GEOTECHNICAL PROPERTIES OF LAKE ERIE CLAYS

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ABSTRACT

Ales J. Zeman: Geotechnical Properties of Lake Erie Clays. M.Sc. thesis, McGill University at Montreal, 1976.

The study has resulted from an offshore geotechnical investigation in the central basin of Lake Erie near Erieau, Ontario. Seven boreholes were cored in three stratigraphic units, consisting of a surficial Recent mud, a glacio-lacustrine deposit, and a till deposit. Sampling of lacustrine sediments was plagued by problems of sediment core disturbance, so the performance of five different thin-walled samplers used was evaluated. The Christensen sampler was the most effective in the conditions of the investigation.

The stratigraphic units can be well distinguished on the basis of plasticity results, which were found to be primarily controlled by the natural water content and the oxidizable matter content. Poor correlation of the plasticity with the shear strength, the clay content, and the compressibility is attributed to higher than expected values of the liquid limit within a three-metre thick weathered topstratum, and to higher than expected shear strength values near the base of the Recent mud. In situ desiccation of the glacio-lacustrine deposit in the near-shore area of the basin during the low-level Early Lake Erie phase is considered responsible for the overconsolidation and stiff to very stiff consistency of the upper portion of the deposit.

The predominant clay minerals of the stratigraphic units studied are illite and iron-rich chlorite. X-ray diffraction analyses have revealed that the high plasticity within the weathered topstratum of the Recent mud is primarily attributable to the presence of up to ten per cent of smectite and interlayered minerals. Scanning electron microscopy has indicated a gradual increase in crystallinity of clay minerals with depth in the Recent deposit, and the occurrence of cemented silt-size non-clay particles within zones containing unexpectedly high shear strength values.

RÉSUMÉ

Ales J. Zeman: Les propriètes géotechniques des argiles provenant du lac Erié. Thèse de maîtrise, Université McGill, Montréal, 1976.

Cette étude résulte des investigations géotechniques réalisées dans le bassin central du lac Erié près d'Erieau, Ontario. On a foré sept sondages dans trois unités stratigraphiques: vases postglaciaires superficielles, argiles glacio-lacustres et argiles à blocaux. L'échantillonage des argiles lacustres ayant souffert de problèmes de remaniement des carottes sédimentaires, on a comparé le fonctionnement de cinq carottiers à paroie mince. Le carottier de Christensen s'est revelé le plus efficace sous les conditions d'investigation.

On peut facilement differencier les unités stratigraphiques selon les résultats de plasticité. La plasticité est determinée avant tout par les teneurs en eau et en matières oxydables. La faible correlation liant la plasticité - à la résistance au cisaillement, - à la teneur en argile et - à la compressibilité est attribuée à la valeur anormalement élevée de la limite de liquidité dans les trois mètres supérieurs de sédiment chimiquement alterés et aussi aux valeurs élevées de la résistance au cisaillement près de la base des vases postglaciaires. La dessiccation in situ des argiles glacio-lacustres dans la zone littorale pendant la phase de bas niveau du "Lac Erié Précose" est considerée comme responsable de la surconsolidation et de la consistance rigide à très rigide de la portion supérieure du dépôt.

L'illite et la chlorite riche en fer sont les minéraux des argiles qui prédominent dans les unités stratigraphiques étudiées. Les résultats de la diffraction aux rayons X ont montré que la plasticité anormalement élevée de la portion supérieure des vases postglaciaires est attribuable avant tout à la presence de smectite et de minéraux interstratifiés d'une teneur parfois égale à dix pour cent. La microscopie électronique à balayage a indiqué une augmentation graduelle de crystallinité de minéraux argileux en fonction de la profondeur dans les vases postglaciaires et l'apparition de particules cimentées non-argileuses ayant la dimension du limon dans les zones possédant des valeurs élevées de résistance au cisaillement.

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The helpful discussions with Dr. B.F. D'Anglejan of Marine Science Centre, McGill University; Dr. C.F. M. Lewis of the Geological Survey of Canada; Dr. P. G. Sly of the Canada Centre for Inland Waters; Dr. B.P. Warkentin of the Macdonald College, McGill University; and Dr. R.N. Yong of McGill University are acknowledged with gratitude.

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CHAPTER 1

INTRODUCTION

1.1 Objectives of the Geotechnical Investigation

The thesis is based upon results of an offshore geotechnical investigation in the central basin of Lake Erie (Figs. 1 and 2) conducted by H. Q. Golder and Associates Ltd. of Toronto (HQGA) from June to September of 1972. HQGA were retained for the investigation by the Consumers' Gas Company of Toronto (CGC) which has been for several years carrying out geophysical and drilling exploration for natural gas in the offshore areas of Lake Erie. The geotechnical investigation was conducted from the beginning in cooperation with Dr. C.F.M. Lewis of the Geological Survey of Canada, and the Geolimnology Section of the Canada Centre for Inland Waters (CCIW). The CCIW supplied some of the offshore sampling equipment and provided facilities for the storage and laboratory testing of samples.

The investigation was undertaken with the purpose to study the geotechnical properties of Lake Erie offshore unconsolidated sediments, and to interpret these properties within the framework of the relatively well-known stratigraphy and the depositional history of the sediments. Information on the variation of the shear strength and other geotechnical properties of the offshore sediments has been required by the CGC as background data for a reconstruction of an existing spudded drilling platform. Particularly important for the new design of platform footing were predictions, based on geotechnical data obtained, of footing penetrations into the soft unconsolidated sediments at selected locations.

The geotechnical appraisal of the sediments for the footing design has been carried out by HQGA and submitted to the CGC in a report containing engineering recommendations (Davis and Kim, 1973). In accordance with an agreement between HQGA and the writer, an additional foundation engineering analysis of similar character has not been attempted within the scope of this thesis, since it was felt that the foundation problem was intricate enough to warrant a separate research topic.

1.2 Scope of the Thesis Research

The CGC and HQGA have allowed the writer to use field data for research into some problems encountered during or resulting from the conducted investigation. The scope of the programme was controlled by the availability of samples to the writer through the courtesy of the CGC and HQGA, and the effectiveness of the sampling techniques employed.

The thesis work has commenced with the evaluation of sampling techniques used during the investigation in relation to the sediments being investigated. The problem of offshore undisturbed sampling in soft lacustrine sediments has been discussed due to its obvious importance for dependable laboratory measurements of sediment geotechnical properties and due to the desirability to improve existing sampling techniques.

A series of basic geotechnical tests has been carried out to characterize each stratigraphic unit and to determine spatial variations of the geotechnical properties within the study area. The depositional history of the sediments in the Lake Erie basin, and in the study area in particular, has been described to show the dependance of the sediment geotechnical properties on the sediment genesis. The results of basic tests thus allow comparison with similar sediments found elsewhere, particularly with lacustrine clays found in the Great Lakes region.

During the research work several attempts have been made to employ known empirical correlations for the prediction of the sediment behaviour. In general, these correlations have been found unreliable for the sediments investigated, primarily due to the effects of chemical weathering, organic matter and diagenetic processes on the geotechnical properties measured. Some fundamental aspects of the geotechnical properties have been therefore investigated by physico-chemical tests that are not commonly employed in geotechnical engineering owing to expense. Determination of specific gravity, oxidizable matter content, total carbon content, and surface area has been carried out to provide a better understanding of geotechnical data.

Variations in geotechnical properties are often attributable to the presence of minor amounts of clay minerals, particularly of the swelling type. Therefore it was considered necessary to examine the mineralogical composition of the clay fraction in some detail. A series of X-ray diffraction analyses and electron-optical studies has been undertaken to obtain a more satisfactory explanation of the sediment behaviour.

This research has proved to be especially suitable for the interpretation of irreversible changes upon drying, which were observed in some but not all sediment samples.

It is fully realized that for a complete foundation investigation any research into fundamental causes of geotechnical properties has to be conducted in conjunction with an engineering evaluation of soil and rock conditions employing mathematical tools of analysis. Nevertheless it is believed that a better understanding of the principal physico-chemical factors influencing the geotechnical properties provides at least a very useful background information for pre-engineering studies and the selection of reliable design parameters.

CHAPTER 2

GEOLOGY OF LAKE ERIE BASIN

2.1 Previous Work

Geological investigations in the Lake Erie drainage basin have been conducted for almost a century. Spencer (1894) published a first map showing tilted glacial lake shorelines attributed to the "infant Lake Erie." First concepts concerning the late glacial and postglacial history of Lake Erie were formulated by Leverett (1902) and Leverett and Taylor (1915). In the latter work the authors noted that the mouths of streams flowing into the lake basin from the west are unusually deep. They suggested that the streams are relics of an earlier drainage system connected with a low level of Early Lake Erie. Bathymetry of the lake basin was mapped by the Canadian and American governments in the early part of this century, and the navigation charts were published as the results of this survey. The first investigation of unconsolidated bottom deposits in the central and eastern basins were made by Fish (1929) and Pegrum (1929). The first determination of the clay mineral composition of Lake Erie sediments was published by Cuthbert (1944).

Since 1945 geological studies in the Lake Erie area have been undertaken by a great number of people.

Hough (1958, 1963, 1966) revised a chronological sequence of glacial lake levels for the whole Great Lakes region, and within this work published valuable information regarding the geological evidence of the major lake stages in the Lake Erie basin. Kramer (1961) studied water chemistry and related it to the clay mineralogy of the sediments. Hartley (1961 a, 1961 b) investigated sediments beneath Ohio waters and in the western island area of the lake. Morgan (1964) used seismic reflection profiling for the identification of major bottom deposits. The most detailed study of Lake Erie bottom sediments to date is an unpublished Ph.D. thesis by Lewis (1966). This thesis contains a comprehensive description of the surficial sediments based on the results of coring, echo sounding, and laboratory tests. Furthermore, geological and palynological evidence for former low water levels of Early Lake Erie was presented, including the age determination of bottom deposits based on several radiocarbon dates. A seismic reflection survey in the central basin of Lake Erie was carried out by Wall (1968). The sedimentation processes in the western basin were studied by Herdendorf (1968). Further recent work has been published e.g. by Lewis et al. (1966), Kemp and Lewis (1968), Hobson et al. (1969), Kemp (1969), Lewis (1969), Thomas (1969), Kemp (1971), Rukavina and St. Jacques (1971), Coakley (1972), Lewis et al. (1972), Sly and Lewis (1972), St. Jacques and Rukavina (1973), Kemp and Dell (1974), Kemp et al. (1974), Fritz et al. (1975) and Coakley (1976).

The stratigraphy of Pleistocene onshore deposits adjoining the Lake Erie basin has been studied by many geologists who have employed lithologic, fabric, fossil, and weathering analysis, accompanied by radiocarbon and palynological dating. Informative summaries concerning the studies of onshore deposits have been published by Goldthwait et al. (1965), Chapman and Putnam (1966), Dreimanis (1969), and Dreimanis and Karrow (1972).

2.2 Physical Characteristics of Lake Erie

Lake Erie (Fig. 1) is the second smallest of the five Great Lakes, being only slightly larger than Lake Ontario. Its area is 9,970 square miles (25,821 km^2). Due to its shallow depth, a maximum of 210 ft (64 m), it has the smallest volume of water (110 cu miles = 458 km^3) of any of the Great Lakes.

The principal drainage system is formed by the Detroit River connecting Lake Erie with Lake St. Clair, and the Niagara River and the Welland Canal, which provide the connection with Lake Ontario. The annual inflow from the Detroit River is 178,000 cfs (5,040 m^3/sec); the annual outflow through the Niagara River and the Welland Canal is 194,000 cfs (5,300 m^3/sec) and 8,000 cfs (22.9 m^3/sec) respectively (The International Lake Erie Water Pollution Board and the International Lake Ontario - St. Lawrence River Water Pollution Board, 1969).

Based on bottom topography, the lake is physiographically subdivided into three distinct basins separated by terminal moraines (Figs. 2 and 5). The moraines are till ridges veneered by sand deposits.

The oval-shaped eastern basin occurs east of the boundary delineated by a moraine connecting Long Point, Ontario and Erie, Pennsylvania. This basin is the deepest of the lake. The north shore of the eastern basin is underlain by resistant Lower Devonian limestones of the Onondaga Formation (Fig. 1). The bedrock surface is irregular and hummocky, forming frequent offshore shoals and promontories along the shore, which rise up to 30 ft (9.1 m) above the lake water level. A thin layer of the till deposit, 3- to 10-ft (0.9- to 3.0-m) thick, overlies the bedrock, and is in turn occasionally overlain by stabilized sand dunes. Several shore bluffs, up to 120 ft (36.6m) in height, occur at the western end of Long Point Bay between Port Dover and Turkey Point. The south shore of the eastern basin extends from Buffalo, New York to Erie, Pennsylvania. The shore is formed by a series of wave-eroded bluffs ranging from several feet up to 40 ft (12.2 m) in height. The lower portion of the bluffs consists of a soft Devonian shale with occasional limestone interbeds, which is overlain by a mantle of till. The upper portion of the bluffs is formed by glacio-lacustrine silty and sandy deposits.

The central basin extends from Long Point to Pelée Point on the Ontario shore, and from Erie, Pennsylvania to Lorain, Ohio on the United States shore. The Ontario shore is characterized by three sand spits - Long Point, Point Aux Pins, and Pelee Point, which represent the sites of the present sand accumulation. The overall relief of the shore is similar to that of the eastern basin. Occasional vertical bluffs rise up to 120 ft (36.6 m) above the lake level. The bluffs are composed of two till sheets overlain by glacio-lacustrine silty and sandy deposits. The south shore of the central basin takes for the most part the form of a wave-eroded bluff. Bluff heights generally vary from 0 to 60 ft (18.3 m) between Lorain, Ohio and Cleveland, Ohio; from 60 to 90 ft (18.3 to 27.4 m) between Conneaut and Erie, Pennsylvania. The bedrock surface occurs at about lake level, and it frequently crops out on the lake bottom in the nearshore areas.

The basin west of Pelee Point and Lorain, Ohio has been subdivided by some writers into the western basin proper and the Sandusky basin (e.g. The International Lake Erie Water Pollution Board and the International Lake Ontario-St. Lawrence River Water Pollution Board, 1969); others refer to western Lake Erie by a single term the western basin (e.g. Lewis, 1966; Hobson et al., 1969). The Ontario shore between Pelee Point and Detroit is a low bluff up to 30-ft (9.1-m) high composed of silty and sandy till. The United States shore of the western basin is low and swampy except for a low bluff extending from Sandusky, Ohio to Lorain, Ohio. Numerous streams drain to the basin from west and southwest. The submerged mouths of these streams provide evidence of an earlier low water level in Lake Erie.

2.3 Regional Bedrock Geology

The Lake Erie region is underlain by Paleozoic sedimentary rocks whose lithology and structure predetermined the shape of the Lake Erie basin. The rocks outcropping within the region range in age from Middle Silurian to Mississippian, and are largely composed of limestones, dolomites, and shales with some interlayers of sandstone. The structure of the rock is controlled by two major basins of sediment accumulation; the Appalachian geosynclinal basin to the southeast and the Michigan basin to the northwest of Lake Erie (Fig. 1). Within the area of Lake Erie, the sedimentary strata dip gently to the south in the central and eastern basins, while they dip to the east in the western basin.

The Appalachian basin and the Michigan basin are divided by the Findlay Arch, which trends to the northeast, and a portion of it extends across the western basin of Lake Erie. Two chains of islands occur in zones of resistant Middle Silurian dolomite formations. Pelee Island and Kelleys Island lie within the zone of the Columbus Limestone while Bass Islands and Sister Islands occur within the zone of the Upper Bass Island Dolomite (Hough, 1966). The central and eastern basins have been eroded in soft Devonian shales and siltstones. The bottom topography along the north shore is controlled by gently dipping bedding planes in the resistant Devonian limestones, whereas the steep slopes along the south shore have been cut across the soft strata of shale and siltstone.

2.4 Pleistocene Geology

Following the marine deposition of the Paleozoic era, the sea withdrew and the Lake Erie region apparently remained above sea level till present; the predominant geologic process from Late Paleozoic to Pleistocene was that of erosion. The preglacial drainage pattern in the Great Lakes region was first suggested by Spencer (1894), however due to later glacial scour, as well as paucity of direct geological evidence, the pattern remains conjectural (Hough, 1958). It is nevertheless suggested, on the basis of bedrock topography, that a master valley extended through the region, in the direction of the central line of the present Lake Erie basin.

The stratigraphy of onshore Pleistocene deposits in the Erie basin has been worked out principally on the basis of nonglacial flora and radiocarbon dating, in conjunction with stratigraphic, lithologic and fabric methods of analysis (Goldthwait et al., 1965;

Dreimanis, 1969; Flint, 1971; Dreimanis and Karrow, 1972). A summary of glacial advances and retreats (stadials and interstadials) in the Great Lakes - St. Lawrence region during the last glacial or Wisconsin stage is shown in Fig. 3. Earlier interglacial deposits of Sangamon or pre-Sangamon stages have not been described in the Erie basin, nevertheless it is possible that an interglacial lake existed in the basin during the Sangamon Interglacial (Dreimanis, 1969).

2.4.1 Early and Middle Wisconsin Deposits

The Early Wisconsin (dated from 70,000 to 53,000 years BP) represented a substage of predominantly cold climate with two stadials and one interstadial. The oldest Pleistocene deposit in the Erie basin is the Bradtville Till unit deposited during the Guildwood Stadial (Fig. 3). The Lower Bradtville Till overlies the Devonian bedrock at Port Talbot, Ontario (Fig. 2), and is in turn overlain by the Middle Bradtville glacio-lacustrine clay. The Upper Bradtville Till contains frequent inclusions of lacustrine clay. It is assumed that toward the end of the Early Wisconsin substage glacial advance extended over the entire Erie basin (Dreimanis, 1969).

The Middle Wisconsin (dated from 53,000 to 23,000 years BP) is characterized by a relatively warmer climate of two glacial retreats, the Port Talbot Interstadial and the Plum Point Interstadial, separated by a minor glacial advance, called the Cherrytree Stadial (Dreimanis and Karrow, 1972). During the Port Talbot Interstadial, ice cover retreated from the Erie and Ontario basins. The lowermost unit of this period is Port Talbot

1 green clay, possibly deposited in a reducing environment in a low-level lake (Quigley and Dreimanis, 1972). This deposit is overlain by proglacial varved clays (Glacio-lacustrine I in Fig. 3) and the Port Talbot II shallow water and alluvial deposits. The Cherrytree Stadial is represented in the Port Talbot area by the Southwold Till and the contorted silt and clay (Glacio-lacustrine II). In Pennsylvania, the Cherrytree Stadial is represented by the Titusville Till. During the Plum Point Interstadial the glacial retreat was probably less extensive than during the Port Talbot Interstadial. The beach deposit from the Port Talbot- Plum Point area has been correlated with this interstade (Dreimanis, 1969).

2.4.2 Late Wisconsin Deposits

The Late Wisconsin substage (dated from 23,000 to 8,100 years BP) is subdivided into five glacial stadials (the Nissouri, Port Bruce, Port Huron, Valders, and Driftwood Stadials) separated by four interstadials (the Erie, Mackinaw, Two Creeks, and North Bay Interstadials). The youngest glacial event, the Driftwood Stadial, belongs to the Holocene according to the internationally-agreed Pleistocene-Holocene boundary of 10,000 years. This event produced the Cochrane Till in northern Ontario, and it is not documented in the Erie basin.

The beginning of Late Wisconsin is characterized by a major glacial advance, the Nissouri Stadial, during which the Erie basin was covered by ice for several thousand years. Onshore glacial deposits correlated with this stadial are the Catfish Creek Till in southern Ontario, the Navarre Till in Ohio, and the Kent Till in northwest Pennsylvania. Ice retreated during the subsequent Erie Interstadial from the Erie basin and glacio-lacustrine clays were deposited in a high-level proglacial lake, which stood approximately 200 ft

(60m) above the present Lake Erie level (Dreimanis, 1969). The readvance of ice during the Port Bruce Stadial deposited the fine-grained Port Stanley Till, which forms the bulk of the Lake Erie bluffs along the Ontario shoreline (Goldthwait et al., 1965; Quigley and Tutt, 1968). Offshore lodgment tills encountered in cores from the central and western basin are of the same age (Lewis, 1966).

The subsequent Pleistocene events are characterized by the formation of proglacial lakes during the oscillation and gradual retreat of the Laurentide ice sheet out of the Erie basin. The Late Wisconsin history of lake levels in the Erie basin has been studied among others by Hough (1958), Kunkle (1963), Lewis (1966), Lewis et al. (1966), Lewis (1969) and Fritz et al. (1975). The sequence of Late Wisconsin lake stages is shown in Table 1 and in Figs. 3 and 4.

The first well-documented Pleistocene lake was formed at the onset of the Mackinaw Interstadial about 14,000 years BP when the Erie ice lobe retreated from Michigan, Indiana, and Ohio. This lake stage is known as Lake Maumee I (Table 1), which stood at the highest elevation of 800 ft (243.9 m) a.s.l. The water of Lake Maumee was ponded within a low area between the ice margin and the Fort Wayne Moraine in Indiana (Fig. 4). The outlet channel of the lake was westward over the Fort Wayne Moraine, and the lake discharged via the Wabash River to the Mississippi drainage system. According to Hough (1958), the further retreat of the ice front lowered the lake level to Maumee II at about elevation 760 ft (231.7 m), and the lake waters drained westward via the Grand River valley to the Michigan basin. The ice front then readvanced and raised the level of the lake to Maumee III at about elevation 790 ft (240.8 m). Hough (1958) suggests that the discharge of this

Table 1. Late Wisconsin lakes in the Erie Basin (modified after Lewis, 1966, and Dreimanis and Karrow, 197

Age C^{14} Years	Glacial Event	Lake Stage	Elevation Feet	a.s.l. Meters	Outlet	D m
		Erie	573.2*	174.4*	Niagara River	S
	Driftwood Stadial	Holocene				S
10,000	North Bay Interstadial Valders Stadial	Pleistocene (Late Wisconsin)				
11,500	Two Creeks Interstadial	Early Erie	470±	143±	Niagara River	S S
12,500		Early Algonquin	605	184.5	Des Plaines R.	B
		Lundy	620	189.0	Des Plaines R.	G
		Grassmere	640	195.1	Michigan Basin	N
		Warren III	675	205.8	Grand River	th
		Wayne	658	200.5	Grand River**	W
	Port Huron Stadial	Warren II	680	207.2	Grand River	
		Warren I	690	210.0	Grand River	A
		Whittlesey	738	225.0	Grand River	
13,000		Ypsilanti	543?	165?	Niagara River?	Be
		Arkona III	695	211.9	Grand River	G
	Mackinaw Interstadial	Arkona II	700	213.2	Grand River	
13,300		Arkona I	710	216.3	Grand River	
		Maumee III	790	240.8	Wabash River	M
		Maumee II	760	231.7	Grand River	St
		Maumee I	800	243.9	Wabash River	M
14,000 - 15,000	Port Bruce Stadial					P L

* International Great Lakes Datum (1955)

** Or possible eastward drainage to the Ontario basin

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Basin (modified after Lewis, 1966, and Dreimanis and Karrow, 1972)

e ge	Elevation Feet	a.s.l. Meters	Outlet	Deposition (Symbols below refer to the map of Lake Erie bottom sediments, Fig. 5)
e	573.2*	174.4*	Niagara River	Sand beach and nearshore deposits (S)
ocene				Surficial Recent mud (SM and M)
istocene te Wisconsin)				
ly e	470±	143±	Niagara River	Sand beach and nearshore deposits (S) Surficial Recent mud (SM and M)
ly Algonquin	605	184.5	Des Plaines R.	Beach and nearshore deposits
ndy	620	189.0	Des Plaines R.	Glacio-lacustrine clays (G1)
assmere	640	195.1	Michigan Basin	Norfolk Moraine and some offshore tills in
rren III	675	205.8	Grand River	the eastern basin (G1)
yne	658	200.5	Grand River**	Wentworth Till (Paris and Galt Moraines)
rren II	680	207.2	Grand River	
rren I	690	210.0	Grand River	Ashtabula Till
ittlesey	738	225.0	Grand River	
silanti	543?	165?	Niagara River?	Beach and nearshore deposits
kona III	695	211.9	Grand River	Glacio-lacustrine clays (G1)
kona II	700	213.2	Grand River	
kona I	710	216.3	Grand River	
umee III	790	240.8	Wabash River	Maitland, Erieau, Pelee Moraines (G1)
umee II	760	231.7	Grand River	St. Thomas, Ingersoll, Blenheim
umee I	800	243.9	Wabash River	Moraines
				Port Stanley Till, Hiram Till Lake Erie offshore lodgment till (G1)

5) ,

)ntario basin

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latest stage of Lake Maumee was again via the Fort Wayne outlet.

