4	sZ	sandy silt
14-5	M	clayey mud
14-6	mG	muddy pebble gravel
14-8	M	mud
14-9	msG	muddy sandy pebble gravel
14-13	gmS	pebbly muddy fine sand
14-15	msG	silty sandy pebble gravel

Sample Number	Folk (1968) Sediment Nomenclature Obtained From Figure 10	
15-1	(g)mS	slightly pebbly silty very fine sand
15-2	gmS	pebbly silty fine sand
15-3	M	mud
15-5	M	clayey mud
15-6	mS	muddy fine sand
15-8	M	clayey mud
15-9	gM	pebbly mud
15-11	M	clayey mud
15-12	gM	pebbly silty mud
15-14	(g)S	slightly granular fine sand
15-16	msG	silty sandy pebble gravel
16-1	M	clayey mud
16-3	zS	silty very fine well sorted sand
16-4	(g)sM	slightly granular very fine sandy mud
16-6	gM	pebbly silty mud
16-8	M	mud
16-11	gmS	granular muddy fine sand
16-13	msG	muddy sandy pebble gravel
19-3	gM	pebbly mud
19-4	(g)mS	slightly granular silty very fine sand
19-6	gmS	pebbly silty fine sand
19-7	M	mud
19-8	gM	pebbly mud
19-9	M	mud
19-11	(g)sM	slightly granular fine sandy mud
19-12	mS	muddy fine sand
19-13	M	clayey mud
19-15	M	silty mud
19-16	M	mud
19-19	gM	pebbly silty mud
19-21	sM	fine sandy mud
19-22	gM	pebbly silty mud