The next lake stage, Lake Arkona, occurred during the glacial retreat from the Lake Border Moraine. According to Hough (1958), the meltwater flooded the entire Erie basin and the southern portion of the Huron basin, forming a single lake. The lake level stood at elevations from 710 ft (216.3 m) a.s.l. (Arkona I) to 695 ft (211.9 m) a.s.l. (Arkona III).

The possibility of a low lake level in the Erie basin at the end of the Mackinaw Interstadial was suggested by Hough (1958). Kunkle (1963) presented evidence for this low-level stage named by him Lake Ypsilanti. The evidence is based on the occurrence of fluvial deposits underlying the bed of the Huron River, which Kunkle dates as post-Port Bruce but preceding the later lake stages. According to Kunkle's estimate, the lake level was at least 30 ft (9.1 m) below the present Lake Erie level.

The ice retreat during the Mackinaw Interstadial produced end moraines of Port Stanley Till along the north shore of present Lake Erie, such as the Blenheim, St. Thomas, and Ingersoll Moraines (Goldthwait et al., 1965). The Pelee, Erieau, and Port Maitland Moraines (Fig. 5) were probably formed during the Lake Maumee - Lake Ypsilanti stages (Sly and Lewis, 1972).

The Lake Ypsilanti stage was terminated by the readvance of the Port Huron Stadial about 13,000 years BP (Sly and Lewis, 1972). The ice eroded the eastern basin and formed the Norfolk Moraine (Figures 4 and 5). The borehole evidence indicates that some tills in the eastern basin were deposited during the Port Huron advance (Lewis, 1966). The marginal glacial Lake Whittlesey stood at an elevation of 738 ft (225.0 m) a.s.l. The lake occupied the central and western basinsof present Lake Erie and extended further to the west and southwest. Drainage from Lake Whittlesey was westward through the Huron and Michigan basins as during the Lake Arkona stage. The youngest onshore glacial deposits found in the Erie basin arethe sandy Wentworth Till occurring in the Paris and Galt Moraines, and the Ashtabula Till occurring along the present Lake Erie shore in Ohio. These tills have been correlated with the Port Huron Stadial.

The lake level in the Erie basin was lowered during the subsequent retreat of the ice from the Port Huron maximum. The glacial retreat enabled the opening of new outlet channels to the west through the Huron basin. Lake waters of Warren I and Warren II stood initially at elevations from 690 ft (210.0 m) to 680 ft (207.2 m) and drained via the Huron basin. Lake waters of Warren I and Warren II stood initially at elevations from 690 ft (210.0 m) to 680 ft (207.2 m) and drained via the Huron basin. Hough (1958) suggested an occurrence of another low-level stage at this time with a drainage to the Ontario basin via the St. David gorge. This extreme low position was followed by a minor glacial readvance and the water surface was raised to elevation 658 ft (200.5 m) of Lake Wayne and then to elevation 675 ft (205.8 m) of Lake Warren III. This sequence is supported by the evidence of submergence and re-working of the Lake Wayne beach, and the evidence of a low-level stage in the Michigan basin (Hough, 1958). The discharge of Lake Warren III was again westward through the Huron basin outlet.

Following the Warren III stage, the ice retreated, and lake levels gradually fell through the Lake Grassmere stage (640 ft = 195.1 m), the Lake Lundy stage (620 ft = 189.0m), and the Early Algonquin stage (605 ft = 184.5 m). Leverett and Taylor (1915) suggested eastward drainage paths for all three lakes, however their view was disputed by Hough (1958) whose studies indicated northwestward discharge through the Huron basin.

The deposition of Lake Erie offshore glacio-lacustrine clays is estimated to have occurred between 13,300 and 12,500 years BP, and thus this unit is tentatively correlated with the Arkona I - Early Algonquin lake stages (Lewis et al., 1972).

During another major ice retreat, corresponding to the Two Creeks Interstadial of the Michigan basin, the Erie basin was freed of glacial cover. Since then no subsequent glaciation occurred in this area. The ice front retreated to the northeast, and about 12,600 years BP (Sly and Lewis, 1972) freed the Mohawk-Hudson valley outlet. This event allowed drainage of the Erie basin through the Niagara River and gave rise to the formation of Early Lake Erie. There is much evidence indicating that Early Lake Erie was below the present lake level from its beginning to about 4,000 years BP. Since 12,600 years BP the water level in the Erie basin has been controlled by the elevation of a dolomitic bedrock sill at the head of the Niagara River at Buffalo, N.Y. The rise, due to an isostatic rebound of the Buffalo sill, was initially quite rapid. Radiocarbon dates on the organic material indicate that from 12,600 to 8,000 years BP the Buffalo sill rose from about 125 ft to 50 ft (38.1 m to 15.2 m) below the present lake level. From 8,000 to 5,000 years BP lake level continued to rise relatively very slowly. Another steep rise in water level, in the order of 30 ft (9.1 m), occurred from 5,000 to 3,800 years BP as a consequence of the transfer of Huron basin drainage from the North Bay outlet to the St. Clair River outlet during Nipissing events (Lewis, 1969). Subsequent slow but progressive rise in lake level to the present elevation of 573.2 ft (174.7 m) reflects the decelerating rate of the isostatic rebound at the Buffalo sill outlet.

Concurrently with rising water level in the lake basin, fine-grained sediments (the surficial Recent mud) have begun to accumulate atop the Pleistocene-Recent unconformity in the shallow areas of the western and central basins, while conformable deposition of these sediments hase been taking place in the deeper areas of the central and eastern basins.

2.5 Unconsolidated Bottom Sediments

Thus on the basis of previous published work (Lewis, 1966; Sly and Lewis, 1972), the unconsolidated deposits in Lake Erie can be subdivided into three principal units. These are:

1) Pleistocene glacial and glacio-lacustrine deposits (symbol G1 in Fig. 5)

2) Beach and nearshore sand deposits (symbol S in Fig. 5)

3) Recent surficial mud (symbols SM and M in Fig. 5)

The main characteristics of the units are shown in Table 2.

1) Pleistocene glacial and glacio-lacustrine deposits - The unit is widely exposed on the lake bottom, particularly in the nearshore zones. It comprises a glacial clayey till and a glacio-lacustrine clay.

The till forms four end moraines as shown in Fig. 5, and it probably covers most of the bedrock in basin areas. In the nearshore zones, the bedrock crops out discontinuously as a result of the till erosion. The coarsest till occurs in the Erieau Moraine, the finest till in the Norfolk Moraine (Table 2). The vertical and lateral extent of the till and its stratigraphic subdivision, particularly in the basin areas, is not very well known. The topography of the till surface in the western basin has been mapped by Hobson et al.(1969), however on the basis of the seismic survey it was not possible to distinguish everywhere the till from the dense glacio-lacustrine deposit, and thus expand interpretations from bottom sampling and offshore corings. In the eastern basin, the till and the glacio-lacustrine deposit have very similar particle size distribution (Table 2) and both sediments have occasionally similar structure characterized by the absence of layering (Lewis, 1966).

The glacio-lacustrine deposit which overlies the till is often laminated, occasionally cross-bedded, and in general contains less gravel-sized material than the till. It is characterized by reddish colour in the eastern half of the lake (derived from the red shale of the Queenston formation) and by greyish brown colour in the western half of the lake (derived from grey carbonates and shales). The sediment is predominantly silty clay with occasional silt and gravel inclusions caused by ice rafting.

The gravel-sized material of the till and the glacio-lacustrine deposit consists mostly of carbonate and shale pebbles together with smaller amounts of igneous-metamorphic pebbles. Sand-sized material contains mostly quartz, carbonate and feldspar grains. The predominant minerals of clay-sized matrix are well-crystallized illite and Fe-rich chlorite (Lewis, 1966, and this study, Section 5.14) Vermiculite, smectite, interlayered minerals and possibly kaolinite occur in minor percentages.

The Pleistocene deposits contain highly variable contents of carbonates. Lewis (1966) determined that the uppermost horizon of the glacial and glacio-lacustrine deposits

Table 2. Summarized characteristics of Lake Erie offshore sediments. The areal extent of the units is shown in Fig. 5.

Sediment Type	Symbol (Fig.5)	Stratigraphic Correlation	Particle Size * % Sand and Gravel .062 mm	% Silt ** .062–.004 mm	% Clay ** .004mm	** % Calcite	% Do
Glacial Till	GI	Port Huron Stadial	3.2	33.2	63.6	2 - 22	5 -
			21.7	37.0	41.3	3 - 15	3 -
			22.9	34.0	43.1		
			14.9	33.1	52.0	6 - 11	7 -
		Port Bruce Stadial	14.1	39.1	46.8	5 - 20	4 -
			28.0	33.9	38.1	5 - 15	7 -
Glacio-lacustrine Deposit	GI	Early Algonquin	2.3	27.2	70.5	2 - 22	5 -
			3.1	35.8	61.1	3 - 15	3 -
			0.9	21.5	77.6	5 - 20	4
			0.6	14.8	84.6		
		Arkona	6.8	38.8	54.4	5 - 15	7 -
Sand (Lag, Beach, and Fluvial Deposits)	S	Pleistocene	13	68	19		
		and/or	70	14	16		
		Recent					
Recent Surficial Mud	SM	Erie	5	30 - 50	50	Traces or Absent	5 -
			0 - 10	30 - 50	40 - 70		
			1.8	32.8	65.4		
		Early Erie	18.9	58.2	22.9	Traces or Absent	Tr
			4.2	58.9	36.9	0 - 5	5 -

* The Wentworth classification used throughout the table.

** Average or range values are shown as available.

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ake Erie offshore sediments. The areal extent of the units is shown

hic n	Particle Size * % Sand and Gravel .062 mm	% Silt ** .062-.004 mm	% Clay ** .004mm	** % Calcite	** % Dolomite	% Total ** Carbon	% ** Organic Carbon	Data Source
	3.2	33.2	63.6	2 - 22	5 - 10			1
	21.7	37.0	41.3	3 - 15	3 - 15			2
	22.9	34.0	43.1			3.46+	1.23+	3
	14.9	33.1	52.0	6 - 11	7 - 8			4
	14.1	39.1	46.8	5 - 20	4 - 13			5
	28.0	33.9	38.1	5 - 15	7 - 15	3.11+	0.63+	6
	2.3	27.2	70.5	2 - 22	5 - 10			7
	3.1	35.8	61.1	3 - 15	3 - 12			8
	0.9	21.5	77.6	5 - 20	4 - 13			9
	0.6	14.8	84.6			3.41+	0.78+	10
	6.8	38.8	54.4	5 - 15	7 - 15			11
e	13	68	19			2.58	1.38	12
	70	14	16			1.56	0.46	13
	5	30 - 50	50	Traces or Absent	5 - 8	3.09+	2.09+	14
	0 - 10	30 - 50	40 - 70		5	3.29+	2.79+	15
	1.8	32.8	65.4			2.51+	1.25+	16
	18.9	58.2	22.9	Traces or Absent	Traces	3.27+	2.47+	17
	4.2	58.9	36.9	0 - 5	5 - 10	3.27+	2.47+	18

ughout the table.
available.

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Table 2 (continued).

Data Source	Lake Area	No. of Analyses	Reference
1	Norfolk Moraine	8	Lewis, 1966
2	Erieau Moraine	14	Lewis, 1966
3	Erieau Moraine	9	This study (Figs. 11.2 and 11.5)
3+	Erieau Moraine	6	This study (Figs. 9.1.1 and 9.1.3)
4	Pelee Moraine	6	Lewis, 1966
5	Central Basin	11	Lewis, 1966
6	Western Basin	2	Lewis, 1966
6+	Pelee Moraine	10	Coakley, Winter, and Zeman, 1975
7	Norfolk Moraine	6	Lewis, 1966
8	Erieau Moraine	7	Lewis, 1966
9	Central Basin	7	Lewis, 1966
10*	Central Basin	11	This study (Fig. 11.4)
10+	Central Basin	2	Mudroch and Zeman, 1975
11	Western Basin	7	Lewis, 1966
12	Lake Erie silts	16	Kemp, 1971
13	Lake Erie sands	14	Kemp, 1971
14	Eastern Basin		Lewis, 1966
14+	Eastern Basin, surface sediment	10	Kemp, 1971
15	Central Basin		Lewis, 1966
15+	Central Basin, surface sediment	25	Kemp, 1971
16	Central Basin	18	This study (Figs. 11.1 and 11.3)
16+	Central Basin	16	This study (Figs. 9.1.1 and 9.1.3)
17	Sandusky Basin	3	Lewis, 1966
18	Western Basin	5	Lewis, 1966
18+	Western Basin, surface sediment	24	Kemp, 1971

contains up to 22 per cent of calcite and up to 15 per cent of dolomite (Table 2). The highest calcite/dolomite ratios were obtained for samples from the eastern and central basins. The highest values of both calcite and dolomite were measured in samples recovered from the nearshore areas in the Ontario sector of the lake, which is underlain by Middle and Lower Devonian limestones and dolomites (Fig. 1).

2) Sand deposits – The sands occur primarily as modern beach and nearshore deposits. Sources of these deposits are eroding shore bluffs, the in situ subaqueous erosion of glacial deposits, and the discharge of sandy material from streams. Long Point, Point aux Pins, Pelee Point, and Presque Isle (Fig. 2) are sand spits in the area of major recent sand accumulation. Submerged sand deposits are also known to occur atop the Norfolk and Pelee Moraines (Sly and Lewis, 1972) where they apparently represent beach deposits of low-level Early Lake Erie. Other submerged sand deposits in the western basin are likely of the same origin. Along the Ontario shoreline, nearshore sand-sized deposits are typically fine to medium well-sorted sands (Rukavina and St. Jacques, 1971; Coakley, 1972; St. Jacques and Rukavina, 1973; Coakley, Winter and Zeman, 1975). On the average, sand deposits become finer in an offshore direction and show a decrease in sorting (an increase in standard deviation). This pattern, however, is not observed everywhere, and local facies exist with no apparent relationship between modal size and depth.

Quartz, carbonates, and feldspars are the main mineral constituents. Heavy mineral suites contain hornblende, hypersthene, augite, garnet, rutile, zircon, apatite, magnetite, and ilmenite (Herdendorf, 1968; Coakley, 1972). In contrast with the textural maturity, i.e. the good sorting, the presence of metastable minerals, such as hornblende, hypersthene, and augite, indicates that the sands of Lake Erie are mineralogically quite immature (Hough, 1958).

3) Surficial Recent mud - The unit occurs primarily in the basin areas of the lake and it covers approximately 60 per cent of the lake bottom. Typically, the mud is very soft to soft dark grey silty clay in the central basin, and silty clay to clayey silt in the eastern and western basins. The mean particle diameter generally decreases in the offshore direction, ranging from 6 to 10 ø (0.016 to 0.001 mm) in the eastern basin, 6 to 9 ø (0.016 to 0.002 mm) in the central basin, and 6 to 8 ø (0.016 to 0.004 mm) in the western basin (The International Lake Erie Water Pollution Board and the International Lake Ontario-St. Lawrence River Water Pollution Board, 1969). In several locations the unit was observed to become finer with depth (Lewis, 1966; this study, Fig. 11.1, Fig. 11.3, and Table 12; Coakley, Winter and Zeman, 1975). The vertical trend observed for the entire lake may reflect an increasingly energetic bottom scouring and the consequent winnowing of fines with rising lake levels during the postglacial history of Lake Erie.

The deposit contains occasional black specks or laminae, which are believed to be caused by bacterial reduction of sulphates or authigenic or early diagenetic formation of sulphides (Sly and Lewis, 1972). The black colour rapidly disappears after exposure to air and the mud oxidizes to brown or brownish grey colour. A thin oxidized or partially oxidized crust up to several centimeters in thickness occurs immediately below the lake bottom. In the topstratum, to the depth of burial of 6 cm, the Eh varies from +0.288 to -0.147 volts with the most negative potential occurring at 5 cm, and the pH values range from 6.9 to 8.3 (Kemp and Lewis, 1968). In general, the increase in pH with depth parallels the fall in Eh values (Kemp and Lewis, 1968). In deeper portions of the post-glacial sedimentary column the Eh is constant with depth remaining at about zero volts (Kemp, 1969).

The top centimeter of the sediment contains on the average 2 to 3 per cent of organic carbon (Kemp, 1969; this study, Table 2). The highest concentration of organic carbon occurs in buried peat deposits from the western basin (Kemp, 1969). The concentration of organic carbon with depth is known to decrease with depth to about 1 per cent. The mud in the central areas of the basins is generally richer in organic matter than the mud that occurs in the nearshore areas. A general inverse relationship exists between the organic carbon and the carbonate carbon (Kemp, 1969). In comparison with the Pleistocene bottom deposits, the surficial Recent mud has generally a lower content of carbonates, containing near the water-sediment interface traces of calcite and up to 8 per cent of dolomite (Table 2). In all three principal basins, carbonate content increases with depth (Lewis, 1966; Kemp, 1969). In the central basin, the carbonate content increases to 15 to 25 per cent in the lower portion of the profile (Table 12).

Illite and Fe-rich chlorite are the predominant clay minerals of the unit. Vermiculite, smectite, and interlayered minerals occur in minor amounts. Presence of kaolinite in minor amounts is likely, but it has not been satisfactorily demonstrated by X-ray diffraction analyses (Lewis, 1966; this study, Section 5.14). In comparison with the Pleistocene sediments, clay minerals are more weathered and they contain higher percentages of amorphous material.

CHAPTER 3

FIELD WORK

3.1 Sampling

During the 1972 offshore investigation, seven boreholes were put down in an area approximately 20 sq miles (32 km^2) large (Figs. 1 and 2), located to the south and the southeast of Erieau, Ont. (Plate 1). The lake bottom in the investigated area is generally flat, with slopes of 0.5 degree or less dipping toward the southeast; i.e. toward the central portion of the basin. The water depth ranges from about 75 ft (22.9 m) in the northwest end to about 85 ft (25.9 m) in the southeast end of the area.

All sites were cored from the drillship "Nordrill" chartered by Underwater Gas Developers Limited, a drilling subsidairy of the Consumers' Gas Company. The "Nordrill" is a modified lake freighter (Plates 2 and 3) 270 ft (82 m) long and 40 ft (12.2 m) wide, equipped with a National T-20 drilling rig, located in the central portion of the ship. The exploratory drilling for natural gas is carried out through a 15-ft (4.6-m) diameter well in the ship surrounded by a turntable. On the drilling site, the turntable is anchored by four anchors (Plate 4), and the ship has then freedom to revolve about the central well. This arrangement permits the bow of the ship to be kept facing the wind and waves during stormy periods. The manœuvering of the ship about the central well is achieved by means of two outboard engines. The ship is not presently self-propelled, and has to be towed by service tugboats, which also help to raise and set the anchors on a drilling site.

The location of the boreholes was predetermined by the location of sites selected for natural gas exploration. The geotechnical coring always preceded the gas exploratory drilling, and on the average was spread over a period of about 48 hours for each borehole.

Preliminary information on the bottom sediments within the project area (Lewis, 1966) indicated the predominance of glacial and recent fine-grained cohesive sediments. All samplers employed were therefore equipped with thin-wall cutters suitable for geotechnical coring. Furthermore, the use of the drillship capable of a fixed location allowed an adaptation of an onshore drilling system with a drill string connection between the water surface and the bottom of the borehole. The onshore method was considered useful for repeated-entry sampling, particularly at greater depths, however, it would not have provided sufficient amount of samples within a 48-hour period allocated for geotechnical coring. It was therefore decided to use oceanographic single-entry samplers to obtain long continous samples of the bottom sediments.

Five types of thin-wall samplers were used for sampling of offshore fine-grained sediments with various degrees of success. The main features of these samplers are shown in Table 3 and Figs. 8.1 to 8.5. Their operating principles are described below in Appendix A. The state-of-the-art techniques of offshore sampling are briefly summarized in Appendix B.

3.2 Evaluation of Sampling Techniques

Several considerations, taken into account for the evaluation of the five samplers and their operation, are listed below to provide a frame of reference for systematic comparison:

a) Compliance of a sampler design with existing criteria for thin-wall tube samplers (Table 4)

b) Actual quality of recovered cores as documented by X-radiographs and shear strength measurements

c) Capability of a sampler to take cores in different sediment types

d) Time required for sampling compared to the length of core recovered

e) Prevention of sample loss during retrieval

f) Ease of sampling operation, the sturdiness of a sampler

g) Type of sample containment used for transportation and storage of samples

3.2.1 The Alpine Free-falling Piston Sampler (1200 lb)

The Alpine sampler (Appendix A.1, Fig. 8.1) was used on all borehole sites, and continuous samples up to almost 60 ft (18.3 m) long were recovered. The obvious advantage of the sampler is its ability to sample a long column of sediment in a very short time. The ratio C_o exceeds appreciably the recommended value in Table 4, thus indicating that the sampler is subjected to excessive outside friction which impedes penetration. More importantly, a very high value of the ratio C_s reveals that cores are likely to be disturbed by the build-up of inside skin friction. A relatively small diameter of core (2.25 in=57 mm) also contributes to core disturbance.

The most serious deficiency of the sampling technique appeared to be the

Table 3. Characteristics of thin-wall samplers used during the 1972 borehole investigation

Identification	D_s inches	D_t inches	D_e inches	D_w inches	L_s feet
Alpine Free-falling Piston Sampler (1200 lbs.)	2.25	3.0	2.20	2.32	Up to 60
Benthos Gravity Sampler	2.50	2.75	2.50	2.75	Up to 6
Thin-wall Open Drive Sampler (Shelby)	4.75	5.0	4.70	5.0	1.5 and 5
Christensen Thin-wall Sleeve Sampler	3.75	4.75	3.69	3.94	5 and 30
Osterberg Fixed-piston Sampler	2.75	3.0	2.75	3.0	2

Definitions (symbols as used by Ling, 1972)

D_s = inside diameter of barrel and diameter of sediment core

D_t = outside diameter of barrel

D_e = inside diameter of cutter

D_w = outside diameter of cutter

L_s = sampling length

C_i = i (

C_o = c (

C_a = c (s v

C_s = r t b

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mplers used during the 1972 borehole investigation

D_t inches	D_e inches	D_w inches	L_s feet	C_i	C_o	C_a	C_s
3.0	2.20	2.32	Up to 60	2.27	22.6	11.2	320.0
2.75	2.50	2.75	Up to 6	0	0	21.0	28.8
5.0	4.70	5.0	1.5 and 5	1.06	0	13.2	3.8 and 12.6
4.75	3.69	3.94	5 and 30	1.63	17.0	14.0	13.2 and 96.0
3.0	2.75	3.0	2	0	0	19.0	8.7

)

meter of sediment core

C_i = inside clearance ratio (controls inside friction) = $\frac{D_s - D_e}{D_e} \times 100$

C_o = outside clearance ratio (controls outside friction) = $\frac{D_w - D_t}{D_t} \times 100$

C_a = area or volume ratio (volume of displaced sediment divided by volume of sample) = $\frac{D_w^2 - D_e^2}{D_e^2} \times 100$

C_s = ratio of sampling length to inside diameter of barrel = $\frac{L_s}{D_s}$

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Table 4. Criteria for thin-wall tube samplers

Characteristic	Criteria	Recommended for	Refere
Inside clearance ratio,[1] C_i	0 - 0.5 0.75 - 1.5 1.0	short corers long corers 2" to 5" Shelby tubes	Rosfelde (1967) ASTM S D 1587
Outside clearance ratio,[1] C_o	0 <2 to 3 [2]	cohesionless sediments cohesive sediments	Rosfelde (1967)
Area ratio,[1] C_a	13 <10 [3]	2" Shelby tubes all sediments	Terzagh (1967) Rosfelde (1967)
Inside diameter of barrel, D_s	>2" (50 mm) >3" (75 mm)	undisturbed sediment sampling samples obtained by pushing	Ling (19
Ratio of safe sampling length to inside diameter of barrel,[1] C_s	<10 <20	dense to loose cohesionless sediments stiff to very soft cohesive sediments	Rosfelde (1967)
Angle of cutter,	<10°, preferably <5° [4]	all sediments	Rosfelde (1967)

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lers

	Recommended for	Reference
	short corers long corers 2" to 5" Shelby tubes	Rosfelder and Marshall (1967) ASTM Standard D 1587
2	cohesionless sediments cohesive sediments	Rosfelder and Marshall (1967)
3	2" Shelby tubes all sediments	Terzaghi and Peck (1967) Rosfelder and Marshall (1967)
mm) mm)	undisturbed sediment sampling samples obtained by pushing	Ling (1972)
	dense to loose cohesionless sediments stiff to very soft cohesive sediments	Rosfelder and Marshall (1967)
4 $<5^{\circ}$	all sediments	Rosfelder and Marshall (1967)

Notes

[1] Symbols defined in Table 3

[2] Unless taper of cutter very small

[3] May be >10 with a piston sampler or a sharp cutter

[4] Except at cutting edge where $\alpha = 20^{\circ}$ to 30° allowed to prevent damage of cutter (Ling, 1972)

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considerable compaction of cores, the amount of which is indicated by data given in Table 5. X-radiographs furnished evidence of differential stretching and compression of cores due to irregularly distributed inside skin friction. The plugging of the cutter with a harder sediment material occasionally prevented full recovery. The effect of core size upon core disturbance can be estimated from data given in Table 6.

Although the sampler was found to be the most suitable for rapid coring of the soft Recent sediment, it was unable to penetrate a heavily overconsolidated crust occurring in the upper portion of the Pleistocene sediment.

The sampling operation averaged 30 to 45 minutes per core, however up to 3 hours were required for the assembly of the sampler. The dismantling of the sampler was likewise time-consuming. No core loss or sliding was observed during the process of retrieval. The triggering mechanism and the piston were found to function satisfactorily throughout the borehole investigation.

Plastic liners provided suitable containment for transportation and storage of samples.

Information on bottom composition is a prerequisite for a successful coring operation. The sampler can be bent easily or damaged if coring of hard bottom is attempted.

3.2.2 The Benthos Gravity Sampler

The sampler (Appendix A.2, Fig. 8.2) was found suitable for the sampling of fine-grained surficial sediments only. Previous penetration tests of the sampler in sandy sediments met with little success (Sly, 1969). In comparison with the Alpine piston sampler, the Benthos sampler generally provided better quality of cores due to its shorter length

Table 5. Compaction of the Alpine cores

Borehole No.	13156	13160	13161	13163
Observed Penetration, ft	54.7	20.0	20.0	22.1
Length of Recovered Core, ft	42.4	16.5	15.6	12.2
Percentage Core Compaction, ΔC	22.5	17.5	22.0	44.8

$$\Delta C = \frac{\text{Observed Penetration} - \text{Core Length}}{\text{Observed Penetration}} \times 100\%$$

Table 6. Comparison of undrained shear strength values (psf) from the same depth for the Alpine cores and the Christensen cores

Borehole No.	Depth Below Lake Bottom Level, ft	Sediment Type	Alpine Core	Christensen Core	Percentage Shear Strength Reduction (Δc_u)
13156	42	Surficial Recent Mud	62	290	78.6
13161	12	Surficial Recent Mud	43	119	63.9
13161	19	Glacio- lacustrine Deposit	1690	2185	22.7
13163	18	Surficial Recent Mud	40	135	70.4
13163	22	Glacio- lacustrine Deposit	1270	1065	-19.2
13194	36	Surficial Recent Mud	120	145	17.2

$$\Delta c_u = \frac{c_u\,(\text{Christensen}) - c_u\,(\text{Alpine})}{c_u\,(\text{Christensen})} \times 100\%$$

and larger inside diameter (Table 3). The stainless steel cutter was not required in soft muddy sediments, and therefore the area ratio, C_a, exceeded the recommended value (Table 4). The compaction of the cores was not measured, however, published data (Sly, 1969) indicate that the compaction may range from 16 to 20 per cent in the most compressible lake bottom sediments. The valve system is skilfully designed since it allows free flow of water through the sampler during descent, and provides efficient sealing of the sampling tube during recovery. The sampling operation was rapid and easy. During shipment and storage cores were contained in plastic liners.

3.2.3 The Thin-wall Open Drive Sampler (Shelby)

The sampler (Appendix A.3, Fig. 8.3) was used only for the sampling of the first borehole. The Shelby sampler, though meeting all the criteria shown in Table 4 and in spite of its widespread use in onshore coring, does not seem to be particularly suitable for offshore coring projects. The sediments with very high natural water content have the tendency to flow into and up the casing during penetration, and the sampler consequently accumulates disturbed sediment material from the upper horizons at the top of the sample. The lower end of the sample is also disturbed during recovery, as it is softened by ambient water. The sample is further subjected to excess hydrostatic pressure when the sampler is above water, which occasionally results in partial or total loss of the sample. Other disadvantages of the Shelby sampler is its short length, relatively high cost of the steel tubing, and considerable weight of the sample enclosed in the large-diameter steel tubing. The sampling technique was found to be simple and only few basic rules for optimum sample recovery had to be followed.

3.2.4 The Christensen Thin-wall Sleeve Sampler

The sampler (Appendix A.4, Fig. 8.4) proved to be superior to all other samplers tested, notwithstanding that it does not meet all criteria listed in Table 4. The sampler provided generally samples of good quality, and up to 20-ft (6.1-m) long samples were recovered within a short span of time. Samples taken with a 30 ft (9.2-m) long barrel were slightly more disturbed than those taken with a 5-ft (1.5-m) long barrel. The relatively large diameter of the core (3.75 in = 9.53 cm), reduced significantly the core disturbance of soft sediments (Table 6).

The sampler has to be used with a standard onshore drilling rig, and requires therefore a fixed jack-up platform or an anchored drill ship. The sampler was capable of penetrating all three sediment types but it met refusal in the till when the bearing capacity of the sediment exceeded the weight of the full sampler and drill rods. The rig was not equipped with a mechanical or hydraulic device to exert an additional driving force.

The ratio C_o for the sampler exceeds the limits shown in Table 4, and it appears therefore that a deeper penetration was impeded by the build-up of outside skin friction.

The sampler suffers from the disadvantages of open-drive samplers, and usually both ends of the sample are disturbed in the manner described in Section 3.2.3. The tendency for the sample disturbance characteristic of open-drive samplers was noted many times throughout the borehole investigation, and can be readily noticed as a reduction in shear strength values on the geotechnical summary plots (Figs. 9.1 to 9.7).

The operation of the sampler required no great labour of effort. The sampling technique resembled that of the Shelby sampler.

3.2.5 The Osterberg Fixed-Piston Sampler

The sampler (Appendix A.5, Fig. 8.5) was found suitable for the sampling of soft lacustrine sediments, and recovered samples were generally of very good quality. The principal disadvantages of the sampler are the relatively short length of core (Table 3), occasional sample loss, and more complicated operation compared to open-drive samplers.

3.2.6 Summary

The conclusion drawn from the performance of five different samplers described above is that each sampling method resulted in a certain disturbance characteristic of the type of sampler employed.

Of the five sampling methods used, the samplers causing the least disturbance were, in order; the Osterberg piston sampler, the Benthos sampler, the Christensen sampler, the Shelby sampler, and the Alpine piston sampler.

For the purpose of the investigation, which was carried out under time constraints, long more disturbed cores were preferred to short less disturbed ones. In view of this decision, the most satisfactory results were obtained with the Christensen sampler. The sampler was capable of taking long cores with little disturbance in all sediment types occurring within the project area. The cores obtained with the Alpine piston sampler were disturbed appreciably as a result of the artifical compacting and the relatively small inside diameter of the sampler. The effect of sampler size upon the amount of disturbance was noted (Table 6).

The Benthos sampler was found to work best in very soft lacustrine sediments but the short length of the sampler limited its use during the project. The Osterberg sampler and the Shelby sampler provided in general cores of adequate quality, however short cores and time-consuming sampling precluded their wider use during the project. In addition, these samplers proved to be least suitable for sampling of very soft surficial sediments in which cores were frequently lost.

The sampling of very soft surficial sediments required the use of core retainers, otherwise even cores obtained with piston samplers (the Alpine and Osterberg samplers) were occasionally washed out during retrieval.

Plastic inside liners, used with the Alpine, Benthos and Christensen samplers, greatly facilitated the shipment and subsequent laboratory subsampling of the cores. The cores contained in the steel sampling tubes had to be either extruded or cut with a power saw to shorter sections. Both of these procedures were time-consuming and resulted in further core disturbance. Furthermore, sediments with high moisture content were found to oxidize rapidly inside the steel tubes. The decomposition of organic matter and the presence of water caused rapid corrosion of the steel tubes. Another disadvantage of the steel tubes was encountered during the X-raying of the cores. Compared to plastic liners, the penetration of steel tubes required higher voltage and amperage of X-rays, which resulted in the loss of details in radiographs. The use of plastic liners appears therefore highly desirable for offshore coring.

CHAPTER 4

LABORATORY PROCEDURES

4.1 Basic Geotechnical Tests (at the Canada Centre for Inland Waters)

Following the field sampling and coring work on each borehole site, 3- to 5- ft (0.9- to 1.5-m) long samples were transferred from the drillship to Erieau, Ont. in the service tugboat, and then shipped in a thermally insulated box to the CCIW in Burlington, Ont. for basic geotechnical testing. The samples were stored in a controlled temperature room at 4°C in order to inhibit the decomposition of organic matter and possible swelling due to the formation of gases. All samples were X-rayed prior to testing to provide information on sample disturbance, depositional contacts, macrostructure, and to help plan the subsequent laboratory programme. The use of the radiographs as a valuable aid in the study of lacustrine sediments is discussed below in Appendix B. Typically, the samples were further cut to 1-ft (0.3-m) long sections, and data were measured and recorded at this interval. In case of the Alpine cores, the average sample length exceeds 1 ft (0.3m), as the logs had to be "stretched" to account for the shortening of the cores due to artifical compaction during sampling.

The laboratory programme at the CCIW was aimed at the determination of the basic geotechnical properties required for the engineering appraisal of lacustrine sediments. The properties comprised the natural water content, the Atterberg limits, the total unit weight, and the undrained shear strength. The writer's participation in this programme consisted in carrying out most of the laboratory work on cores from Boreholes 13156, 13160 and 13163. The testing of cores from the three remaining boreholes was carried out by members of the

HQGA engineering staff.

The natural water content and the Atterberg limits were measured in accordance with the standard ASTM methods of test (standards D 2216 and D 423/424 respectively). The total unit weight was determined by weighing each sample on the shipping scales with a precision of ± 1 g, subtracting the tare weight of the liner or the steel tube, and then dividing the net weight by the sample volume.

The undrained shear strength was measured with a Wykeham-Farrance laboratory hand-operated vane apparatus. The standard four-bladed 0.5 x 0.5 - in. (12.7-mm) vane was used. The tests were conducted on unextruded cores with the vane axis parallel to the core axis. The undisturbed shear strength represents the first highest or any further higher value obtained. For a second shearing the vane was rotated through 360 degrees, stopped, and re-rotated. The second value is referred to as the remolded shear strength. The sensitivity, indicating the loss of strength upon soil disturbance, was calculated as the ratio of the undisturbed shear strength to the remolded shear strength.

4.2 Additional Geotechnical Tests (at H.Q. Golder and Associates Ltd.)

The grain size analysis, the consolidation test and the triaxial compression test were conducted on representative samples in the HQGA soil mechanics laboratory. The writer did not participate in these tests, except for the grain size analyses, conducted at McGill University on samples from Borehole 13163 (Figs. 11.1 and 11.2).

The grain size analyses were performed using the standard sieve and hydrometer method. Fractions coarser than the No. 40 sieve (420 μ) were determined by dry-sieving, fractions coarser than the No. 200 sieve (74 μ) by wet back-sieving after the hydrometer test, and fractions passing the No. 200 sieve were calculated according to Stokes' law using the hydrometer readings. Methods recommended by ASTM standard D 422 were employed, including the use of constant temperature bath, distilled water, sodium hexametaphosphate as dispersing agent, and an ASTM-type hydrometer.

The one-dimensional consolidation tests were carried out on 2-in. (50.8-mm) diameter specimens with the load increment ratio of unity. The range of vertical consolidation pressures used was 0.05 to 6.0 tsf (4.8 to 574.6 kN/m^2) for specimens of the surficial Recent mud, 0.18 to 20.0 tsf (17.2 to 1915.2 kN/m^2) for specimens of the glacio-lacustrine deposit; and 0.16 to 40.0 tsf (15.3 to 3830.4 kN/m^2) for specimens of the till deposit.

Three unconsolidated-undrained (Q-type) triaxial compression tests and two consolidated-undrained (R-type) triaxial compression tests were performed on 1.4-in. (35.6-mm) diameter specimens of the surficial Recent mud and the glacio-lacustrine deposit from Borehole 13156. The primary purpose of these tests was to determine shear strength parameters under controlled drainage conditions, to compare results with laboratory shear vane tests, and to obtain stress-strain characteristics of the sediments. Budgetary restrictions precluded triaxial testing of more specimens, and therefore the limited test data available cannot be considered as representative for sediments studied.

4.3 Research Complementary Tests (at McGill University)

A complementary series of tests was carried out in order to provide more information on the causes of geotechnical behaviour of the lacustrine sediments. All complementary tests were performed on sediment samples from Borehole 13163.

The specific gravity of sediment solids was determined using the pycnometer method, and following the procedures recommmended by Lambe (1951). The experimental method of pycnometer calibration was used since it was found more reliable than theoretical computations.

The organic matter content was determined using the method proposed by Schollenberger, which is described in detail by Royse (1970). The method consists in the oxidation of organic matter and other oxidizable compounds (e.g. ferrous iron or higher oxides of manganese) by chromic acid. Following the oxidization, the excess chromic acid was back titrated with a ferrous-ammonium sulfate solution. As recommended by Royse, the results are reported as total oxidizable matter and are considered an approximation of the organic matter content and an index of the reducing potential of the sediment. It is believed that most of the ferrous iron was oxidized prior to testing since the samples were initially air dried for several days.

The total carbon content was measured by heating the dried sample at about 1300°C in the induction furnace analyser. Since total carbon includes both organic carbon and carbon in carbonates, an attempt was made to measure organic carbon content in samples after the removal of carbonates by sodium acetate following the method given in Black, et al.(1965). The results obtained showed a very high scatter caused probably by incomplete removal of carbonates. For this reason the results are not considered reliable, and are not reported. For future work it seems preferable to remove carbonates by sulphurous acid at room temperature. This method has been used with success by the CCIW geochemical laboratory (Kemp and Lewis, 1968; Thomas, 1969).

The surface area was determined using the ethylene glycol retention method proposed by Bower and Goertzen (1959). Samples used in the tests were untreated with any chemicals but they were sieved through a 40 mesh sieve, and were oven-dried at 105°C to constant weight. The sieved samples had an average weight of 5 g. Excess ethylene glycol was removed in a vacuum desiccator containing anhydrous $CaCl_2$ and a free surface of ethylene glycol. The samples were kept under vacuum for several days till a constant weight (within a few tenths of a milligram) of retained ethylene glycol was achieved.

The modified Penfield method (Penfield, 1894) was used for the quantitative determination of uncombined and combined water in two samples from Borehole 13163. The use of this determination was suggested to the writer and performed by Mrs. Horska of McGill University. In the method, an air-dried sample was sieved through a 40 mesh sieve. The sample (about 5 g) was then dried in an oven at 117°C for 24 hours. The loss in weight due to the uncombined water, expressed as percentage of the total weight, was designated as H_2O^-. A second portion of the sample was placed in a thoroughly dried, hard glass bulb with a long stem. The bulb was heated to approximately 1000°C for 20 min and the liberated water was condensed in the cooler portion of the stem. The stem containing condensed water was cut off, weighed, ignited and reweighed. The difference between the weights of the stem containing the condensed water and the stem after drying, expressed as percentage of total weight, was designated as total H_2O. The difference between total H_2O and H_2O- represents the amount of combined water in the sample H_2O+.

The clay mineralogical composition was studied by the X-ray powder diffraction method. Most of the X-ray analyses were run on a Philips X-ray diffractometer, however some initial analyses were obtained on a Siemens diffractometer. In addition, Prof. Quigley of the University of Western Ontario provided the writer with the X-ray diffraction traces of compressed specimens (centrifuge oriented), which were analysed on a General Electric diffractometer. The X-ray patterns were obtained for specimens in the following states:

(1) air-dried bulk fraction, finer than No. 40 sieve

(2) naturally-moist (never dried) clay size fraction ($< 2\ \mu$)

(3) air-dried clay-size fraction ($<2\ \mu$)

(4) air-dried fine-clay fraction ($<1\ \mu$)

(5) clay-size fraction after the removal of carbonates

(6) clay-size fraction after the removal of organic matter

(7) ethylene glycol solvated clay-size fraction

(8) K^{+}- saturated clay-size fraction

(9) clay-size fraction treated with 2N HCL

(10) clay-size fraction heated to 180°C, 550°C and 600°C

The details of specimen preparation technique and the instrumental settings used for the X-ray analyses are presented in Appendix D.

The scanning electron micrographs were obtained with Stereoscan 600, manufactured by Cambridge Scientific Instruments Ltd., England. Representative sediment specimens were prepared using five samples of the surficial Recent mud and two samples of the till deposit. All samples are from Borehole 13163. The specimens were obtained from the dilute suspensions of the bulk fractions which were ultrasonically dispersed to destroy aggregates of sediment particles. Few drops from the dispersed suspensions were then placed atop a mica microslide attached by an epoxy resin to a mounting pallet. Prior to an examination in the electron microscope, the specimens were coated with a gold-palladium alloy in a vacuum chamber to achieve electrical conductivity of the mounting pallet.

The magnification used for viewing ranged from 200 x to 5,000 x. The electron images above magnification 5,000 x were already out of focus, and therefore this value had to be used as the upper limit for viewing.

CHAPTER 5

RESULTS

5.1 Stratigraphy from Borehole Cores

A detailed interpretation of the stratigraphy in the project area has been prepared from the visual description of the cores and the results of laboratory tests described below in this chapter. Summarized borehole data are shown in Table 7, and individual borehole logs are shown in Figs. 9.1 to 9.7 inclusive. The results of core examination were used for the following discussion of the stratigraphic units, which can be compared to the overall discussion of Lake Erie geology in Sections 2.4 and 2.5.

The lowest stratigraphic unit encountered was the brownish grey clayey silt with fine to coarse gravel. This unit, T, (Fig. 7) appears to represent a flank till deposit of the Erieau Moraine in Boreholes 13160 and 13163. A till deposit of very similar texture was encountered in Boreholes 13189 and 13194, where it probably belongs to a basal till sheet overlying the bedrock. The thickness of the till unit is quite variable, and it was estimated from the known bedrock surface elevations that were recorded for each borehole during exploratory gas drilling (Table 7). The greatest thickness was found at the site of Borehole 13160 (93 ft = 28.3m), and the least one at the site of Borehole 13193 (24 ft = 7.3 m). The unit generally decreases in thickness in the eastward direction away from the Erieau Moraine. It is quite likely that the till sheet is continuous across the whole investigated area, and that it would have been found also in Boreholes 13156 and 13161, had they

Table 7. Summarized borehole data

Borehole No.	W °	W '	W ''	N °	N '	N ''	Water Depth ft	Water Depth m	Borehole Length ft	Borehole Length m	Sediment Th[ickness] Surficial Recent Mud ft	Sediment Th[ickness] Surficial Recent Mud m
13156	81	30	25	42	10	05	83	25.3	77.4	23.6	55	16.8
13160	81	53	15	42	01	35	82	25.0	59.6	18.1	17.9	5.4
13161	81	37	45	42	13	45	81	24.7	34.8	10.6	18.0	5.5
13163	81	47	40	42	09	00	76	23.2	45.6	13.9	19.9	6.1
13189	81	35	35	42	15	15	82	25.0	69.1	21.0	24.5	7.5
13193	81	28	20	42	14	15	81	24.7	91.5	27.9	60.2	18.3
13194	81	39	45	42	04	10	84	25.6	100.0	30.5	40.0	12.2

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Water Depth		Borehole Length		Sediment Thickness in Borehole: Surficial Recent Mud		Glacio-lacustrine Deposit		Till Deposit		Overburden Thickness (Estimated from Gas Testhole)	
ft	m	ft	m	ft	m	ft	m	ft	m	ft	m
83	25.3	77.4	23.6	55	16.8	22.4	6.8	-	-	128	39.0
82	25.0	59.6	18.1	17.9	5.4	-	-	41.7	12.7	111	33.8
81	24.7	34.8	10.6	18.0	5.5	16.8	5.1	-	-	100	30.5
76	23.2	45.6	13.9	19.9	6.1	-	-	25.7	7.8	99	30.2
82	25.0	69.1	21.0	24.5	7.5	39.5	12.0	5.1	1.5	120	36.5
81	24.7	91.5	27.9	60.2	18.3	25.8	7.9	5.5	1.7	110	33.5
84	25.6	100.0	30.5	40.0	12.2	24.5	7.5	35.5	10.8	151	46.0

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been cored to greater depths. The upper part of the till horizon in Borehole 13163 (Samples 8-3 to 10-1 in Figs. 9.1.2 and 9.1.3) contains more of the clay-size fraction, and it has the character of a reworked till. The reworked till could have been redeposited either by slumping or viscoplastic flows in a glacier margin lake. As mentioned in Section 2.4.2, the till deposition is considered to have occurred during the Port Bruce Stadial about 14,000-13,500 years ago (Table 1).

The glacio-lacustrine deposit, GI, (Fig. 7) overlies the till in all boreholes with the exception of Boreholes 13160 and 13163. The maximum thickness of the unit is in the order of 40 ft (12.2 m) in the vicinity of Borehole 13189 and possibly also in Borehole 13156. The glacio-lacustrine clay is typically brownish grey with occasional varved laminations, crossbeddings, and irregular lenses. These structures occur intermittently between zones in which any signs of layering are absent. Regular varve laminae 1/16 to 1/2 in. (0.2 to 1.5 cm) in thickness were by far the most common structures observed. Based on particle size analyses, the deposit is a silty clay, containing 60 to 80 per cent of the -2 micron fraction (Fig. 11.4). Rare sand grains and pebbles were observed in some cores. The age of the deposit is estimated to range between 13,300 and 12,500 years ago, being laid down during the Lake Arkona stage and subsequently formed lakes of the Mackinaw Interstadial and the Port Huron Stadial (Table 1).

A prominent unconformity was seen in most of the cores between the Pleistocene deposits, T and GI, and the overlying Recent mud, M, (Fig. 7). This unconformity is marked by a desiccated crust that occasionally contains lag sand grains and reddish brown colouring characteristic of strongly oxidizing conditions. The Pleistocene deposits immediately below the unconformity have generally much lower water content than the overlying Recent mud. The desiccated crust is clearly visible in nearshore cores (Boreholes 13160, 13161 and 13163) where the unconformity occurs above elevation 470 ft (143.3 m) a.s.l. In deeper offshore cores, the unconformity is less conspicuous and its position had to be ascertained from radiographs. The conspicuous desiccation of the Pleistocene deposits above elevation 470 ft (143.3 m), attributed to the subaerial exposure during the low-level stage of Early Lake Erie, is known to occur in other areas of the Lake Erie basin (Lewis, 1966).