Appendix C

Computer Program for Folk Statistical Parameters

Computer Program for Folk (1968) Statistical Parameters of Grain Size

Computer: IBM 360/40 Western Washington State College

Computer Language: PL/1

<u>Sequence of data cards and key punch information</u>

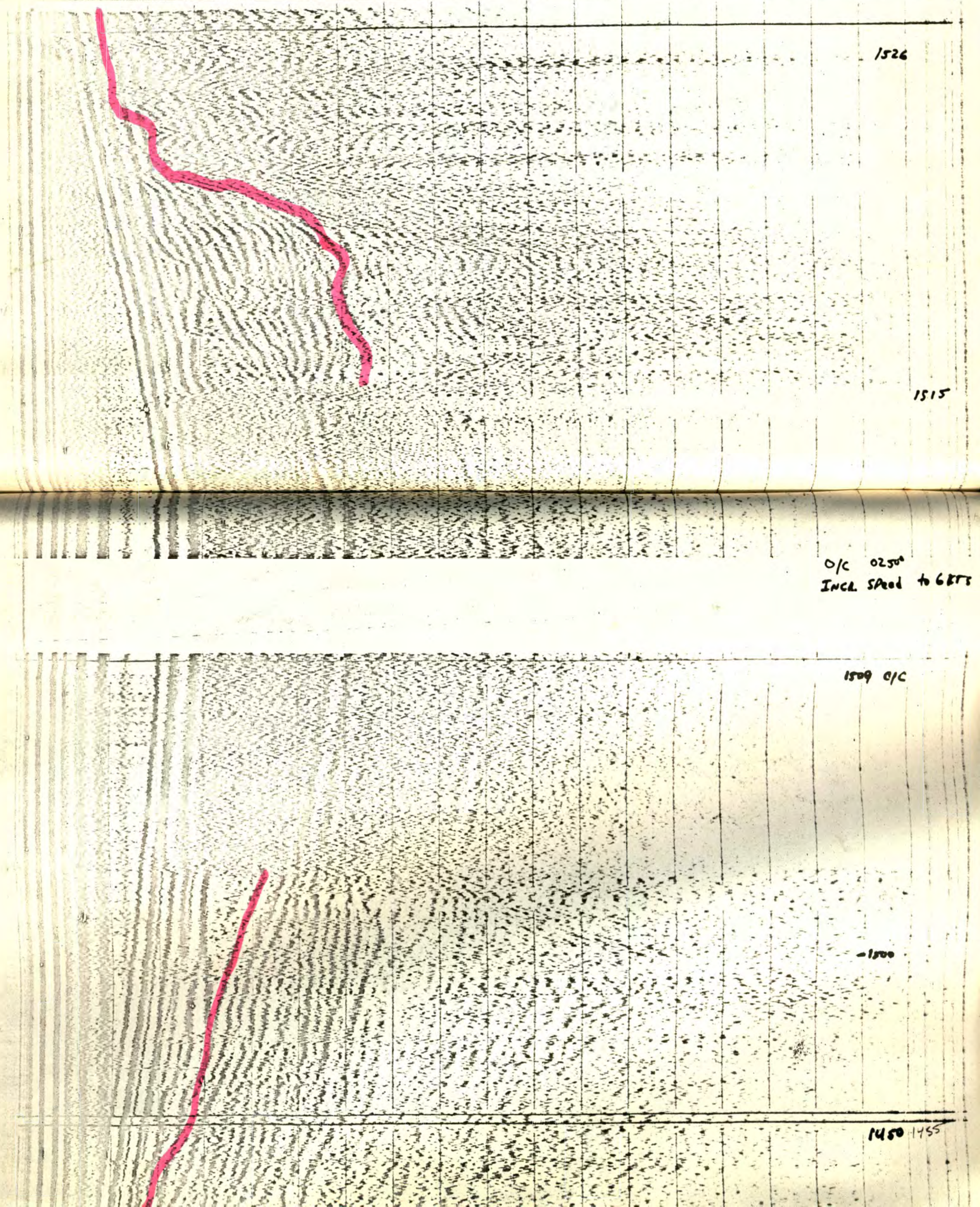
1. Job title, accounting information, programmer
2. // SED EXEC PLILFCG
3. SED: PROCEDURE OPTIONS (MAIN);
4. DECLARE SPECIMEN CHAR (6), (O_5, O_{16}, O_{25}, O_{50}, O_{75}, O_{84}, O_{95}) FIXED
5. DEC (4,2), (O_i, O_g, SK_g, SK_i, K_g, M_z) FIXED DEC (4,3);
6. START: GET LIST (SPECIMEN, O_5, O_{16}, O_{25}, O_{50}, O_{75}, O_{84}, O_{95});
7. $O_i = (O_{84} - O_{16}) / 4 + (O_{95} - O_5) / 6.6$;
8. $O_g = (O_{84} - O_{16}) / 2$;
9. $SK_g = (O_{16} + O_{84} - 2 * O_{50}) / (O_{84} - O_{16})$;
10. $SK_i = (O_{16} + O_{84} - 2 * O_{50}) / (2 * (O_{84} - O_{16})) + (O_5 + O_{95} - 2 * O_{50})$