The surficial Recent mud occurs everywhere in the investigated area, ranging in thickness from about 18 ft (5.5 m) in Boreholes 13160, 13161 and 13163 to about 60 ft (18.3 m) in Borehole 13193. The new data have been added to Lewis' 1966 work (Fig. 6). The Recent mud is a silty clay, with the clay-size fraction (<2 μ) constituting typically 50 to 70 per cent of the sediment (Figs. 11.1 and 11.3), thus being slightly coarser than the underlying glacio-lacustrine deposit. The mud is typically of homogeneous appearance, dark grey to grey. Numerous black specks and the laminae of amorphous sulphides, which are suggestive of reducing potential of the sediment, were seen throughout cores. On exposure the sediment oxidized to brown colour within several hours. The decomposition of organic matter with time in stored cores was not studied beyond the visual observations of gas formation. This process was particularly noticeable in the case of cores taken from the sediment topstratum, which contains about 3 per cent oxidizable matter (Fig. 9.1.1). The decomposition of organic matter is likely accompanied with formation of gases such as carbon dioxide, methane, and other volatile hydrocarbons (Royse, 1970).

5.2 <u>Natural Water Content (Figs 9.1 to 9.7)</u>

The results indicate very high values of water content for the sediment at the lake bottom interface, typically in excess of 200 per cent dry weight. A maximum value of 323 per cent was measured for the bottom surface sediment in Borehole 13160. In the surficial Recent mud the water content decreases gradually with depth, reaching 55 to 80 per cent at the Pleistocene erosional unconformity. The highest rate of decrease occurs within the uppermost portion of the sediment column. The values show no apparent lateral variation and are not related to the thickness of the mud deposit.

An abrupt decrease in the water content occurs below the erosional unconformity, indicating the desiccation due to the subaerial exposure of the Pleistocene sediments. The sediments are heavily desiccated in nearshore boreholes (13160, 13161, 13163) where the unconformity is above elevation 470 ft (143.3 m). The desiccated crust in the nearshore boreholes has the water content of about 20 per cent (13160, 13163) in the till deposit and about 35 per cent in the glacio-lacustrine deposit (13161). The difference in the two values is probably attributable to the variation in particle size (Figs. 11.4 and 11.5), as well as a different consolidation history of the two Pleistocene deposits (Section 5.7 below). In offshore boreholes (13156, 13189, 13193, 13194), the unconformity occurs below elevation 470 ft (143.3 m) and the crust in the glacio-lacustrine deposit is much less desiccated. The water content in the offshore boreholes immediately below the unconformity ranges from 70 to 45 per cent.

The water content within the glacio-lacustrine deposit decreases slightly with depth to about 25 to 30 per cent at the bottom of the deposit (13161, 13189, 13193, 13194). Within the till deposit the water content remains relatively constant with depth ranging from 20 to 25 per cent in the offshore boreholes (13189, 13193, 13194) and from 15 to 20 per cent in the nearshore boreholes (13160, 13163).

5.3 Atterberg Limits (Figs. 9.1 to 9.7 and 10.1 to 10.3)

The liquid limit values measured on samples of the Recent mud at or close to the lake bottom interface were generally in the excess of 100 per cent. The maximum value obtained was 154 per cent for a sediment sample from Borehole 13160 (Fig. 9.3.1). Within the Recent mud, the liquid limit follows a similar trend as the water content, i.e., it decreases with depth, the rate of decrease being the highest within the uppermost 10 ft (3.0 m). In the nearshore boreholes (13160, 13163), the liquid limit decreases from the maximum values of the lake bottom to about 65 per cent at the levels immediately above the erosional unconformity. In the offshore boreholes (13156, 13193, 13194), the decrease in the liquid limit was observed only within the upper 30 ft (9.1 m) of approximately 50-ft (15-m) thick deposit. The results indicate that once the natural water content decreases to the value of the liquid limit, i.e., when the liquidity index reaches the value of 1.0, there is no further significant decrease in the water content or the liquid limit. The minimum liquid limit values were approximately the same as those obtained in the near-shore boreholes, i.e., about 65 per cent. Thus, the liquid limit values in this unit appear to show no lateral trends and can be almost everywhere positively correlated with the water content.

The plastic limit of the Recent mud shows substantially lesser dependence on depth than the liquid limit, ranging from about 30 per cent at the lake bottom interface to about 25 per cent at the bottom of the deposit. The plasticity index, i.e., the difference between the liquid limit and the plastic limit, is thus basically controlled by the liquid limit values.

The liquid limit of the glacio-lacustrine deposit ranges from 60 to 40 per cent. (Boreholes 13156, 13193, 13194) and, similarly to the natural water content, it slightly decreases with depth. Since the liquid limit typically exceeds the natural water content, the liquidity index is mostly less than 1.0, varying between 0.8 and 0.2. The values of plastic limit (Boreholes 13156, 13193, 13194) vary between 25 and 20 per cent.

The tests on the till deposit (Boreholes 13160, 13163, 13193, 13194) indicate very small vertical and lateral variations in the liquid limit and the plastic limit. The liquid limit values vary between 30 and 25 per cent, those of the plastic limit between 15 and 10 per cent. The liquidity index varies typically between 0.5 and 0.1, with occasional higher values up to 1.0.

The distribution pattern of the results plotted on the Casagrande plasticity chart shows that each sediment type forms a well-defined cluster on the chart. The results are plotted for Borehole 13163 in Fig. 10.1, Borehole 13156 in Fig. 10.2, and for all boreholes in Fig. 10.3. On the plasticity chart (Fig. 10.3) all values fall above and parallel to the "A" line, indicating that all three sediments can be regarded as "inorganic soils" which probably have a similar mineralogical composition of the clay-size fraction, i.e., they are derived from the same geological source. According to the Unified Soil Classification System (Terzaghi and Peck, 1967), the Recent mud can be classified as the silty clay of a broad range of high plasticity (the CH group), the glacio-lacustrine deposit as the silty clay of medium to high plasticity (close to the boundary of the CH and CL groups), and the till deposit as the clayey silt of low plasticity (the CL-ML group).

In comparison with marine and fresh-water sediments of comparable particle size distributions (e.g., data published by Harrison et al., 1964; McClelland, 1967; and Silva and Hollister, 1973), the liquid limit values determined for the uppermost zone of the Recent mud are considered to be unusually high. The relationship between plasticity and other geotechnical properties is discussed in Section 6.1 below. The research into the causes of high plasticity is described in Section 6.2.

5.4 Total Unit Weight (Figs. 9.1 to 9.7)

Values of total unit weight are required for the calculation of total and effective overburden pressures at a particular depth. The results indicate that the variation in this parameter is principally inversely related to the natural water content, and to a lesser degree influenced by the specific gravity of sediment particles that increases with depth from 2.64 to 2.75 (Figs. 9.1.1 and 9.1.3). The total unit weight of the Recent mud ranges from 70 to 100 pcf (1.12 to 1.60 g/cm^3), that of the glacio-lacustrine deposit from 100 to 115 pcf (1.60 to 1.64 g/cm^3), and that of the till deposit from 110 to 135 pcf (1.76 to 2.16 g/cm^3).

The unit weight of the Recent mud compares well with the range of 78 to 94 pcf (1.25 to 1.51 g/cm^3) reported by Keller (1969) for the upper few feet of sediments from the North Pacific Basin. The values for the glacio-lacustrine deposit can be compared with the range of 114 to 116 pcf (1.83 to 1.86 g/cm^3) reported by Soderman et al. (1960) for onshore lacustrine clays in the Lake St. Clair region. The till values are comparable to the range of 120 to 134 pcf (1.92 to 2.15 g/cm^3) reported by Soderman et al. (1960) for the Lake St. Clair onshore tills.

5.5 Undrained Shear Strength from Laboratory Vane Tests (Figs. 9.1 to 9.7)

The Recent mud is generally of very soft consistency, i.e., its undrained shear strength does not exceed 250 psf (12.0 kN/m^2). At the water-sediment interface the shear strength is in the order of 25 psf (1.2 kN/m^2). Below the interface, the shear strength shows only a slight tendency to increase with depth, reflecting the underconsolidated state of the sediment. The thickness of the underconsolidated topstratum is approximately 10 ft (3.0 m) in the nearshore boreholes (13160, 13161, 13163), 12 ft (3.7 m) in Borehole 13189, and 15 ft (4.6 m) in Boreholes 13156, 13193 and 13194. The underconsolidated topstratum coincides with the section of the sediment profile in which the liquidity index exceeds unity. The approximately linear trend of the shear strength versus depth below the topstratum indicates a normally consolidated sediment with the liquidity index close to unity. Several zones of higher shear strength, which depart from the expected linear trend, occur in the lower section of the Recent mud profile (Figs. 9.3.1, 9.6.1 and 9.7.1). The possibility of an increase in the shear strength due to a natural interparticle cementation is discussed in Section 6.3 below. At the contact with the Pleistocene deposit the Recent mud reaches the value of about 200 psf (9.6 kN/m^2). The sensitivity of the Recent mud generally increases with depth from about 2 to about 4, and occasionally values as high as 8 were obtained. The relationships of the undrained shear strength of the Recent mud to the effective overburden pressure and the plasticity are discussed in Section 6.1.

The consistency of the glacio-lacustrine deposit is soft to stiff with the undrained shear strength values ranging from 200 to 2000 psf (9.6 to 95.8 kN/m^2). The maximum values were measured on samples from a 3-ft (0.9-m) thick desiccated crust occuring at elevations 474 to 471 ft (144.5 to 143.6 m) in the nearshore borehole 13161. Below this crust the average shear strength is about 1200 psf (57.5 kN/m^2). In the offshore boreholes (13156, 13189, 13193, 13194), a generally softer sediment was encountered, and the maximum value of 1420 psf (68.0 kN/m^2) was measured on a sample at elevation 448 ft (136.5 m) in Borehole 13194. The data from all boreholes indicate a positive correlation between the shear strength and the water content, and no obvious relationship between the shear strength and elevation. The shear strength generally decreases with depth in

Boreholes 13161 and 13189, and shows a reverse trend in Boreholes 13193 and 13194. The sensitivity of the glacio-lacustrine deposit ranges from about 4 to 10, with the average of about 7.

The till deposit shows a similar variation in the measured values of shear strength but the values are generally higher, especially towards the bottom of the boreholes. The values range from 400 to 2600 psf (19.2 to 124.5 kN/m^2), and the deposit can be classified as of soft to very stiff consistency. The sensitivity of the till deposit ranges from about 3 to about 10.

5.6 Grain Size Analysis (Figs 11.1 to 11.5, Table 2)

The grain size distribution of the Recent mud is relatively uniform throughout the sediment profile with a clay content (less than 2 microns) ranging from 50 to 65 per cent. The cumulative distribution curves (Figs. 11.1 and 11.3) indicate a possible slight increase in the content of clay-size particles with depth. This trend has been confirmed by a detailed grain size analysis of the sediment in core 13194 (Anderson, 1975).

The lower threshold for hydrometer determination is about 1 micron, and, therefore, by this method it is not possible to establish whether any appreciable change with depth occurs in the finest clay fraction. The results of electron microscopy (Section 5.15), glycol retention tests (Section 5.12), and X-ray diffraction analyses (Section 5.14) indicate that very fine poorly crystalline material shows a reverse trend compared to crystalline clay-size particles; i.e., an inconspicuous but consistent decrease with depth.

The results of grain size analyses of the glacio-lacustrine deposit indicate that the deposit is somewhat finer than the overlying Recent mud. As shown in Fig. 11.4, the glacio-lacustrine deposit contains on the average 60 to 80 per cent of particles finer than 2 microns.

The till deposit (Figs. 11.2 and 11.5) contains up to 30 per cent of sand and gravel, approximately 40 per cent silt, and 30 per cent clay. The maximum gravel size is about 2 in. (5 cm).

The grain size analyses are in general agreement with data published by Lewis, 1966 (Table 2).

5.7 Consolidation Test (Figs. 12.1 to 12.3)

Five consolidation tests were carried out on samples of the Recent mud from Borehole 13193 (Fig. 12.1). The first four samples (2-2, 4-2, 4-3 and 5-1) were selected from the uppermost 12 ft (3.7 m) of the sediment and the samples were trimmed from the Alpine cores. These samples were almost too soft to be tested in a consolidometer, and the test results show the influence of sampling disturbance. The compression portions of the void ratio versus log pressure (e-log p) curves are steep and almost linear at low consolidation pressures, indicating a very high compressibility. The compression index, C_c, i.e., the slope of the field consolidation line of the e-log p curve, ranges between 1.55 and 1.15. The C_c values are very high in comparison with the empirical relationships for normally consolidated clays (Terzaghi and Peck, 1967; McClelland, 1967).

The commonly used method (Casagrande, 1936) of determining the preconsolidation pressure, P_c, i.e., the pressure under which the sediment has been consolidated during its depositional history, gives uncertain results and, therefore, only a range of probable values is shown in Fig. 12.1. In the case of Samples 4-2 and 5-1, the compression portions of the e-log p graph are virtually straight lines, and the P_c values cannot be determined. The fifth sample (21-1) represents the sediment 6.2 ft (1.9 m) above the contact with the glacio-lacustrine deposit and the sample was trimmed from the Christensen core. A more regular e-log p curve was obtained, however the determination of P_c is still uncertain. The compression index 0.63 compares well with the published data for normally consolidated clays (Fig. 15.4).

The test data indicate that Samples 4-3 and 21-1 are normally consolidated, while Sample 2-2 appears to be overconsolidated by 0.085 to 0.365 ~~tsf (8.1 to~~ 35.0 kN/m^2). Since the sediment at this depth has a shear strength ~~of about 25~~ psf (1.2 kN/m^2) and the water content of 130 per cent, the apparent overconsolidation is probably caused by the volumetric deformation of the sample prior to testing. It is of interest to note, however, that Richards and Hamilton (1967) attributed the apparent overconsolidation of marine sediments found at the depths of 0.5 to 1 m below the bottom to a "chemical, cement-like, intergrain bonding" due to possible "solution and redeposition of silica, calcium carbonate, iron or manganese". On the basis of the C_c values and their comparison with published data (Fig. 15.4), the test results indicate the "underconsolidation" of the topstratum (Samples 2-2, 4-2, 4-3 and 5-1) and the normal consolidation of the underlying sediment (Sample 21-1). This conclusion is in agreement with the interpretation of the shear strength results given in Section 5.5.

The values of the coefficient of consolidation, C_v, were found to vary from 8×10^{-4} to 7×10^{-5} cm^2/sec, and remained approximately constant during the tests. The results obtained fall within the range of data given by Terzaghi and Peck (1967) for clays of high plasticity.

Four consolidation tests were carried out on the glacio-lacustrine deposit, two on the samples from Boreholes 13189 above elevation 440 ft (134.1 m), and two on the samples from Borehole 13193 below elevation 440 ft (134.1 m). The results of the tests are shown in Fig. 12.2. The glacio-lacustrine deposit in Borehole 13189 is overconsolidated by 1.28 tsf (122.6 kN/m^2) in the case of Sample 8-1, by 1.57 tsf (150.3 kN/m^2) in the case of Sample 12-1. The results on Samples 26-2 and 26-4 from Borehole 13193 suggest that the deposit below elevation 440 ft (134.1 m) is normally or near normally consolidated. The compression index was found to range between 0.45 and 0.65, with the average value of about 0.5. Once again, these values appear to be high in comparison with the compressibility of an average clay with medium to high plasticity.

The coefficient of consolidation values range from 2×10^{-3} to 3×10^{-4} cm^2/sec. The minimum values, indicating the maximum times required to reach 100 per cent consolidation, were obtained for consolidation pressures from 2 to 3 tsf (191.5 to 287.3 kN/m^2).

Four samples of the till deposit were tested (Fig. 12.3); three samples from Borehole 13160 located above elevation 440 ft (134.1 m), and one sample from Borehole

13189 located below elevation 440 ft (134.1 m). All samples are overconsolidated. The preconsolidation pressure in excess of the present effective overburden pressure ranges from 1.74 to 4.05 tsf (166.6 to 387.8 kN/m^2). The compression index varies from 0.20 to 0.11. The coefficient of consolidation varies from 5×10^{-5} to 4×10^{-3} cm^2/sec, and the values generally increase with increasing consolidation pressure.

It is concluded that the consolidation test results in general confirm the Late Wisconsin and postglacial depositional history of Lake Erie described above in Section 2.4.2 and summarized in Table 1.

5.8 Triaxial Compression Test (Fig. 9.2.2)

The undrained shear strength results from the unconsolidated-undrained (Q-type) triaxial compression tests are in very good agreement with the laboratory vane tests described in Section 5.5. The undrained shear strength of the Recent mud ranges from 240 to 300 psf (11.5 to 14.4 kN/m^2). The undrained shear strength of the glacio-lacustrine deposit is 410 psf (19.6 kN/m^2). The unconsolidated samples of both the Recent mud and the glacio-lacustrine deposit failed by plastic deformation of the sample base. Axial strains at failure varied from 4 to 7 per cent.

In the two consolidated-undrained (R-type) triaxial compression tests, the samples were first consolidated under the computed values of effective overburden pressure and then sheared under undrained conditions by applying the axial load. The resulting undrained shear strength values are 710 psf (34.0 kN/m^2) for the Recent mud and 800 psf

(38.3 kN/m^3) for the glacio-lacustrine deposit, i.e. the results are approximately twice as high as those obtained from the Q-type tests. The consolidated sample of the Recent mud failed along a 45-degree failure plane in the upper half of the sample, and the consolidated sample of the glacio-lacustrine deposit failed at the midheight of the sample by shear failure along two 30 to 45-degree conjugate shear planes and some horizontal shearing within the finer-grained dark laminations. The samples failed at axial strains of 3 to 5 per cent.

The difference in undrained shear strength values is obviously primarily a function of the testing method applied. The considerably higher values obtained in the R-type tests are attributable to the following causes:

(1) The sediment samples do not behave as elastic materials and thus the consolidation to _in situ_ stresses results probably in a lower void ratio and a lower water content compared to _in situ_ conditions.

(2) The ratio of _in situ_ lateral effective stresses to vertical effective stresses, termed the coefficient of earth pressure at rest, K_o, is less than unity. The ratio is known to vary from 0.7 to 0.35 for saturated sediments (Bishop and Henkel, 1962). Thus the laboratory consolidation under equal all-round pressure exceeds the values of lateral effective stresses occurring in the natural strata.

For the above reasons, the R-type test values are believed to overestimate the _in situ_ undrained shear strength, which would be measured in a field vane test. A pertinent discussion dealing with the influence of a testing method upon undrained shear strength results was published by Kenney (1968).

5.9 Specific Gravity (Figs. 9.1.1 and 9.1.3)

The specific gravity results obtained on samples from Borehole 13163 show a consistent increase in measured values with depth, ranging from 2.64 at the water-sediment interface to 2.75 at 42 ft (12.8m) below lake bottom. The increase with depth is more pronounced in the Recent mud than in the till deposit. The variation in measured values can be principally accounted for by:

(1) The decrease in organic matter with depth, in particular within the Recent mud (Section 5.10 below).

(2) The higher percentage of calcite (specific gravity 2.71) and dolomite (specific gravity 2.85) near the base of the Recent mud and in the till deposit (Section 5.11 below).

5.10 Oxidizable Matter Content (Figs. 9.1.1 and 9.1.3)

The oxidizable matter content of the Recent mud in Borehole 13163 decreases with depth from 3.4 per cent at the water-sediment interface to 1.0 per cent close to the Pleistocene unconformity. The latter relatively low value indicates strong oxidation of the sediment immediately above the unconformity (Section 5.1).

Within the Pleistocene deposit, the oxidizable matter content remains practically constant, ranging from 2.0 to 2.2 per cent, i.e. it is slightly higher than the minimum content in the mud. Using the conversion coefficient of 1.72 (Kemp and Lewis, 1968), the values correspond to 1.23 per cent organic carbon (Table 2). The values are slightly higher than those obtained for a lodgment till deposit, also probably Port Bruce, from the Point Pelee shoal area (Coakley, Winter, and Zeman, 1975).

Two samples were prepared for each determination to check the reproducibility of measured values. The reproducibility was found to be about ± 4 per cent of the mean value. Compared to the Christensen core samples taken at comparable depths, the Alpine core samples gave values approximately 0.5 per cent lower. The difference is probably caused by more rapid oxidation of the Alpine cores during the sample storage period.

5.11 Total Carbon Content (Figs. 9.1.1 and 9.1.3)

The amount of total carbon in the Recent mud in Borehole 13163 decreases within the uppermost 5 ft (1.5 m) of the sediment, below which it was generally found to increase with depth as expected. Most likely the decrease with depth in the upper zone can be attributed to the sharp decrease in organic carbon. The maximum carbon value obtained was 3.8 per cent dry weight at the base of the unit.

Within the till deposit, the values remain fairly constant with depth, ranging from 3.4 to 3.8 per cent dry weight. Two separate samples were prepared for each determination, and the reproducibility was found to be about ± 3 per cent of the mean value.

5.12 Surface Area (Figs. 9.1.1 and 9.1.3

The results are reported in mg of retained ethylene glycol per gram of oven-dried sediment, and as surface area values calculated from the equation (Bower and Goertzen, 1959),

$$A = W_g / (W_s \times 0.00031) \qquad (1)$$

where A = surface area in m^2/g

W_g = weight of retained ethylene glycol

W_s = weight of an oven-dried sample

0.00031 = the Dyal-Hendricks constant

The results obtained on the specimens of the Recent mud range from 87 to 62 m^2/g (27.0 to 17.2 mg/g). There appears to be only a slight decrease in surface area with depth and quite a high scatter in measured values. The surface area values of the till deposit range from 51 to 38 m^2/g (16.0 to 11.5 mg/g).

The surface area values are generally significantly lower than those reported for the -2 micron fractions by Soderman and Quigley (1965) and Warkentin (1972). The relatively low values most probably result from the use of bulk samples (-40 mesh) rather than the -2 micron fractions in the present investigation.

5.13 Modified Penfield Test (Table 8)

The results of the test (Table 8) indicate a higher water retention capacity of the Recent mud compared to the till deposit, and thus they appear to have bearing on the measured plasticity difference between the two deposits. The results indicate that even after oven drying to 117°C the high-plasticity surficial Recent mud adsorbs or combines with appreciably higher amount of water than the low-plasticity till. As described in Section 5.14 below, it was decided to study whether the different water retention capacities of high-plasticity and low-plasticity clays could be correlated with their mineralogical composition.

The Penfield test demonstrates the unreliability of a burning method sometimes employed in soil mechanics for the determination of organic matter content. According to this method, all water designated as H_2O + in Table 8 would be included into organic matter.

Table 8. Quantitative determination of uncombined and combined water in air-dried samples, Borehole 13163, and its correlation with plasticity

Sample No.	1 - 2	12 - 1
Sediment Type	Surficial Recent Mud	Till
	% total weight	
H_2O - (at 117° C for 24 hrs)	0.80	0.87
H_2O + (to 1000° C for 20 min)	4.02	2.76
	% dry weight	
Wl (natural moisture)	96.2	27.1
Wl (air-dried)	58.7	30.8
	% dry weight	
Pl (natural moisture)	29.8	17.7
Pl (air-dried)	26.8	17.8
	% dry weight	
Ip (natural moisture)	66.4	9.4
Ip (air-dried)	31.9	13.0

5.14 X-ray Powder Diffraction Analysis

5.14.1 Bulk Specimens

In the first series of tests, specimens were prepared from bulk samples of the sediment fraction finer than No. 40 sieve. The analyses were run in the scanning range of 2° to 48° 2θ, and they are re-drawn for the range of 2° to 24° 2θ in Fig. 13.1. As expected, the diffraction traced showed high background scatter and prominent peaks for non-clay minerals. Among these, the most conspicuous peaks (not shown in Fig. 13.1) were noted for quartz at 3.34 Å (101) and at 4.25 Å (100); dolomite at 2.88 Å (104); plagioclase at 3.20 Å (002), and relatively weak peak for orthoclase at 3.22 Å (002). No substantial difference in clay mineralogy was observed between samples of high-plasticity and low-plasticity clays. As shown in Fig. 13.1, the traces show easily distinguishable peaks for the first-order and higher-order basal reflections of illite, chlorite and possibly kaolinite.

5.14.2 Clay-Size (<2 μ) Fraction, Untreated Specimens

In the second series of analysis, the sediment fraction finer than 2 microns was examined. Representative diffraction curves are presented in Fig. 13.2. Fractionation reduced considerably the background scatter as well as the intensities of non-clay mineral reflections. The specimens of the surficial mud (Sample 1-1) appear to be quite different from the specimens of reworked till and till (Samples 8-5 and 12-1 respectively). The surficial mud appears to be weathered as indicated by generally weaker reflections of chlorite and illite peaks (especially noticeable is the variation for the 7 Å peak). The difference between the diffraction traces can be possibly accounted for by the partial disruption of the crystalline structure as well as the presence of amorphous material in the surficial mud. Furthermore, the low-angle ($2\theta = 4^{\circ} - 6^{\circ}$) traces of surficial mud indicate the presence of a swelling mineral and mixed-layer minerals, the abundance of which was found to decrease with depth. This finding is considered important for the correct interpretation of the plasticity results.

5.14.3 Ultrafine (<1 μ) Fraction, Untreated Specimens

The untreated ultrafine fraction of three representative samples (Nos. 1-1, 8-5 and 12-1; Borehole 13163) was further studied. No significant change was observed. The traces showed that the material finer than one micron was predominantly crystalline and of the same mineralogical composition. The peaks of the ultrafine fraction were broader and lower than those of the clay-size fraction, which is in accordance with a generally observed relationship between particle size and peak intensities (Carver, 1971).

5.14.4 Effect of Chemical Pretreatment

Several recommended pretreatments (Black et al., 1965; Gillot, 1968) were tested in order to reduce background [illegible]ter and possibly reveal some new peaks. The effect was studied on the three samples whose diffractometer traces for untreated specimens are shown in Fig. 13.2.

For the removal of carbonates the writer followed a method described by Brewer (1964) using 1 N sodium acetate buffer stabilized by acetic acid at pH 5. No appreciable change occurred after this treatment except for a total destruction of the calcite peak at 3.04 Å. The dolomite peak at 2.88 Å remained completely unaffected. In an alternative method (Brewer, 1964), carbonates were removed by dilute hydrochloric acid, and the suspension was then filtered through a Buchner funnel and flocculated with sodium chloride. This method destroyed completely the 3.04 Å calcite peak, lowered the intensity of 2.88 Å dolomite peak, and it had no effect on the peaks pertaining to clay minerals.

Organic matter was removed by treatment with hydrogen peroxide (Black et al., 1965), using the same samples which remained after the removal of carbonates by sodium acetate. No conspicuous change in diffractometer traces was observed, however a low-intensity peak at 17.33 Å (smectite) became more distinct for Sample 1-1 after this treatment.

The removal of amorphous or poorly crystalline iron and aluminum hydrous oxides was not attempted. A citrate-dithionite extraction method (Mehra and Jackson, 1958) was tested in another study on several samples from Lake Ontario, Lake Erie, and Lake St. Clair (Mudroch and Zeman, 1975). The citrate-dithionite extraction caused an effective dispersal of clay particles, changed some chlorite to vermiculite and decreased the content of amorphous or poorly crystallized components. A sodium citrate extraction of the Port Talbot 1 green clay (Quigley and Dreimanis, 1972) likewise did not result in any significant mineralogical change which would have indicated extensive complexing of aluminum and iron hydroxides.

5.14.5 Effect of Air Drying

The air drying of the surficial mud specimens caused a marked collapse of the low-angle peaks (2 θ = 3° - 6°) pertaining to smectite and interlayered minerals. In the case of the till deposit, however, this effect was much less pronounced (Fig. 13.3). The intensities of low-angle peaks were investigated in a series of tests run on specimens X-rayed during different moisture conditions (Fig. 13.4). The ratios of the low-angle peaks (2 θ = 4° - 8°) to the illitic peak (2 θ = 8° - 11°) confirm the decreasing abundance of swelling and randomly interstratified minerals in the sediment column with depth, and they further indicate only partial expansion of the swelling and interstratified minerals after rewetting. A smilar behaviour was reported for weathered clays at Sarnia, Ontario, which contains 15 per cent swelling clay minerals (Quigley and Ogunbadejo, 1973).

Changes in clay mineralogy during the air-drying process explain the plasticity results obtained for moist and air dried sediment samples (Fig. 14.1 and 14.2). While pronounced decrease in the liquid limit occurred upon air drying of the surficial mud, the plasticity of the till deposit remained unchanged. Further tests (Mudroch and Zeman, 1975) indicate that decrease in plasticity upon air drying occurs also in the case of Lake Ontario and Lake St. Clair postglacial surficial sediments.

5.14.6 Effect of Glycolation, Potassium Saturation, and Furnace Heating

As shown in Fig. 13.3, glycolation of the surficial mud specimens caused an expansion of basal spacings from 14 Å to about 20 Å characteristic for swelling and interlayered minerals, and the diffractogram traces resembled generally those of the wet specimens. A distinct peak at 17.7 Å was noted on several traces (Sample 1-2, Fig. 13.3) of the surficial mud specimens. In contrast, only inconspicuous increase in the background at low angles of 2 θ (4^{o} to 8^{o}) was observed in the case of the till specimens (Fig. 13.3) and the glacio-lacustrine specimens (Mudroch and Zeman, 1975).

The 14 Å peak, which was found present in all specimens tested, could have been attributed to the basal reflection of vermiculite (002) as well as that of chlorite (001). It was therefore tested to see whether the K^{+}-saturation would contract the 14 Å peak to 10 Å peak of illite (Black et al., 1965). The homoionizing procedure (Black, et al., 1965) was followed, using 1 N solution of KCl, centrifuge decantation, and subsequent washing with 50 per cent and 95 per cent methanol. The results shown in Fig. 13. 5 indicate collapse of all swelling minerals, with practically no change in the intensity of the 14 Å peak. Therefore the 14 Å reflection is most probably caused by chlorite. The strong 7 Å reflection compared to the 14 Å reflection suggests that the chlorite belongs to a high iron chlorite group (Martin, 1955). The citrate-dithionite extraction can change some pseudochlorites into vermiculite by removing adsorbed aluminum and iron hydroxide cations (Soderman and Quigley, 1965). Increase in 10 Å reflections relative to 14 Å reflections after the citrate-dithionite extraction and K^{+}-saturation, which is indicative of collapsible vermiculite, was observed in all postglacial and Pleistocene sediment samples studied by Mudroch and Zeman (1975).

The effect of furnace heating (Brown, 1961) also confirms the presence of high iron chlorite (Fig. 13.5). The 14 Å peak remained unaltered or slightly strengthened after heating to 500^{o} C and 600^{o} C while the 7 Å peak decreased significantly when the specimens were heated to 500° C and virtually disappeared at 600° C. A slight shift of the 14 Å peak to a smaller 2 θ value after heat treatment, which is characteristic of the iron-rich chlorite, was also observed (Fig. 13.5).

5.14.7 Attempts at Distinction between Chlorite and Kaolinite

Several methods were tried to distinguish kaolinite and chlorite, which have similar basal spacings at 7 Å and 3.5 Å.

The resolution of peaks at 3.5 Å using low scanning speed and untreated samples recommended by Biscaye (1964) proved to be inconclusive since in all cases only one broad peak was obtained. The distinction on the basis of heat treatment was considered uncertain. The most reliable method appeared to be that of Vivaldi and Gallego (1961), in which the presence of kaolinite is determined from the persistence of 7 Å reflection after the acid treatment. 2 N HCl warmed to the temperature of 80°C was used, in which the samples were immersed for 2 hours. After the treatment the acid became distinctly pale green, which may have been caused by the removal of interlayer iron from chlorite particles. About 70 per cent of the 14 Å peak area and 90 per cent of 7 Å peak area were destroyed by this treatment, indicating that kaolinite, if present, occurs only in very small amounts. Persistence of the 7 Å peaks of specimens heated to 550° C (not shown) gives further supporting evidence that the 7 Å peak is essentially a reflection of chlorite for both Recent and Pleistocene sediments. Lewis (1966), on the basis of other diagnostic tests, came to a similar conclusion.

5.14.8 Semiquantitive Interpretation of Clay Mineral Abundances

The particle size distribution tests, discussed in 5.6, revealed that the surficial mud and the glacio-lacustrine deposit contain from 50 to 80 per cent clay-size fraction ($< 2\ \mu$). These values can be misleading when the actual percentage of clay minerals is considered. Thomas (1969) calculated the clay component for the surficial mud of Lake Erie from the following equation:

$$\% \text{ Clay} = 100\% - (\% \text{ Organic Matter} + \% \ CaCO_3 + \% \text{ Feldspar})$$

The clay content reported ranged between 29.3 and 67.2 per cent for all three basins of Lake Erie, and the maximum value was obtained in the vicinity of the 1972 bore-hole investigation.

Using above data (Sections 5.14.2 to 5.14.7) and data published by Lewis (1966) and Thomas (1969), the very approximate composition of the surficial mud and the till deposit within the area of the 1972 borehole investigation is estimated in Table 9. Due to lack of data it is not possible to estimate the composition of the glacio-lacustrine deposit.

Among clay minerals, illite appears to be by far the most abundant mineral, followed by chlorite. The amount of smectite is in the order of 5 per cent at the water-sediment interface, and it decreases with depth in the sediment column. The amount of interlayered minerals likewise decreases with depth. Kaolinite and vermiculite are absent or occur in trace amounts. The semiquantitative estimate of the clay faction composition was carried out following the method described by Carver (1971) using the peak-height ratios for glycolated specimens and for specimens heated at 180°C for one hour. In

Table 9. Estimated sediment composition in weight percentage of dry sediment.

	Surficial Mud	Till and Reworked Till
Clay Minerals	55 - 70	30 - 45
Quartz and Feldspar	25 - 35	30 - 40
Calcite	0 - 20	10 - 20
Dolomite	0 - 10	5 - 8
Oxidizable Matter	1 - 4	2

Table 10. Estimated composition of clay fraction in per cent

	Surficial Mud		Till and Reworked Till
	Depth 0 Ft	Depth 10 Ft	
Illite	75	80	85
Chlorite (including vermiculite)	15	13	11
Kaolinite	trace or absent	trace or absent	trace or absent
Smectite	5	3	2
Interlayered Minerals	5	4	2

addition, the estimate is based on test results described in 5.14.5 to 5.14.7. The estimate, which should be considered as a very crude approximation, is presented in Table 10.

5.15 Study of Particle Size and Shape by Scanning Electron Microscopy

The primary purpose of the electron-optical study was to determine the shapes and sizes of clay and silt particles in the sediment column. For the study, sediment specimens were ultrasonically dispersed prior to viewing, and, consequently, no information on in situ microstructure was obtained.

Seven speciments from Borehole 13163 were examined; five specimens of the surficial Recent mud (Samples 1-1, 1-2, 3-1, 4-2, and 8-1), and two specimens of the Pleistocene till (Samples 8-5 and 12-1). The study did not reveal any conspicuous changes in particle morphology with depth. The most noticeable vertical trend observed was a gradual decrease in the amount of fine ($< 1\ \mu$) amorphous or poorly crystalline material with depth. This trend is documented by the comparison of Plate 24 (Sample 1-1) and Plate 39 (Sample 8-5). An increase in the average size of clay flakes with depth was also observed (Plates 25 and 40). With the exception of Sample 12-1, all samples were weathered, as documented by the abundance of amorphous fines (Plates 25, 28, 31, 36 and 39) and disturbed surfaces of silt-size particles (Plates 27, 31, 32, 33 and 36).

Four morphologically different particle types were distinguished:

(a) Clay Flakes. The particles were found in both Recent and Pleistocene sediments, either as individual flakes or flocs. The particle sizes range from approximately

2 μ (Plate 26) to approximately 10 μ (Plates 30 and 41). Their outlines are mostly irregular, however several crudely hexagonal platelets, suggesting a high degree of crystallinity, were encountered in the till samples (Plates 41 and 42). The clay flakes were often seen to form discrete, closely adhering coatings on silt-size particles (Plates 34 and 38). The X-ray diffraction results (Section 5.14) and EDAX (Electron Dispersive Analysis of X-rays) microanalyses carried out on samples from Boreholes 13156 and 13163 (Mudroch and Zeman, unpublished) indicate that these are phyllosilicates predominantly of illitic composition.

(b) Amorphous Material. The amorphous material was found to be quite ubiquitous in both sediments, occurring either in the form of dense masses (Plate 25) or in the form of coatings on clay and non-clay particles (Plates 27 and 41). Much of this material in samples of comparable lacustrine sediments was found to be dithionite-soluble (Mudroch and Zeman, 1975). The EDAX microanalyses on samples from Boreholes 13156 and 13163 yielded very similar elemental compositions for both amorphous material and clay crystalline particles. The formation of amorphous material is thus most probably closely associated with the weathering and degradation of the clay-mineral fraction.

(c) Silt-Size Particles with Basal Cleavage. The micaceous silt-size particles were observed throughout both sediments (Plates 24, 27 and 39). The particles are mostly weathered as evidenced by the irregular surface morphology, the contortion of cleavage surfaces, and fractures along (hko) edges (Plate 24). Most likely some clay minerals and amorphous material are formed by chemical weathering and physical disintegration of these particles.

(d) Clay-Size and Silt-Size Accessory Minerals. Mineral particles included in this group are angular (Plates 22 and 36) to subangular (Plates 27, 33 and 37, with no apparent basal cleavage. The X-ray diffraction analyses (Section 5.14.1), as well as the preliminary EDAX data, indicate that these particles are, in the order of decreasing abundance, quartz, calcite, dolomite, plagioclase, orthoclase, and amphibole. Rare occurrences of gypsum and heavy minerals were also detected by the EDAX equipment. The surfaces of some non-clay particles show morphological features characteristic either of dissolution or secondary precipitation (Plates 33 and 44). The apparent cementation of these particles was noted on several occasions (Plates 33 and 38). The apparent cementation, as seen under the microscope, is formed either by interparticle bonds or by fine material precipitated during the preparation of the specimens. The possibility of natural cementation in the Recent mud deposit is discussed below in Section 6.3.

In summary, the results of electron-optical observations illustrate the close association of crystalline particles and amorphous material. For the sediments studied, there seems to exist a continuous gradation from well-crystallized to poorly crystallized, and amorphous material. The greatest amount of amorphous material was observed in the surficial zone of the Recent mud. The amorphous material was found to decrease with depth but to be present even in deeper parts of the sediment profile. The apparent cementation of non-clay particles was noted in the case of two specimens coming from the lower zone of the Recent mud (Samples 4-2 and 8-2). No similar cementation of clay crystalline particles was observed. Due to mostly irregular outlines of clay particles, it was not possible to identify clay minerals on the basis of their morphology. A systematic method for the identification of individual clay-size particles using the transmission electron microscope and the EDAX equipment has been developed in a later study (Mudroch, Zeman and Sandilands, 1976).

CHAPTER 6

DISCUSSION OF ENGINEERING - GEOLOGY RELATIONSHIPS

6.1 Correlation of Geotechnical Properties

In this chapter, geotechnical properties are examined and mutually compared for the purpose of noting whether any direct relationship among the properties can be observed. Two approaches were used. In the first approach, two properties with a commonly noted empirical relationship were correlated. An example of this type of correlation is the plot of the liquid limit versus the plasticity index on the Casagrande plasticity chart discussed above in 5.3 (Figs. 10.2 to 10.3). Such a correlation allows a meaningful comparison with data obtained for similar sediments elsewhere, and reveals whether the properties follow or depart from the expected trend. Three other correlations of this type are Skempton's activity (Fig. 15.1), the undrained shear strength versus the plasticity (Figs. 15.2 and 15.3), and the compressibility versus the plasticity (Fig. 15.4). The geological and engineering significance of these correlations is evaluated in Sections 6.1.1. to 6.1.3. In the second approach, the properties that appear to possess a causative link between themselves are compared. These are the water content versus the plasticity (Fig. 15.5), the oxidizable matter versus the plasticity (Fig. 15.6), and the sensitivity versus the total carbon content (Fig. 15.7). The latter correlations are considered to be characteristic for the Lake Erie sediments only. They may be, however, of significance for other localities. The correlations are discussed in Sections 6.1.4. to 6.1.6.

6.1.1 Activity

The term activity was coined by Skempton (1953), and it is defined as the ratio of the plasticity index to the clay fraction content. The activity ratio can be usually related to the clay mineralogy and geological history of a particular sediment stratum, and it often represents a characteristic constant. For natural clays containing some coarser particles Skempton (1953) gave the following values: Na-montmorillonite 7.2, Ca-montmorillonite 1.5, illite 0.9, and kaolinite 0.33 to 0.46. On the basis of the activity ratio Skempton (1953) further divided clays into the inactive group (activity less than 0.75), the normal group (activity between 0.75 and 1.25), and the active group (activity greater than 1.25).

In examining the data presented in Figs. 15.1.1 and 15.1.2, the most conspicuous feature is a large scatter of results obtained for the surficial Recent mud, whose activity decreases significantly with depth primarily due to the decrease in the plasticity index. As previously noted although the clay fraction becomes more abundant with depth, the plasticity decreases. This trend suggests that the plasticity of the surficial mud is not controlled by the clay fraction content.

The glacio-lacustrine deposit forms a well-defined cluster with an average value of about 0.4. The till deposit forms another cluster characterized by the lower plasticity index and the lower clay fraction content with the activity ratio of about 0.3.

6.1.2 Undrained Shear Strength versus Plasticity

Skempton (1957) suggested that the rate of increase in shear strength compared to the effective overburden pressure, expressed by the ratio s_u/p', is a function of a clay type and of the clay plasticity. He proposed the following empirical relationship for normally consolidated clays:

$$s_u/p' = 0.11 + 0.0037\, I_p \qquad (2)$$

where s_u is the undrained shear strength, p' is the effective overburden pressure, and I_p is the plasticity index.

A very similar relationship, referred to as the Skempton-Bjerrum correlation, was presented in the form of a mathematically undefined curve by Bjerrum and Simmons (1960). These authors pointed out that the Skempton-Bjerrum correlation represents a lower limit for the s_u/p' ratio, and in the case of a fresh-water environment the ratio can be significantly higher.

The empirical relationship given by Eq (2) has been used solely for the evaluation of the surficial mud, since the other two sediment types are most likely not normally consolidated. Plotted results for Boreholes 13163 and 13156 reveal generally higher values of s_u/p' with regard to Skempton's correlation, and furthermore, the results are not in any obvious agreement with the correlation. The greatest departures from this correlation occur for samples taken close to the lake bottom interface and those taken immediately above the Pleistocene contact. The first anomalous group represents high plasticity clays, and the high s_u/p' values can be possibly attributed to the causes of very high plasticity. The second group represents zones with higher shear strength values which may be caused by the natural cementation of sediment particles (such a possibility is discussed below in Section 6.3). The results that fall below Skempton's correlation represent for the most part tests on partially disturbed samples. The data from other boreholes were not plotted, however they reveal similar trend as the data shown in Figs. 15.2.1. and 15.2.2. It is concluded that Skempton's correlation is not applicable to the surficial mud, and due to the large scattering of data no other positive correlation between s_u/p' and I_p can be proposed.

Bjerrum and Simmons (1960) suggested an empirical correlation between s_u/p' and the liquidity index based on the tests of normally consolidated clays with a wide range in plasticity (W_l from 26 to 127 per cent, I_l from 0.28 to 3.43). It can be seen in Figs. 15.3.1. and 15.3.2 that the data for the surficial mud bear no resemblance to this correlation. Once again, the s_u/p' values fall mostly above the suggested correlation, and the random dispersion of data precludes any other positive correlation.

6.1.3 Compressibility versus Plasticity

Terzaghi and Peck (1967) proposed for "an ordinary clay of medium to low sensitivity" an empirical relationship between the compression index and the liquid limit represented by the equation

$$C_c = 0.009\ (W_l - 10\%) \qquad (3)$$

McClelland (1967) suggested a somewhat similar relationship for the delta and prodelta clays of the Mississippi River, expressed by the equation

$$C_c = 0.0011\ (W_l - 16\%) \qquad (4)$$

These two relationships are compared to the results of consolidation tests (Section 5.7) on the surficial mud samples of Lake Erie in Fig. 15.4. Based on the limited data available, it appears that for a given magnitude of the liquid limit the surficial mud is appreciably more compressible than typical normally consolidated clays. Unusually high compressibility of the surficial mud is likely caused by an open structure of clay and silt particles at a very high water content. Furthermore, the presence of a swelling mineral within the mud would augment its compressibility. As pointed out by Grim (1962), the inactive clays, i.e. those containing illite, chlorite and kaolinite, are considerably less compressible than active montmorillonite clays. Laboratory data by Samuels, quoted in Grim (1962), can be used as an experimental evidence for the difference in compressibility attributable to clay mineral composition.

A paucity of consolidation data for the Lake Erie sediments precludes the proposition of an empirical relationship, however the few data available indicate the likelihood of a considerably steeper slope of a correlation line, compared to the correlations shown in Fig. 15.4.

6.1.4. Water Content versus Plasticity

A consistent relationship between the natural water content and the liquid limit of the surficial mud has been noted in six boreholes for which the liquid limit values were determined. This relationship, illustrated in Fig. 15.5, indicates a conspicuous increase in the liquid limit with the increasing water content. It has been commonly observed that freshly sedimented clays have the liquidity index close to 1 (Grim, 1962). The proposed correlation is shown to lie above the line $I_l = 1$, which represents the equality between the water content and the liquid limit, for the liquid limit in excess of 70 per cent. The relationship also reflects the influence of the depth of burial since the samples with the liquidity index above unity are, for the most part, those taken within the uppermost 20 ft (6.1 m) of the lacustrine sediment column.

6.1.5 Oxidizable Matter versus Plasticity

On the basis of limited amount of data available (Section 5.10), a positive relationship appears to exist, for the surficial mud, between the liquid limit and the amount of oxidizable matter (Fig. 15.6). No such relationship could have been established for the till deposit, which has approximately constant values of the two properties discussed. The relationship for the surficial mud is in accordance with the general observation that an increase in organic matter content causes an increase in the liquid limit (Seed *et al.*, 1964 b; Schmidt, 1965; and Yong and Warkentin, 1966). Seed *et al.* (1964 b) ascribed this effect to the two following causes:

a) presence of organic matter increases water absorption capacity of a sediment;

b) anorganic sediment has greater capability to adopt a loose structure having high void ratio.

Thus it is quite likely that the decrease in plasticity with depth in the surficial mud is controlled not only by the desiccation of the sediment, but it is also irreversibly affected by the oxidation phase of the organic matter and ferrous and manganous compounds.

The influence of natural organic compounds upon geotechnical properties of lacustrine sediments warrants further research. Grim (1962) pointed out that high plastic properties of some clays can be in part attributed to a minor presence of organic compounds. He further mentioned that certain polar or ionic organic compounds can have the reverse effect, since they lower the affinity for water of clay minerals and thus decrease plasticity.

Jerbo (1967) described interesting laboratory tests with glutamic acid, one of the amino acids present in marine sediments. On the basis of the tests he was able to show that infiltration of a clay sample with a low concentration glutamic acid solution resulted in an appreciable reduction of the remolded shear strength and an increase in the cation exchange capacity. The effect on plasticity was not studied, however it seems reasonable to expect that such treatment would tend to increase the plastic properties of clay minerals.

6.1.6 Sensitivity versus Total Carbon Content

As described above (Section 5.5), the sensitivity of the surficial Recent mud was generally found to increase with depth. A plausible explanation for this phenomenon seems to be the presence of cementing compounds which may precipitate at the contacts of clay particles. Carbonates and amorphous hydrous oxides can act as cementing agents, in particular in Recent clays (Mitchell and Houston, 1969; Sangrey, 1972). The apparent correlation shown in Fig. 15.7 between the sensitivity and the amount of total carbon may be compatible with the hypothesis that natural carbonate cementation is at least partially responsible for the clay medium sensitivity in the lower zone of the surficial mud. The possible occurrence of natural cementation zones in the surficial mud is discussed below in Section 6.3.