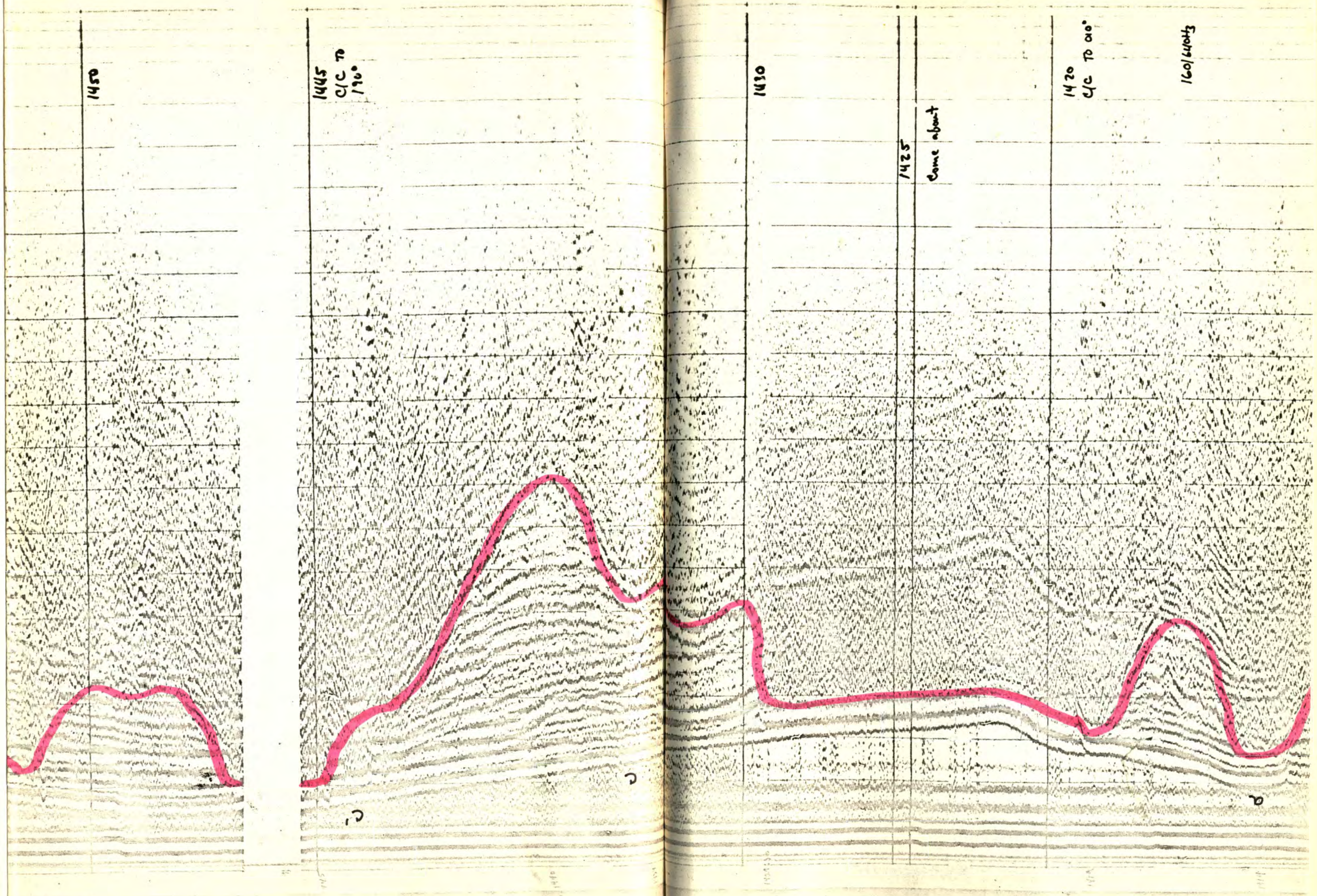
    $/ (2 * O_{95} - O_5))$;
11. $K_g = (O_{95} - O_5 / (2.44 * (O_{75} - O_{25}))$;
12. $M_z = (O_{16} + O_{50} + O_{84}) / 3$;
13. PUT DATA (SPECIMEN);
14. PUT SKIP;
15. PUT DATA (O_i, O_g, SK_g, SK_i, K_g, M_z);
16. PUT SKIP (2);
17. GO TO START;
18. END SED;
19. // GO. SYSIN DD*
20. SPEC. NO. '9 - 1' -4.62 -3.42 -2.81 -1.50 1.12 2.37 5.30

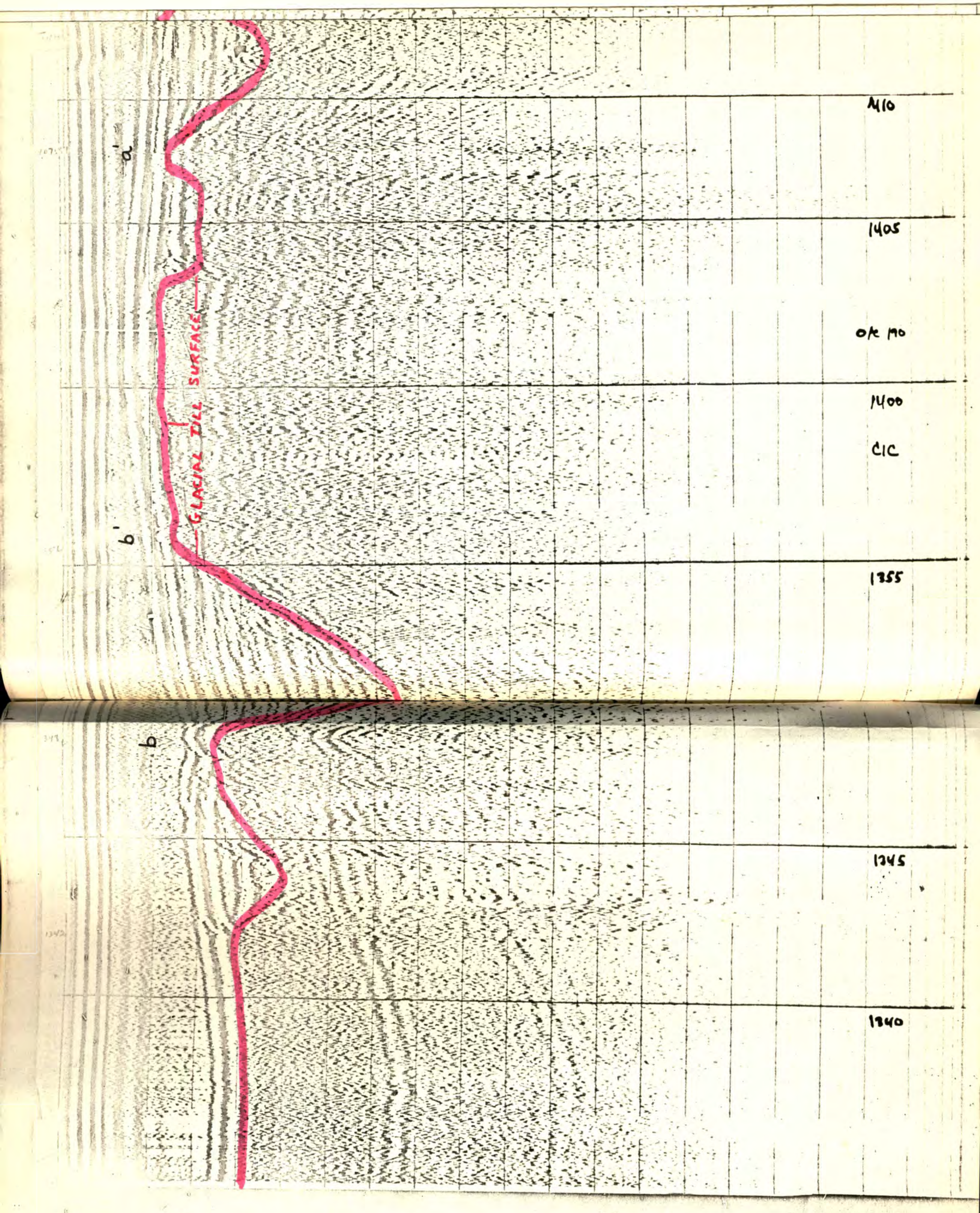
    (EXAMPLE)
21. //

Appendix D

Sub-bottom Profile Recording near Sample Area shown in Fig.11


1526
1515
O/C 0250
INCL SPEED to 6KTS
1509 O/C
-1500
1450 1455


1450
1445
C/C TO
190°
1430
1425
Come about
1420
C/C TO 010°
160/640Hz


1410
a'
1405
o/c 190
GLACIAL TILL SURFACE
1400
C/C
b'
1355
b
1345
1340