The sensitivity values of the surficial Recent mud and the Pleistocene deposits are not strictly comparable. In the Recent mud with a relatively high water content the initial failure of the sediment is caused primarily by the disruption of cohesion at small strains and the disturbance of metastable fabric. Upon remolding, interparticle water acts as a lubricating agent and consequently the remolded shear strength is low. The high sensitivity values in the Pleistocene deposits were recorded for overconsolidated sediments with the water content close to the plastic limit. The undisturbed shear strength is primarily due to the sediment resistance to dilatancy and interparticle friction. The initial failure occurs typically at larger strains through the formation of macroscopic or microscopic fissures. The behaviour of the remolded sediment is that of a fissured stiff clay.

6.2 Research into the Causes of High Plasticity

One of the most significant findings of the laboratory geotechnical testing was the unusually high plasticity of the surficial mud, and its very good correlation with the natural water content and the depth of burial. It was felt that an understanding of this phenomenon would be of importance for any attempt to extrapolate geotechnical properties to other portions of Lake Erie. Plasticity results were found to be well suited for classification purposes since, as shown in Fig. 10.3, the three lacustrine sediments can be easily distinguished on the basis of the Atterberg limits. Furthermore, the importance of plasticity is underscored by the fact that the plasticity can be empirically correlated with the clay mineralogy, the undrained shear strength and the compressibility of clay sediments (Section6.1.1. to 6.1.3). In this connection it was found that the surficial Recent mud displays a rather anomalous behaviour in comparison with typical normally consolidated clays described by others. The research of pertinent literature revealed that the high plasticity may be a distinguishing feature of the Lake Erie clays.

6.2.1 Theoretical Aspects of the Atterberg Limits

Variations in measured values of the Atterberg limits are principally influenced by the abundance and the properties of the clay fraction in sediments. The liquid and plastic limits generally tend to increase with a decrease in particle size, an increase in the organic matter content and a decrease in the order of crystallinity. Interparticle forces of attraction and repulsion are believed to play a dominant part in the mechanistic portrait of clay plasticity. The net magnitude of interparticle forces is essentially influenced by clay mineralogy, particle shape and size, the chemistry of interstitial fluid, and the type of adsorbed exchangeable cations. Active clay minerals, such as montmorillonite, have a large negative charge, and therefore the net interparticle force is that of repulsion. The liquid and plastic limits of montmorillonites vary considerably; the variation being primarily caused by the type of exchangeable cation but also by the variation in the structure and composition of the clay mineral itself (Grim 1962). Montmorillonites saturated with monovalent cations, such as lithium or sodium, have particularly high Atterberg limits. Increase in the salt concentration of the interstitial fluid or the substitution of a divalent for a monovalent cation tend to decrease the net repulsive force and therefore also the interparticle distance, which results in the lowering of the Atterberg limits. On the other hand, inactive clays, such as kaolinite, show a reverse effect. The sodium and lithium saturated kaolinites tend to have slightly lower Atterberg limits than those saturated with divalent cations. This behaviour can be accounted for by the smaller attractive force of a monovalent cation and a subsequent change of the particle arrangement from an edge-to-face flocculated structure to a more parallel one (Yong and Warkentin, 1966). In general, the values of the liquid limit are found to vary over a considerably larger range than those of the plastic limit, and the effect of the type of exchangeable cation is likewise more pronounced in the case of the liquid limit.

Grim (1962), in his penetrating analysis of the physical significance of the Atterberg limits, suggested that the adsorbed water in addition to the net charge of a clay particle plays an active role in the plasticity behaviour of clays. He assigned importance to the different physical state of adsorbed water on clay particles. As he pointed out, molecular layers of adsorbed water close to the particle surface consist of oriented molecules, which are rigidly held to the particle. The oriented water has greater viscosity and greater density compared to the ordinary water. The rigidity of water decreases in the direction from the particle, and the water gradually becomes mobile and unoriented at some distance from the particle. According to this concept, the plastic limit represents the adsorption capacity of a sediment to such degree that sediment particles hold all fixed water plus some mobile or semi-mobile water in the outermost layer, which allows slight lubrication action between particles. The attractive force between particles is still quite strong. When more water is added, the outermost layers become less and less rigid. The liquid limt then represents the adsorption capacity of a sediment in which semi-mobile water is still adsorbed to the particle surface with a sufficient force to prevent the separation of particles. Within the plastic range, the magnitude of which is expressed by the plasticity index, the outermost layers of water possess the lubrication properties, and hence the sediment yields to a slight applied force as demonstrated in the standard test.

Seed et al. (1964 a) studied the Atterberg limits for artifical mixtures containing bentonite, illite, kaolinite and sand. The authors showed that a mixture of 5% bentonite and 95% illite has lower plasticity (Ip = 25.1), and therefore lower activity and swelling capacity, than a similar mixture of bentonite and kaolinite (Ip= 40.9), even although for the "pure" clays used kaolinite had Ip of 10.2 and illite one of 23.1. The difference was accounted for by possible interstratification of bentonite and illite particles. Grim (1962) pointed out that the presence of 5 to 10 per cent montmorillonite associated with inactive clay minerals may greatly increase the limit values.

Other factors that may significantly influence the plasticity results are air drying (discussed below in 6.2.2), which generally decreases the Atterberg limits (Lambe, 1951; Grim, 1962; Warkentin, 1972) and the presence of organic matter as mentioned in 6.1.5.

Several investigators (Casagrande, 1932; Norman, 1958; Seed et al., 1964b) have pointed out that the determination of liquid limit represents a dynamic shear strength test, and that the number of blows required to close the standard groove, from which the liquid limit is computed, can be correlated with the remolded shear strength. This shear strength was estimated to be in the order of 40 psf or 1.9 kN/m^2. (Norman, 1958).

The measurement of the Atterberg limits suffers from several shortcomings that are inherent in the testing methods. The liquid limit value can be appreciably influenced by the hardness of the base of the liquid limit device. Thus it was found by Norman (1958) that the bases of different hardness caused variation in the liquid limit values between 63 and 70 per cent. Further disadvantages are encountered during testing of sediments with low plasticity, in which it is difficult to cut a groove or roll them into threads, and which exhibit a tendency to slide in the cup rather than to flow as a plastic. The very sensitive or quick clays are difficult to test since they liquefy after slight disturbance. Clays with amorphous coating, e.g. formed by a silica gel, can have much higher plasticity after extensive remolding in comparison with their plasticity behaviour in situ (Mencl, 1966). There have been several attempts to substitute the Casagrande liquid limit test by various cone-penetrometer methods (Vasilev, 1949; Sherwood and Ryley, 1970). These methods appear to be more reproducible than the Casagrande method, however to date they have not achieved widespread application.

6.2.2 Interpretation of the Plasticity Results

As the first attempt to explain high plasticity, a relationship between grain size distribution and plasticity was examined. While interdependence of the two properties would require higher plasticity for finer sediments, no such relationship was found. As shown by the grain size curves in Figs. 11.1, 11.3 and 11.4; as well as by the activity charts in Figs. 15.1.1 and 15.1.2, the surficial Recent mud appears to become finer with depth, and the glacio-lacustrine deposit of medium plasticity on the average has higher clay-size content ($<2\ \mu$) than the surficial Recent mud. Consequently it is concluded that the plasticity is not controlled by the clay content present in the two sediment types. The glycol retention results (Figs. 9.1.1 and 9.1.3) likewise do not furnish satisfactory explanation for the high plasticity values obtained.

As mentioned in 6.1.5, a good correlation exists between the plasticity and the amount of organic matter in cohesive sediments. However, it is believed that the plasticity data cannot be adequately explained solely on this basis since the organic carbon values (Table 2) do not appear to be sufficiently high to cause measured plasticity values. Furthermore, organic clays should fall on the Casagrande chart below the "A" line, which, however, was not the case for the deposits studied. On the basis of limited experimental data it is believed that the presence of the organic matter in the lacustrine deposits causes a slight increase in plasticity but, on the other hand, the organic matter does not appear to act as the principal contributing factor. This assertion is further supported by the results of plasticity tests on samples before and after the removal of organic matter by hydrogen peroxide (Fig. 14.1 and 14.2).

The effect of air drying in the laboratory was studied using five samples from Borehole 13163. The results shown in Figs. 14.1 and 14.2 indicate a pronounced decrease in the liquid limit and a moderate decrease in the plastic limit for the surficial Recent mud after air drying (Samples 1-1, 1-2 and 3-1). In contrast, the plasticity of the till deposit (Samples 12-1 and 13) is unaffected by air drying. The trends and changes in the Atterberg limits on air drying are primarily attributed to the different depositional history, and therefore different degree of chemical weathering in the Pleistocene and Holocene sediments.

The strong drying effect in the case of the surficial Recent mud is in agreement with the relationship between w and W_l demonstrated in Fig. 15.5, the Penfield test results (Table 8), and the X-ray diffraction results (Section 5.14.5, Figs. 13.3 and 13.4). Drying accompanied with the partial oxidation of organic matter and other oxidizable compounds in the sediment probably causes a non-reversible collapse of clay structure and a substantial decrease in the water adsorption capacity after re-wetting. The X-ray diffraction analyses (Section 5.14) and the electron-optical observations indicate that the surficial Recent mud is a weathered clay with relatively high content of amorphous aluminosilicates. The sediment has a similar mineralogical composition, and it shows similar sensitivity to air drying as the weathered clay till at Sarnia, Ontario, described by Quigley and Ogunbadejo (1973).

In the case of the till deposit, no change in plasticity after air drying indicates a possibility that this sediment was subaerially exposed and therefore dehydrated and oxidized during its deposition or during subsequent low-level lake stages (Chapter 2). Plasticity tests and cation exchange tests carried out on the samples of glacio-lacustrine deposit (Mudroch and Zeman, 1975) showed likewise no appreciable changes on air drying.

6.3 Research into Suspected Interparticle Cementation of the Lake Erie Postglacial Sediment

Several unusually high shear strength measurements (Section 5.5), as well as several electron-optical observations (Section 5.15), indicated a possible occurrence of naturally-cemented zones within the surficial mud. As an introduction to this topic, main types of cementing agents are briefly reviewed in Section 6.3.1. A presentation of available supporting evidence for the cementation of the surficial mud follows in Section 6.3.2.

6.3.1 Nature of Cementation Bonds in Clayey Sediments

Interparticle cementation has been attributed in the literature to at least three mineralogically different precipitates.

Carbonates are probably the most frequently mentioned sources of natural cementation. Müller (1967) considers calcium carbonate to be the most important pore cement in argillaceous sediments, which can precipitate even at the beginning of the shallow burial stage. Einsele (1967) found an increase in shear strength values in a marine sediment when the carbonate content exceeded 40 per cent. Cementation due to the presence of 20 to 40 per cent carbonates has been postulated for a marine clay from the Labrador Basin (Kelly et al., 1974). The interparticle bonding of this type has been proposed by the latter authors since shear strength values were found to increase with increasing carbonate content, and the lack of agreement was found between predicted and observed s_u/p' values.

Another possible cementing agent is silica, occurring either in an amorphous form or in very fine crystalline quartz particles. Interparticle quartz cementation has received an increasing attention in connection with research on the extrasensitive behaviour of quick clays (Cabrera and Smalley, 1973; Krinsley and Smalley, 1973). These authors postulated a new approach to the failure mechanism of quick clays, according to which fine quartz particles, reduced to clay-size dimensions during abrasion and crushing, form inactive short-range bonds. The bonds are basically Van der Waals bonds augmented by cementation (Cabrera and Smalley, 1973). The short-range bonds permit elastic deformation followed by a brittle failure resulting in a complete and irreversible breakdown of the sediment skeleton. This is essentially a behaviour well documented for sensitive clays. Whalley (1974) proposed that quartz-quartz bonds can develop under low stresses due to a localized formation of high pH in interstitial water. As he pointed out, amorphous quartz has much higher solubility at the same temperature in comparison with crystalline quartz, and at values higher than pH 9 amorphous quartz goes readily into solution.

Apart from crystalline particles, glacially derived clays are known to contain amorphous hydrous and anhydrous oxides of iron, aluminum and manganese. These compounds may also act as cementing agents. Thus Kenney et al. (1967) found that the removal of soluble iron by EDTA (disodium salt of ethylene diamine tetraacetic acid) caused a 60 per cent decrease of the apparent preconsolidation pressure of a sensitive marine clay from the east coast of Labrador. Sangrey (1972) concluded that amorphous hydrous and anhydrous oxides are frequently responsible for the natural cementation of glacially derived normally-consolidated clays. The removal of poorly-ordered sediment material by chemical dissolution techniques (e.g. Follett et al., 1965) generally results in the dispersion of individual particles, suggesting that these compounds bind primary particles into larger aggregates. McKyes et al. (1973) examined Champlain Sea sediments from two locations in Quebec containing up to 12 per cent of amorphous silicon-iron hydroxides, and concluded that the presence of amorphous material may be a major factor in the extreme sensitivity of these sediments.

6.3.2 Supporting Evidence for the Interparticle Cementation of the Lake Erie Postglacial Sediment

The examination of the undrained shear strength profiles of the surficial mud (Figs. 9.1, 9.2.1, 9.3.1, 9.4, 9.5.1, 9.6.1, and 9.7.1) reveals that in all boreholes there exist one or two zones of unexpectedly high shear strength values. A similar conclusion has been reached by Davis and Kim (1973). The difference between observed shear strength values and those predicted for a normally consolidated deposit using Skempton's correlation is shown in Fig. 15.2.1 for Borehole 13163 and in 15.2.2 for Borehole 13156. The location of the zones (Table 11) can be determined only approximately due to the interfering effect of core disturbance, and gradual, rather than sharply defined, boundaries. In nearshore boreholes (13160, 13161, 13163, and 13189), only one zone was found occurring from 10 to 25 ft (3 to 7.6 m) below lake bottom. In offshore boreholes (13156, 13193, and 13194) two zones seem to exist; the upper one occurring between 13 and 25 ft (4 and 7.6 m) below lake bottom, and the lower one at 30 to 45 ft (9.2 to 13.7 m). In general, all zones occur in the lower portion of the postglacial sedimentary column.

The possibility of natural cementation is also supported by the results of electron-optical observations described above in Section 5.15. Several electron micrographs (e.g. Plates 33 and 35) of the sediment coming from the zone of the relatively high shear strength in Borehole 13163 show apparent cementation bonds of silt-size particles. It is however possible that these bonds may have been also produced by the sedimentation of very fine amorphous material during specimen preparation.

Table II. Zones of apparent cementation in the postglacial sediment

Borehole	Elevation				Depth			
	from ft	to ft	from m	to m	from ft	to ft	from m	to m
13156	475.0	466.5	144.7	142.2	15.0	23.5	4.6	7.2
13156	451.0	444.5	137.5	135.5	39.0	45.5	11.9	13.9
13160	481.0	473.1	146.6	144.2	10.0	17.9	3.0	5.5
13161	476.5	474.0	145.2	144.5	15.5	18.0	4.7	5.5
13163	485.5	477.1	148.0	145.4	12.5	19.9	3.8	6.1
13189	481.0	466.7	146.6	142.3	10.0	24.3	3.0	7.4
13193	479.0	472.0	146.0	143.9	13.0	20.0	4.0	6.1
13193	456.5	448.0	139.1	136.6	35.5	44.0	10.8	13.4
13194	474.0	464.0	144.5	141.4	15.0	25.0	4.6	7.6
13194	456.5	449.0	139.1	136.9	32.5	40.0	9.9	12.2

In comparison with the overlying surficial layer, the zones of apparent cementation occur within a sediment with a higher shear strength, a higher specific gravity, and a higher unit weight. The limited amount of grain size analyses available for the surficial mud (Figs. 11.1 and 11.3) indicates that the "cemented" zones have a higher content of clay-size particles. This trend was confirmed by a detailed examination of samples from Borehole 13194, for which a gradual decrease in the mean particle size with depth was obtained (Anderson 1975). A conspicuous increase in the total carbon content with depth has been determined for Borehole 13163 (Section 5.11). Quantitative analyses of calcium carbonate in Borehole 13194 (Anderson, 1975) indicate that the sediment near the Pleistocene unconformity, which falls within the "cemented" zones shown in Table II, contains 15 to 25 per cent calcium carbonate. Similar calcium carbonate values have been established for the "cemented" zones in Borehole 13156 (Mudroch and Zeman, unpublished). In all boreholes the "cemented" zones are further characterized by a lower liquid limit, a lower plastic limit, a lower moisture content, and probably also a lower oxidizable matter content. Typical shear strength, water content, plasticity, and carbonate content values from "cemented" and "uncemented" zones are compared in Table 12.

Independent evidence that appears to support the possibility of the diagenetic cementation within the lower portion of the postglacial sediment comes from results of a sub-bottom reflection survey in the central basin of Lake Erie (Wall, 1968). The geophysical records indicated an occurrence of a distinct reflecting horizon referred to as the reflecting horizon "a" (Wall, 1968, p. 96). The horizon was found to cover an approximate area of 120 sq miles (310 km^2) in the offshore central portion of the basin (Wall, 1968, Fig. 3). The boundaries of the area roughly coincide with a 10-m isopach contour shown in Fig. 6. The horizon "a" was found at elevations from 475 to 490 ft (145 to 149 m), which corresponds to depths from 10 to 20 ft (3 to 6.1 m) below the lake bottom. The reflections from this horizon are described as without sharp beginning and extending further down to the Holocene-Pleistocene unconformity. Wall (1968, p.100) interpreted the reflecting horizon and the underlying layer as "a buried shallow-water deposit probably containing sand and silt lenses with shells, shell fragments and peat and plant-rich clay layers within which entrapped gas may be present". This conclusion is, however, in conflict with the character

Table 12. Comparison of representative physical and compositional properties in "cemented" and "uncemented" zones of the surficial Recent mud

Borehole	Depth ft	m	s_u psf	s_u kN/m^2	$\frac{s_u}{p'}$	w %	W_l %	<4 μ %	Total Carbon %	Calcium Carbonate %
					Surficial "Uncemented" Zone					
13156	3.5	1.1	40	1.9	0.8	152	120	-	1.40**	-
13160	3.0	0.9	50	2.4	1.4	160	108	-	-	-
13161	3.0	0.9	40	1.9	0.8	160	-	-	-	-
13163	0.0	0.0	20	1.0	-	289	123	67	2.00	-
13163	2.0	0.6	25	1.2	0.6	150	94	-	1.66	-
13163	9.4	1.6	30	1.4	0.4	120	86	67	1.53	-
13189	3.0	0.9	20	1.0	0.4	120	90	-	-	-
13193	4.0	1.2	30	1.4	0.5	135	85	-	-	-
13194	0.0	0.0	-	-	-	219	-	75*	-	4.1*
13194	4.4	1.3	-	-	-	-	-	73*	-	1.0*
13194	9.0	2.7	-	-	-	130	105	69*	-	2.5*
					Upper "Cemented" Zone					
13156	20.0	6.1	80	3.8	0.4	95	85	-	2.15**	-
13160	15.0	4.6	140	6.7	0.5	80	70	-	-	-
13161	17.5	5.3	105	5.0	0.5	80	-	-	-	-
13163	13.4	4.1	80	3.8	0.2	115	87	47	1.62	-
13163	16.0	4.9	65	3.1	0.2	70	50	68	3.75	-
13189	21.0	6.4	120	5.7	0.2	65	-	-	-	-
13193	16.0	4.9	110	5.3	0.3	85	80	-	-	-
13194	17.4	5.3	95	4.5	0.2	95	90	72*	-	9.5*
13194	23.9	7.3	110	5.3	0.2	85	-	81*	-	22.0*
					Lower "Cemented" Zone					
13156	39.0	11.9	125	6.0	0.2	72	70	-	3.87**	-
13156	42.5	13.0	180	8.6	0.3	70	68	90	-	-
13193	39.0	11.9	350	16.8	0.3	40	50	68	-	-
13194	32.6	9.9	115	5.5	0.2	75	-	87*	-	25.6*
13194	36.3	11.1	125	6.0	0.1	70	75	93*	-	22.0*

* Unpublished data, Anderson, 1975

** Unpublished data, Mudroch and Zeman.

of sediments in cores 13156, 13193, and 13194 (Figs. 9.21, 9.6.1, and 9.7.1 respectively). These three boreholes all lie within the area in which the "a" reflections were found. The depth of "a" horizon in these boreholes corresponds to the occurrence of the upper zone of apparent cementation (Table II).

Future research should determine whether carbonates occurring in apparently cemented zones are predominantly of autochtonic or allochtonic origin. Recent EDAX microanalyses on samples from Borehole 13156 indicate that carbonates are present in the < 1 μ fraction of the sediment, and that Ca also occurs as an enrichment of illites and and chlorites, indicating either adsorbed Ca cations or carbonate coatings (Mudroch and Zeman, unpublished). The study of original microstructure on freeze-dried specimens or ultra-thin sections combined with electron-optical chemical microanalyses may furnish more conclusive results and shed new light on diagenetic changes occurring in recently deposited lacustrine clays.

6.4 Application of Geotechnical Results

While much detailed geotechnical information on lacustrine clay-size sediments exists where they are found on land, the amount of such information available for the off-shore parts of the Great Lakes region is still relatively scarce. This is primarily due to high cost of offshore borehole investigations and little economic justification for such projects in the past.

In recent years, however, there has been a steadily increasing demand for geotechnical investigations in shallow and deep waters. The information derived from the 1972 investigation and the subsequent thesis research may be therefore of interest to those who design offshore facilities, such as drilling platforms for extraction of oil and natural gas, water intake tunnels, subaqueous pipelines, breakwaters, dock structures, and offshore towers. In general, the geotechnical data contained herein may be applied to estimates of bottom hardness and to predictions of penetration of various objects into sediment strata within the study area. The extrapolation of results to other areas of the lake should be carried out with caution using geology as a guide.

A better understanding of geotechnical properties and behaviour is also required for studies of erosion and deposition of offshore clay-size sediments. The physical behaviour of very soft muds near the water sediment interface does not obey commonly used theories of soil mechanics and therefore it is not very well understood at present (Einsele et al., 1974). Poor correlations of the plasticity and the shear strength with the clay-size content of the surficial Recent mud, discussed in Sections 6.1.1. and 6.1.2, suggest that the erosion of offshore clay-size sediments is not principally controlled by the sediment particle size, as rather widely believed. The knowledge of geotechnical parameters, such as the shear strength, the plasticity, and the compressibility, is obviously very important, but does not describe the sediment physical behaviour completely. The effects of sediment depositional history, clay mineralogy, organic and amorphous matter content, and other environmental factors must be also considered.

Another need for the knowledge of sediment geotechnical properties has emerged during manifold problems associated with open water and land disposal of polluted dredged materials from the Great Lakes region. The dredged material is predominantly fine-grained and the contaminants may significantly influence sediment physical behaviour (Mudroch and Zeman, 1975). In order to minimize the deleterious effect of contaminants on lake water quality, it is necessary to study the dispersion of dredged material during open water disposal as well as to predict physical and chemical changes that will occur in dredged slurries confined in disposal areas. A comprehensive physicochemical characterization of the lake bottom sediment appears to be a prerequisite for further research into optimum disposal methods of polluted dredged materials.

6.5 Application Examples

6.5.1 Penetration of Gravity Corers Into Overconsolidated Sediments

The undrained shear strength of nearshore cohesive sediments may occasionally reach very stiff to hard values, 2000 to 4000 psf (96 to 192 kN/m^2), as a result of previous subaerial exposure and desiccation.

The penetration of the corer due to its static weight can be estimated from the bearing capacity equation for a cylindrical pile (Terzaghi and Peck, 1967, Eq. 34.1, p. 225) but taking into account both the inside and outside skin friction, i.e.:

$$Q_d = q_p A_c + 4\pi r\, f_s D_f \qquad (5)$$

where Q_d = required load (tons or kg)

q_p = bearing capacity per unit area of the sediment beneath the base of the corer (psf or kN/m^2)

A_c = cutting shoe area (sq in. or cm^2)

f_s = skin friction (psf or kN/m^2)

r = radius of corer (in. or cm)

D_f = penetration depth (ft or m)

Assume r = 3 in. (7.62 cm) and A_c = 2.82 sq in. (18.2 cm^2). The cutting shoe area complies with a recommended cross-sectional area for offshore corers (Rosfelder and Marshall, 1967). Assume further f_s = 2000 psf (96 kN/m^2), which is the maximum value for dense gravel and intermediate value for very stiff clays (Terzaghi and Peck, 1967, p. 563).

For computation of q_p, Eq. 33. 13, Terzaghi and Peck, 1967, p. 223, may be used, i.e.:

$$q_p = 1.2\, c\, N_c + \gamma' D_f\, N_q + 0.6\, \gamma' r\, N_\gamma \qquad (6)$$

where c (cohesion) = s_u (undrained shear strength) for an undrained (ϕ = O) condition. Assume s_u = 4000 psf (192 kN/m^2).

γ' = submerged unit weight of the sediment, e.g. 67.6 pcf (1.08 g/cm^3) and N_c, N_q and N_γ are bearing capacity factors, which are dimensionless quantities depending only on ϕ.

Substituting into Eq. (6) yields:

N_c = 5.14 $\quad$ N_q = 1.0 $\quad$ N_γ = 0 and

$q_p = 24740$ psf (1188 kN/m^2)

Then, substituting into Eq. (5), the load required for 1-ft (0.3 -m) penetration is:

$Q_d = 3.38$ tons or 3066 kg

The result demonstrates why attempts to sample overconsolidated Pleistocene sediments with gravity corers are rarely successful. The amount of penetration is almost completely controlled by the skin friction.

6.5.2 Consolidation of the Surficial Recent Mud in a Confined Disposal Area

Assume a 20 ft (6.1.-m) thick layer of the Recent mud stored in a diked disposal area. The consolidation behaviour of this material is as established by the consolidation test carried out on Sample 2-2, Borehole 13193, Fig. 12.1.

Then the amount of consolidation S can be estimated from the following equation (Terzaghi and Peck, 1967, Eq. 13.8, p. 72):

$$S = H \frac{C_c}{1 + e_o} \log \frac{p + \Delta p}{p} \qquad (7)$$

where H is the initial thickness of the sediment, i.e. 20 ft (6.1 m)

C_c = compression index, i.e. 1.55 (Fig. 12.1)

e_o = void ratio at surface pressure, say, 0.1 tsf, i.e. 3.17 (Fig. 12.1)

p = surface pressure, in this case 0.1 tsf (9.6 kN/m^2)

Δ p = pressure surcharge, e.g. 0.3 tsf (28.8 kN/m^2)

Substituting the above parameters into Eq. (7) yields:

S = 7.43 log 4.0

S = 4.47 ft or 1.36 m

Time to reach 60 per cent consolidation can be estimated from the following equation (Terzaghi and Peck, 1967, Eq. 25.10, p. 180):

$$t = 0.28 \frac{H^2}{c_v} \qquad (8)$$

where the coefficient of consolidation $c_v = 2 \times 10^{-4}$ cm^2/sec (Fig. 12.1)

Substituting into Eq.(8) yields:

t = 6029 days = 16.5 years (for single drainage)

The results for S and t demonstrate why diked disposal areas filled with fine-grained dredge spoil (e.g. those built around Detroit and Toledo) cannot be used for construction purposes.

6.5.3 Penetration of Jack-Up Drilling Platform into the Recent Mud

The following analysis foll ows a method proposed by Gemenhardt and Focht (1970) who obtained close agreement between theoretical predictions and observed performance of large marine platforms. The method disregards the effect of skin friction along embedded legs since it is assumed that the diameter of the legs is appreciably smaller than the diameter of footings. On the other hand, no reduction of shear strength values is considered to account for the effect of local disturbance around the legs and the footings (Terzaghi and Peck, 1967).

Assume a circular 6-ft (1.83-m) dia. footing and the shear strength profile as established by laboratory vane measurements on samples from Borehole 13156 (Fig. 9.2.1).

A bearing capacity equation for round footing (Gemenhardt and Focht, 1970) is used,

$$q_u = c\,N_c' + \gamma' D \qquad (9)$$

where $c = s_u$ (psf or kN/m^2) for an undrained ($\phi = 0$) condition

D = footing penetration (ft or m)

N_c' = dimensionless bearing capacity factor computed according to the following equation (Skempton, 1951):

$$N_c' = 6.0\,(1 + 0.2\,\frac{D}{B}) \qquad (10)$$

On the basis of the empirical evidence, N_c' is limited to a maximum value of 9.0 at a $\frac{D}{B}$ ratio of 2.5 (Skempton, 1951).

B = footing diameter, i.e. 6 ft or 1.83 m

First, the ultimate bearing capacity vs. depth relationship has to be established. This is done by arbitrarily selecting D and then calculating q_u from Eq. (9). The s_u value used is the one determined one diameter (B) below the depth D; e.g. for D= 10 ft, s_u measured at 16 ft is used.

The q_u values are computed and tabulated below for values of D = 10, 30 and 50 ft.

Table 13. Theoretical bearing capacities q_u for different penetrations D

D		s_u (D+6) from Fig. 9.2.1		$\frac{D}{B}$	N'_c	γ' from Fig. 9.2.1		q_u	
ft	m	psf	kN/m^2			pcf	gcm^{-3}	psf	kN/m^2
10	3.0	60	2.88	1.67	8.0	23.6	0.38	716	34.4
30	9.1	90	4.32	5.0	9.0	29.6	0.47	1698	83.3
50	15.2	200*	9.60*	8.3	9.0	32.6	0.52	3430	164.7

* Disregarding the obvious effect of core disturbance during sampling (see Fig. 9.2.1)

More q_u values can be found, if required, using the same procedure. The relationship can be approximated by a logarithmic curve fit of the form:

$$D = a + b \log q_u \tag{11}$$

Using the selected values of D and computed values of q_u, the best fitting curve has the following coefficients:

$D = -157.9 + 58.6 \log q_u$; r^2 (coefficient of determination) = 0.997

The footing penetration can be estimated from a footing load, which depends on the total weight of the drilling platform. For example, if the footing load is 100 tons (90720 kg), the value of q_u is obtained by dividing this load by the footing area. Using the footing load of 100 tons, the footing penetration is obtained from Eq.(11):

D = 67.7 ft or 20.6 m

The result demonstrates why the Consumers' Gas Company experienced problems with their jack-up drilling platforms operating on the central portion of the Lake Erie basin. The above computation should be considered only as a general example of how geotechnical data may be applied. As mentioned in Section 1.1, the intricacy of similar problems requires a thorough foundation analysis, which has not been attempted within the scope of this thesis.

6.6 . Recommendations for Future Research

There is a need for more frequent application of physicochemical and mineralogical methods to the problems of soil mechanics, especially to those that deal with clay-size sediments.

The limitation of soil mechanics tests has become particularly apparent during investigations that have aimed to determine the causes of "quick" behaviour of the Norwegian and Canadian sensitive clays. Recent discussions (Mitchell and Houston, 1969; Gillot 1971 ; Sangrey, 1972; McKyes et al., 1973; Cabrera and Smalley, 1973) have revealed an unexpected complexity of the quickclay problem, as well as the existence of several plausible explanations for the very high sensitivity of natural quickclays.

The influence of organic matter upon geotechnical properties of clays have been studied e.g. by Schmidt (1965) and Franklin et al.,(1973), however more research is needed to determine whether organic matter acts as a mechanical admixture or is chemically complexed with crystalline and amorphous constituents in clay sediments.

The effect of amorphous material upon the physical behaviour of clay sediments has not been satisfactorily explained and, as Jones and Uehara (1973) pointed out, the explanations proposed are largely speculative.

Many offshore engineering problems require in situ and laboratory testing of stress-strain behaviour. This is often very difficult because samples are frequently too soft to be tested in a consolidation or a triaxial cell. Thus a need arises to study mechanics of very soft clay-water mixtures for which the knowledge of mineralogical and chemical composition is essential. In addition, new testing methods and instruments have to be developed (Migniot, 1968; Salem and Krizek, 1973; Einsele et al., 1974).

CHAPTER 7

CONCLUSION

The principal findings resulting from the field and laboratory investigation of Recent and Pleistocene sediments encountered in the central basin of Lake Erie are:

1. Among five different sampling methods employed during the offshore borehole investigation, coring with the Christensen sampler was found to give the most satisfactory results.

2. The surficial Recent mud, the Pleistocene glacio-lacustrine clay, and the Pleistocene clayey till have geotechnical properties that closely reflect their depositional history. The sediments can be best distinguished by their different plasticity. The undrained shear strength correlates well with the natural water content but not with the plasticity of the sediments. The Pleistocene sediments encountered in the nearshore area above elevation 440 ft (134 m) have been preconsolidated, most probably by subaerial desiccation during low-lake stages of Early Lake Erie. The till deposit of the Erieau moraine is also over-consolidated, possibly due to the weight of a glacier sheet. The surficial Recent mud has the characteristics of a normally consolidated sediment, however in the upper portion it is more compressible than average normally consolidated clays. This phenomenon is attributed to the high plasticity of the deposit. Grain size analyses revealed that the glacio-lacustrine deposit generally contains a higher percentage of clay-size fraction than the surficial mud, indicating that the plasticity is not primarily influenced by the content of clay-size particles. A gradual decrease in mean particle size with depth within the

surficial mud was also noted.

3. Complementary analyses of total carbon content showed that carbonates are leached from the upper portion of the Recent mud deposit. The carbonate content within the Recent mud was found to increase gradually with depth of burial. The total carbon and oxidizable matter values determined for the lower zone of the Recent mud in Borehole 13163 correspond to 15 to 25 per cent calcium carbonate. The total carbon and calcium carbonate values for Recent and Pleistocene sediments have been confirmed by subsequent quantitative analyses carried out at CCIW on samples from Boreholes 13156 and 13194. Values of oxidizable matter content were found to decrease gradually with depth within the Recent mud column, while constant values were obtained for the Pleistocene deposits. Determinations of specific surface area by ethylene glycol retention indicated inconspicuous decrease of amorphous material content with depth, and the results were found to be in agreement with electron-optical observations.

4. The predominant clay mineral in both Recent and Pleistocene sediments is illite which appears to be little affected by weathering, as evidenced by distinct X-ray diffraction peaks obtained for all specimens. On the contrary, chlorite, which is present as the second most abundant clay mineral, is poorly crystallized in the weathered horizon of the surficial mud. The oxidation of chlorite is believed to be responsible for the presence of smectite, the occurrence of which was proven by glycolation, and interlayered minerals in the weathered horizon. A series of X-ray diffraction analyses on wet, air-dried, and rewetted specimens yielded results that agree with the interpretation of the measured plasticity. For the Recent mud these tests indicated significant collapse of peaks with

high d-spacings upon air drying with only partial expansion of these spacings after rewetting. The diffraction traces of the low-plasticity till showed no significant change after air drying and glycolation. A similar insensitivity to air drying and glycolation was later established for the glacio-lacustrine deposit. Potassium saturation and heating of specimens to 500 and 600°C indicated that the mineral with the first-order basal reflection at 14 Å is essentially an iron-rich chlorite. Minor amounts of vermiculite were detected in the weathered horizon of the Recent mud. Diffraction analyses of specimens treated with hydrochloric acid revealed that kaolinite, if present, occurs only in negligible amounts.

5. The scanning electron micrographs showed that the Pleistocene sediments have lower amorphous material content than the surficial mud. Silt size particles with apparent cementation bonds were found within the lower zone of the Recent mud, which is characterized by relatively high shear strength, sensitivity, and carbonate content values. Subsequent electron-optical studies carried out at CCIW have revealed that carbonates at this level are abundant in the clay-size fraction of the sediment.

6. The geotechnical data can be used to estimate lake bottom hardness and its penetration resistance due to static weight. The physicochemical tests of bottom sediments may be applied to studies of cohesive sediment transport and to predictions of dredged material behaviour.

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APPENDICES

A. Description of Samplers Used during the 1972 Borehole Investigation

A.1 The Alpine Free-Falling Piston Sampler (1200 lb)

The free-falling piston coring apparatus, manufactured by the Alpine Geophysical Associates Inc. of Norwood, N.J., was used on all boreholes for sampling of the uppermost soft bottom sediments. The sampler and the basic operating principles are shown in Fig. 8.1, and in Plates 5 to 12. The sampler was borrowed from the CCIW and was slightly modified by HQGA in order to improve the quality of recovered cores. The modification consisted in replacing the existing cutter with a thin-wall cutter. The sampler consists of a 1200-lb (544-kg) head weight with guide fins, a triggering mechanism, and 10-ft (3-m) long coring tubes, which are connected by steel couplings (Plate 7). Up to 60 ft (18 m) of tubing was used at sites where thick deposits of soft Recent sediments were expected. A 2.25-in (57-mm) I.D. plastic liner fits snugly into the coring tubes (Plate 6). Prior to coring, the piston is installed at the bottom of the coring tube just above the core retainer. The piston is then fastened to a wire leading through the coring tubes and the head weight to a come-a-long, which is a part of the triggering mechanism.

A typical coring operation was carried out as follows:

1. A required length of coring tube was estimated based on the expected thickness of soft sediments. The previous experience of the CCIW personnel with the sampler indicated that the sampler usually stops its penetration within the uppermost foot of the Pleistocene glacio-lacustrine sediments.

2. Following the assembly of the coring tubes, thepiston, and the cutting edge, a triggering mechanism was fastened to the piston wire leaving a 10-ft (3-m) slack (scope) wire as shown in Fig. 8. 1a. The installation of a safety pin prevented accidental triggering. The trigger weight was then attached to the triggering mechanism, and the sampler was prepared for lowering.

3. By means of the stationary crane and two hand winches, the sampler was brought to a vertical position. The safety pin was removed and the sampler slowly lowered into the water. As shown on Fig. 8.1c, the length of the trigger weight wire was pre-calculated to keep the trigger weight 10 ft (3 m) below the cutting edge of the sampler.

4. The impact of the trigger weight on the lake bottom released the sampler, which was allowed to fall freely through 10 ft (3 m) to gain sufficient impact force. (The triggering was occasionally accomplished by another method, which was found generally more reliable than self-triggering. In this method, another wire was attached to the triggering arm. This wire was then abruptly pulled from the deck when the cutting edge was 10 ft (3 m) above lake bottom, thus releasing the sampler).

5. After the 10-ft (3-m) free-fall, the sampler, driven by its weight and the impact force, penetrated through the sediment while the piston stayed put at the lake bottom. The sampler was then hoisted slowly by the crane. The penetration depth was estimated from two independent measurements. The first one was based on the distance travelled by the piston inside the tubing before it reached the piston stop, located immediately below the head weight. This distance was quite difficult to measure since the sampler and the wire were usually quite far from the side of the ship. The end of the piston travel was noticed as

a sudden pull to the wire, which during further hauling carried the full weight of the sampler. The second measurement was the length of mud covering the outside of the coring tube, which was measured after the sampler was brought up on deck. The second measurement was considered to be more reliable and therefore recorded, with the first one used as a check. After several trials, it was concluded that the use of the core retainer (Plate 9) was necessary in order to prevent partial or total loss of a core during hoisting.

6. Finally, the sampler was hoisted to the deck level, and turned to horizontal position, again using the hand winches. The sections of the sampler were then dismantled, and the liner extruded from the coring tube. The cores were cut with a hack saw to 3-ft (0.9-m) long sections, sealed with plastic caps and friction tape, labelled, and stored in a large refrigerator to keep the samples at an approximate lake bottom temperature of 4°C.

A.2 The Benthos Gravity Sampler

The sampler was used for sampling of the top sediment, and core up to 6 ft (1.8m) long were recovered. The cores were collected for sedimentological and palynological studies carried out by the CCIW and consequently the cores were not used for geotechnical tests. The sampler shown in Fig. 8.2 consists basically of a head weight and a 2.5-in (64-mm) I.D. plastic liner equipped at the lower end with a stainless steel cutter. The sampler has a disc valve which is left open in a vertical position during lowering. Prior to hoisting, the valve is closed by releasing a locking pin, which is attached to a thin line operated from the deck. The Benthos cores were logged and stored in a similar manner as the Alpine cores.

A.3 The Thin-Wall Open Drive Sampler (Shelby)

The sampler consits of a 5-in.(127-mm) O.D. open steel tube with a tapered cutting edge, as shown in Fig. 8.3. The sampler is mounted to the sampler head with four Allan screws. The sampler head is equipped with two vent holes and a check valve.

The sampling was accomplished by mechanically driving the sampler downward in one continuous move. After the sampler had been driven to the required depth, the drill rods and the sampler were rotated in order to shear off the bottom of the sample. The samples were then brought to the deck, and immediately sealed with beeswax.

The sampler was used on the first borehole (No. 13156) only, since it was felt that coring with other samples, particularly with the Alpine sampler, was less time-consuming, and much longer cores were recovered. The 18-in.(46-cm) long sampling tubes were used in Borehole No. 13156. Later in the project, 5 -ft (153-cm) long tubes became available but these were not tried out since, as mentioned earlier, preference was given to other sampling methods.

A.4 The Christensen Thin-Wall Sleeve Sampler

The sampler designed by HQGA especially for the project, was manufactured for Consumers' Gas Company by Christensen Diamond Products Ltd. of Edmonton, Alberta. The principal features of the sampler are shown in Fig. 8.4. The sampler head contains four vent holes and a tapered valve seating. The check valve is a 7.2-in. (18.3-cm) long, 1-in. (2.54-cm) diameter steel rod, which is dropped from the surface prior to recovery. The valve ensures that during hoisting hydrostatic pressure does not push the sample out of the coring tube. The coring tube consists of a 4.75-in. (121-mm) O.D. outer barrel which contains a 3.75-in (95-mm) I.D. plastic liner. 5 - ft (1.52-m) long and 30-ft (9.14-m) long barrels were available; the latter was generally used more frequently than the former. The cutter of the sampler contains the core basket of a similar type as the one used in the Alpine sampler.

At the beginning of the investigation program, the Christensen sampler was not available, and in the meantime the performance of other samplers was tested. On the second borehole (No. 13161), the use of the Christensen sampler was found to result in a simple and rapid coring method. Furthermore, it was noted that the quality of samples was at least as good as of those obtained by means of other samplers, and hence the Christensen sampler was employed exclusively on all following boreholes for deeper coring using the National T 20 drilling rig, while the coring with the Shelby sampler and the Osterberg sampler was discontinued. In soft sediments continuous 3.75-in. (95-mm) diameter cores up to 20 ft (6.1m) in length were recovered. Difficulties were encountered during the coring of stiff and very stiff till deposits owing to lack of mechanical or hydraulic equipment that could exert an additional force in the excess of the weight of the sampler, drill rods, and drilling rig block weight. Thus coring was usually terminated when the bearing capacity of the soil exceeded the gravitational force of the sampler. The cores, contained in the plastic liner, were cut to 5-ft (1.52-m) long sample sections sealed with improvised plastic caps and friction tapes and stored in the refrigerator on the drillship.

A.5 The Osterberg Fixed-Piston Sampler

The sampler was used only on the first borehole. The design of the sampler and the sampling procedure is shown in Fig. 8.5. The principal features of the sampler are a fixed piston attached to a hollow piston rod, an outer barrel, an inner sampling tube, and a movable piston sliding inside the outer barrel. Initially, the sampler was lowered to the bottom of the 8 5/8-in. (21.9-cm) dia. casing. The piston at the lower end of the sampler prevented any sediment entering the sampling tube during lowering. The sampling tube was then forced into sediment by water pumped through the drill rods (Fig. 8.5b). When the movable piston descended to the fixed piston , i.e. when the sampling tube was fully extruded (Fig. 8.5c), water began to escape out of the sampler through the hole in the piston rod and the vent. The sampler was then rotated through 360 degrees to shear off the sample from sediment underneath, and lifted from the borehole. The sampling tubes were sealed with beeswax and stored in the refrigerator. For laboratory testing, 2-ft (61-cm) long steel sampling tubes were cut to short sections since it was felt that the extraction of the whole sample from the tube would result in considerable disturbance of the clayey sediment.

B. General Features of Modern Offshore Samplers

Recent research in marine sedimentology and marine geotechnique has resulted in some new designs of offshore samplers that give favourable promises with respect to improved offshore undisturbed coring.

Offshore equipment of potential use for geotechnical investigations can be divided into four principal categories:

(1) Single-entry samplers, usually attached to cables and raised and lowered by means of cranes and winches located aboard a supporting vessel.

(2) Multiple-entry samplers, requiring a fixed platform which enables the use of onshore drilling or coring techniques.

(3) Bottom-rest remotely controlled platforms.

(4) Equipment for underwater *in situ* testing.

B.1 Single-Entry Samplers

The single-entry samplers are widely employed in shallow and deep oceanographical and limnological investigations. The main types include gravity samplers, piston-gravity samplers, propelled samplers, and vibration samplers. Research trend aims at the design of large-diameter samplers, the reduction of wall friction, the experimentation with various driving methods, and the development of more efficient core catchers, release systems, pistons, and check valves. Comprehensive summaries of these trends were presented by Rosfelder and Marshall (1967), Noorany (1972), and Ling (1972).

Modern gravity samplers are usually equipped with noncorrosive inside liners and cutters meeting requirements for thin-wall samplers (Table 4). Rectangular core barrels have a higher flexural strength than the circular barrels made of the same amount of material, i.e. they are more economical (Rosfelder and Marshall, 1967). The rectangular cross section also inhibits rotation of the sampler during penetration. Several new designs of core catchers have been developed. A swinging spade is used in the Reiseneck sampler (Noorany, 1972), closing flaps in the Kastenlot sampler (Kogler, 1963), and the SIO-USNEL long box sampler (Rosfelder and Marshall, 1967). An improved core catcher for the Kastenlot sampler, consisting of a nylon sleeve curtain which seals the lower end of the barrel prior to recovery, was developed by Werner (1973).

Piston gravity samplers on the average achieve deeper penetration than gravity samplers of comparable weight or diameter, and the suction of a piston decreases the possibility of core loss during retrieval. On the other hand, piston movements during penetration and retrieval can produce serious disturbance of core samples. A promising design is the "Sphincter" corer developed by Kermabon et al. (1966). The sampler is equipped with a watertight nylon core catcher, a split piston, which prevents the upward pull of the piston during the raising operation, and a relatively light electrical triggering system. An improved version of the "Sphincter" corer includes a recoilless piston which is completely independent of the main cable (Kermabon and Cortis, 1969). A piston immobilizer based on a different design was developed by Benthos, Inc. (Ling, 1972). Internal wall friction can be significantly reduced when core conveyors are used. The core conveyors unreel inside the sampler at a rate equal to the penetration of the sampler. The conveyors can consist of steel foil strips as in the Swedish foil sampler (Kjellman and Kallstenius, 1950) or of a flexible high tensile strength liner (Rosfelder and Marshall, 1967).

The Norwegian Geotechnical Institute developed a gas-propelled piston sampler (Andresen et al., 1967) which is designed to penetrate soft bottom sediments due to its own weight. A maximum penetration depth of 32 ft (9.7 m) was reported. After the sampler comes to rest, a 2.1-in. (54-mm) thin-wall sampling tube 5.5 ft (1.65 m) in length is driven into the sediment by gas pressure generated by the ignition of a solid rocket propellant. The piston system closely resembles that of the Osterberg sampler (Appendix A.5, Fig. 8.5).

B.2 Multiple-Entry Samplers

The multiple-entry samplers are commonly used with onshore drilling rigs mounted on fixed platforms, e.g. spudded barges, jack-up elevated platforms, and sunken barges. Thin-wall piston samplers of larger diameters (approximately 3 in. = 76 mm) appear to be best suited for undisturbed sampling. Long open-drive samplers, e.g. similar to the Christensen design (Appendix A.4, Fig. 8.4), can be used at sites where rapid sampling is required and the high quality of cores is not absolutely necessary. The coring with multiple-entry samplers is usually expensive and time-consuming. On the other hand, repeated sampling allows the penetration of sediment strata to predetermined depths and the recovery of samples with minimum disturbance. The system appears therefore suitable for detailed foundation investigation in shallow waters.

The sampling operation normally requires a string of casing lowered through the water column and the soft bottom sediments. Since the casing has to withstand dynamic loads due to waves and currents, the maximum recommended length of a bottom-embedded casing (Ling, 1972) is in the order of 150 ft (45 m). The use of drilling mud is recommended for sampling in cohesionless sediments, otherwise cores are frequently lost by washout during retrieval. The drilling mud also inhibits core disturbance by preventing water seepage through cohesionless sediments.

B.3 Bottom-Rest Platforms

Several remotely controlled submersible platforms which appear suitable for geotechnical sampling were discussed by Rosfelder and Marshall (1967), Noorany (1972), Tirey (1972), and Ling (1972). The platforms are principally used in waters deeper than 100 ft (30 m). Power is transmitted to the platforms hydraulically, pneumatically, or electrically. A remote control eliminates the necessity of a stabilized platform and consequently coring is less limited by adverse weather conditions. The platforms can be operated in wave heights of 8 to 10 ft (2.5 to 3 m) from vessels as small as 70 ft (21m) in length (Tirey, 1972).

An example of a submersible vibration platform is the Alpine Vibracore (Babcock and Miller, 1972) which is suitable for penetration of dense cohesionless or hard cohesive sediments. The air-powered Vibracore operates in the maximum depth of 200 ft (61 m) and takes 3.5 -in. (87.5-mm) dia. samples contained in plastic liners. The maximum sampling length is 40 ft (12.2 m). During coring, a vibratory hammer, powered by an on-board compressor, slides down along a supporting H-beam without rotation; consequently it is possible to recover oriented cores. Penetration rates, indicative of in situ shear strength or relative density, are electronically recorded by an on-deck recorder.

Another type of a bottom-rest platform is the Geodoff II (Ling, 1972) developed by Conrad-Stork, Haarlem, Holland, and the Dutch Geological Survey Department. The platform contains a rotary drilling device and a rotating supply disc with twelve 13-ft (4-m) long barrels. The Geodoff II combines two penetration methods; in soft sediments the barrel is advanced by pushing, in hard sediments coring is achieved by rotary drilling. The maximum penetration is 157 ft (48 m) into the sediment. A similar automatic sampler has been designed by Texas A & M University (Noorany, 1972) which is capable of taking a 3-in. (76-mm) dia. sample 49.5 ft (15.1 m) in length.

Tirey (1972) described several bottom-rest platforms which use rotary drilling for penetration of hard sediment strata. These include the Wimpey drill (England), the Institute Francois du Petrole drill (France), the Wirth drill (Germany), and the Koken drill (Japan).

B.4 Underwater In Situ Testing Equipment

The underwater in situ testing of geotechnical properties closely resembles methods used in onshore investigations. In situ shear strength of cohesive sediments is usually measured by vane shear devices (Richards et al., 1972) or cone penetrometers

(Hirst et al., 1972).

In general, in situ test results are not influenced by sediment disturbance caused by sampling, and consequently measured values are often significantly higher than those measured in the laboratory on core samples. The vane results are readily convertible to undrained shear strength values. The cone results cannot be directly related to undrained shear strength but they provide a continuous profile of sediment resistance with depth.

The ultimate bearing capacity of bottom sediments can be measured with an underwater plate bearing device (Noorany, 1972) with which applied loads and measured deformations are monitored from a surface vessel. Stress-strain properties of offshore sediments have been measured with Menard's pressure meter in underwater borings in water up to 2600 ft (792 m) deep (Noorany, 1 972). Of particular interest for in situ testing of soft bottom sediments is the development of the Cambridge In Situ Measuring Device which monitors stress-strain behaviour of sensitive clays. The measuring probe is essentially a pressure meter combined with a miniature tunnelling machine, which drills its way through the sediment and removes the material upwards through the probe. As of November, 1973, the prototype was under further development to enable the use of the device with a standard drilling rig (Wykeham Farrance Engineering Ltd., 1973).

C. X-radiography

C.1 Use of X-radiography in Geotechnical Investigations

The use of X-radiographs in geotechnical investigations is an excellent aid for detailed logging of boreholes, scheduling of laboratory testing programs and subsequent interpretations of measured geotechnical properties. In the laboratory geotechnical work, the X-radiography has been further used for such purposes as localization of shear planes in unconfined compression, triaxial, vane, and direct shear tests (Sopp, 1964), study of stress-strain behaviour of soils, determination of degree of consolidation of compressible sediment layers, detection of sample damage, and correlation of varve stratigraphy (Kenney and Chan, 1972). Thus it is evident that X-radiography represents a valuable tool for a geotechnical engineer, and that much useful information can be derived from this nondestructive method of sediment testing.

All cores recovered during the borehole investigation described in this text were X-rayed prior to laboratory subsampling and testing in order to obtain information on stratigraphy, sedimentary structures, and the amount of sample disturbance. The cores were X-rayed within several days after their arrival from the field. Since cores were X-rayed prior to extrusion, the quality of radiographs was considerably influenced by the type of sample confinement. Good quality radiographs were obtained in the case of the Alpine cores and the Benthos cores. On the other hand, the radiographs of cores enclosed in thick plastic liners (the Christensen cores) and steel tubes (the Shelby cores and the Osterberg cores) were barely sufficient for the study of sediment stratigraphy and structure.

Four representative radiographs (Plates 17 to 20) from two boreholes were selected to indicate the type of information that has been obtained from radiograph examination. In order to prepare radiograph prints from radiograph films, it was first necessary to make contact prints, which were then scaled down to small-size prints. In general, the direct observation of films yielded more detailed information on sample material than the amount which can be derived from an examination of the small-size prints.

C.2 Instrumental Settings

The radiographs were obtained by means of the X-ray equipment developed by C.H.F. Muller, Hamburg, West Germany (tube PV 7102/00, tripod tubestand PV 7080/00, and control console PG 200). The radiographic film used was Kodak Industrex AA, 14 in. x 17 in.

The following procedure was used:

Type of Sampler	mA	kV	Exposure Time, Minutes
Christensen	4	160	4
Shelby	4	180	20
Alpine	4	100	2 1/4
Osterberg	4	150	6
Benthos	4	100	2 1/2

All films were processed for 5 minutes in a developer, 4 minutes in a fixer, and 50 minutes in a drier. The temperature of the developer and the fixer was held constant at 68° F (20° C).

D. X-ray Powder Diffraction

D.1 Specimen Preparation

Specimen for X-ray powder diffraction analyses were prepared by a sedimentation-on-glass slide technique, in which a clay suspension is placed into an evaporating dish and then is allowed to dry at room temperature. This technique, which is rapid and does not require special equipment, is commonly used for routine X-ray analysis work (Royse, 1970). The technique was criticized by Gibbs (1965) who pointed out that the sedimentation of particles results in segregation due to different particle sizes, and therefore, in a quantitative analysis, the technique yields higher values for montmorillonite relative to illite and kaolinite. According to Gibbs (1965), centrifuge-oriented specimens give even higher values for montmorillonite, relative to a smear-on-slide technique which was recommended by Gibbs for quantitative analyses.

The writer is in full agreement with the above criticism of the sedimentation technique, nevertheless this technique was used for the following reasons:

1. The previous mineralogical work (Lewis, 1966) indicated that montmorillonite in Lake Erie clays is absent or present only in small amounts.

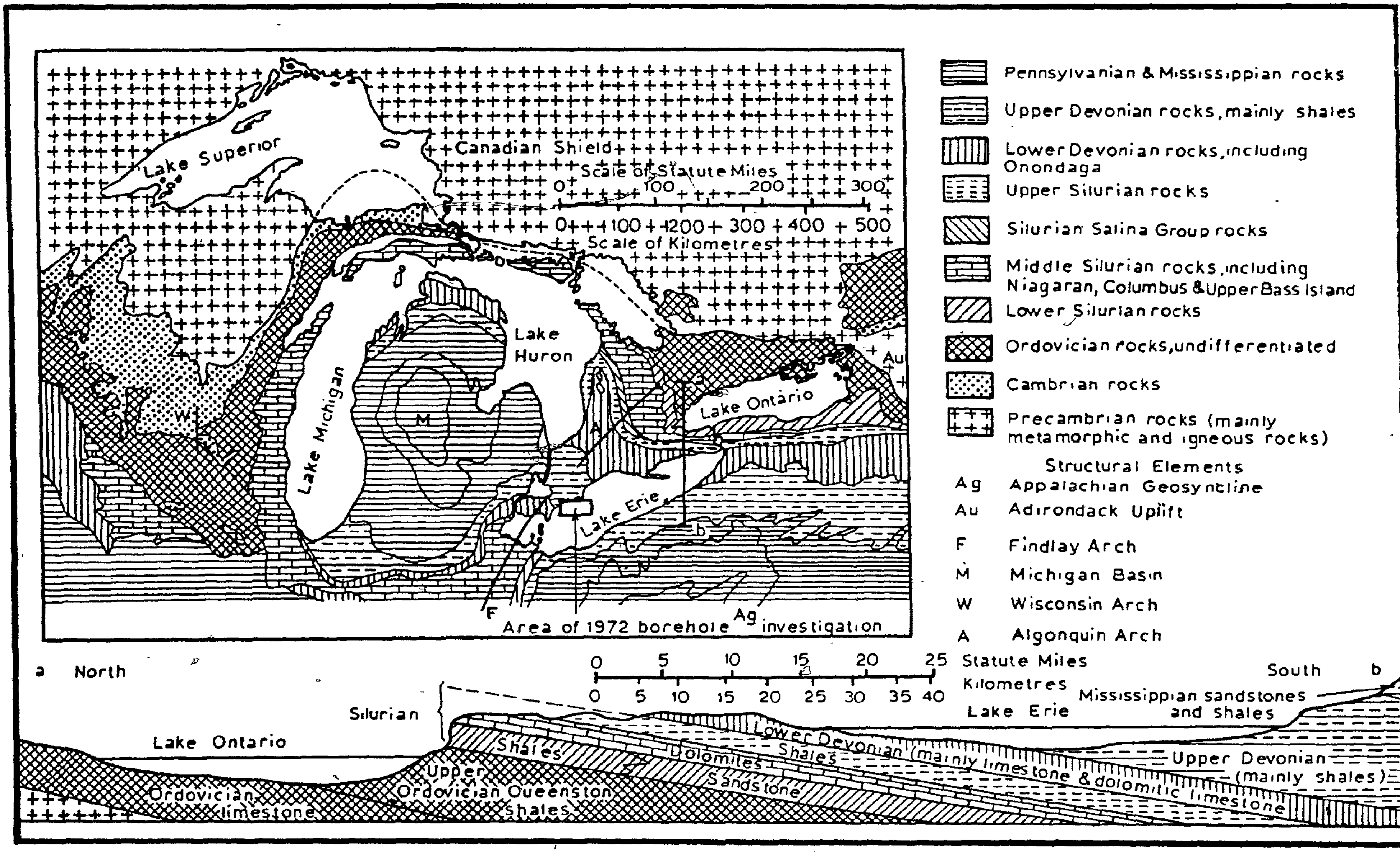
2. The smear technique, which was tested in several initial trials gave no significant information with regard to low 2θ values so that diffraction traces showed no difference between high plasticity and low-plasticity clays.

3. The smear technique produced generally higher background scatter in comparison with the sedimentation technique, and tended to mask some low-intensity peaks.

D.2 Instrumental Settings

After some experimentation with the operation of the Philips X-ray diffractometer, it was found that the following settings yield required information within a reasonable length of time:

Type of Radiation	cu $K\alpha$, Ni filter, $\lambda = 1.5418$
kV	35
mA	20
Divergence and Scattering Slits	1°
Receiving Slit	0.1 mm
Scanning Rate	2°/ min. (routine scanning)
	$1/8^{\circ}$/min. (slow scanning)
Scanning Range	$2^{\circ} - 48^{\circ}$ (untreated bulk and -2 micron specimens)
	$2^{\circ} - 24^{\circ}$ (moist-never dried, glycolated, potassium saturated, and furnace heated specimens)
	$12^{\circ} - 13^{\circ}$ slow scanning
	$24^{\circ} - 25^{\circ}$ slow scanning
Counter Frequency	100 counts/second
Time Constant	10 seconds
Chart Speed	0.5 in./min.



— Fig.1 Bedrock geology of the Great Lakes region (adapted from Hough, 1958).

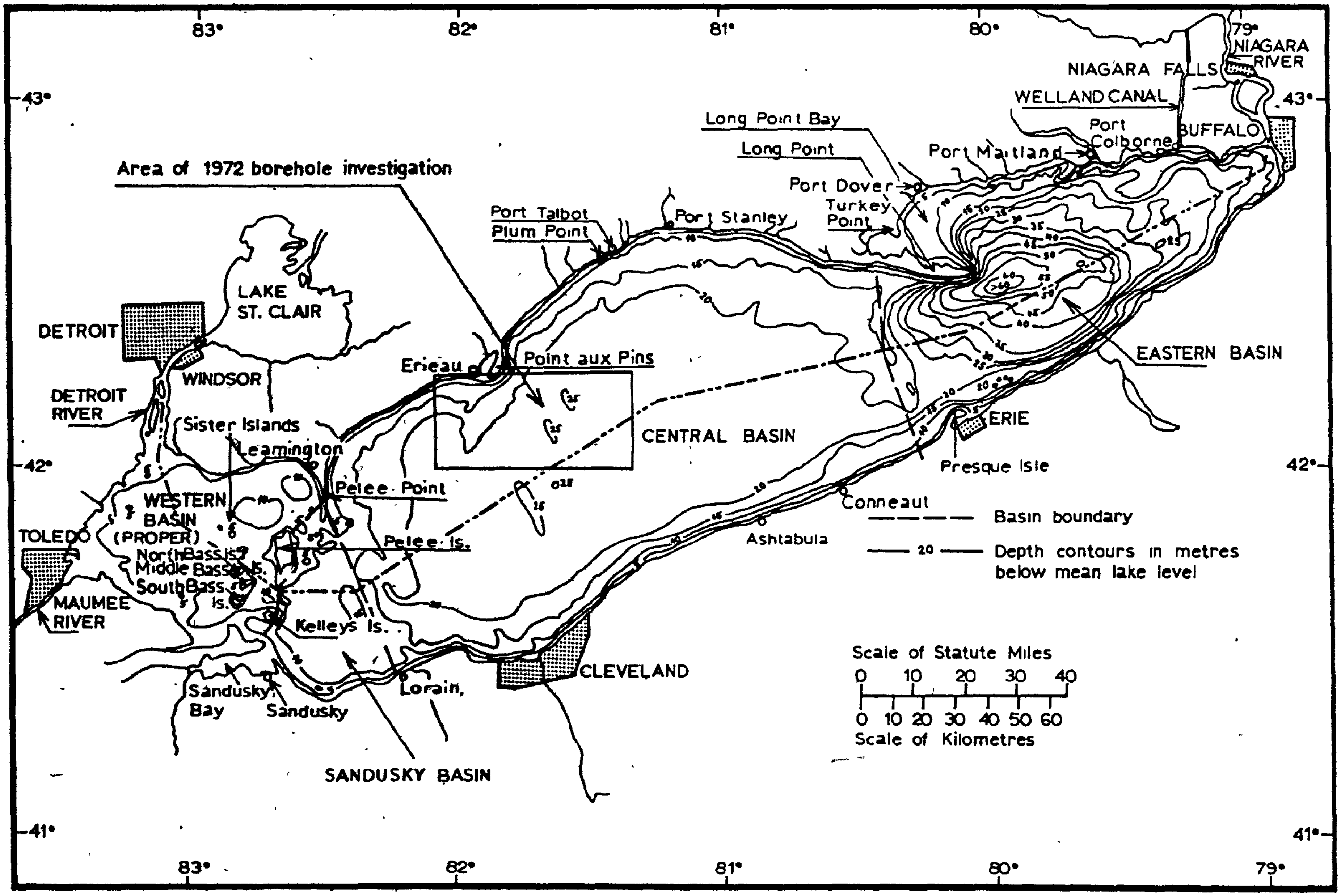
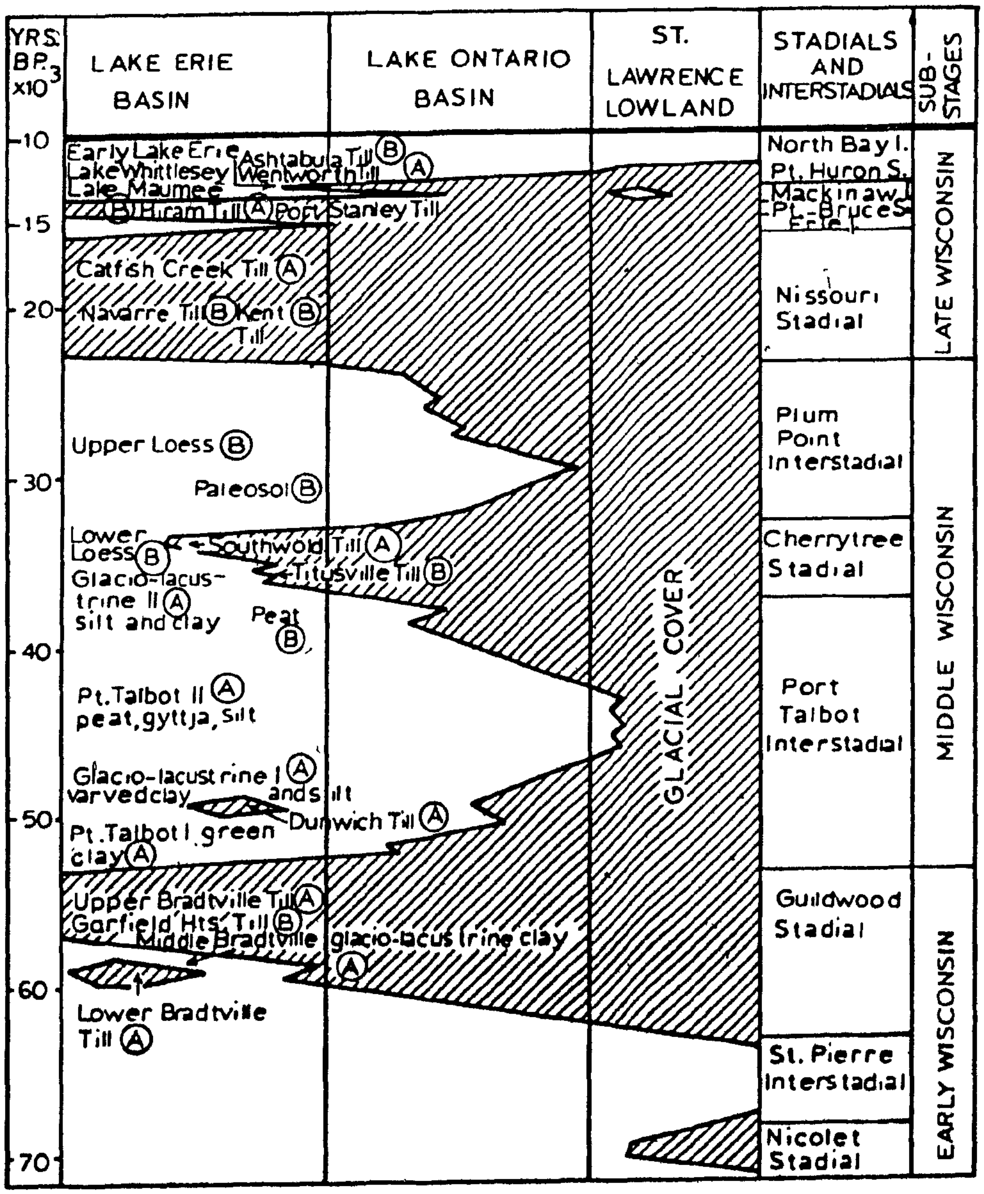


Fig. 2 Lake Erie bathymetry (metres), adapted from the Report to the IJC, 1969.



NOTE: The heavy jagged line represents the oscillation of the glacial margin in the Great Lakes-St. Lawrence region.

OCCURRENCE OF DEPOSITS: (A) Southern Ontario
(B) Northeastern Ohio and Northwestern Pennsylvania

Fig.3 Diagrammatic stratigraphy of onshore Pleistocene deposits in the Lake Erie basin (adapted from Dreimanis and Karrow, 1972).

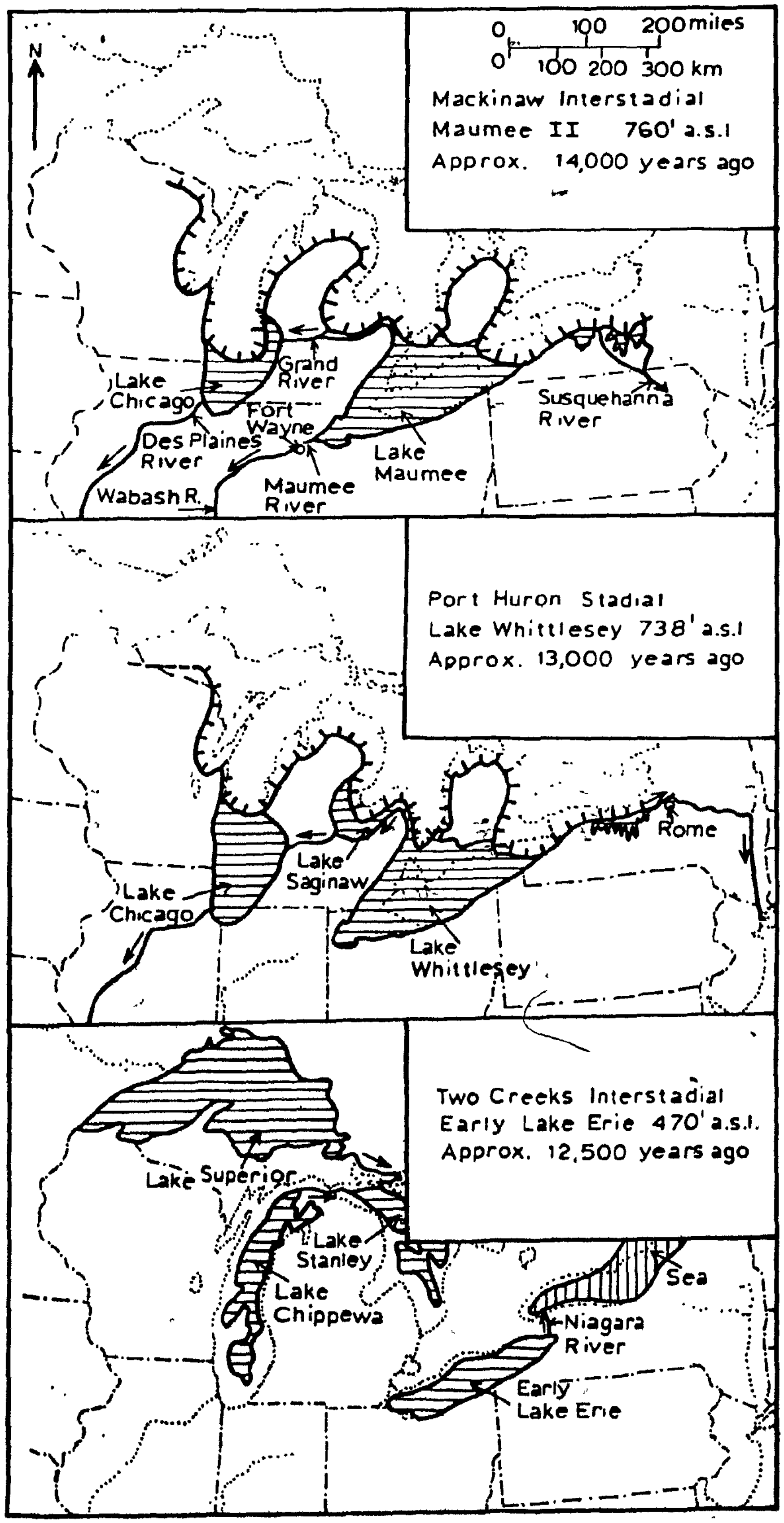


Fig.4 Sketch maps showing extent of glacial Great Lakes during three phases of Late-Wisconsin deglaciation (adapted from Flint, 1971).

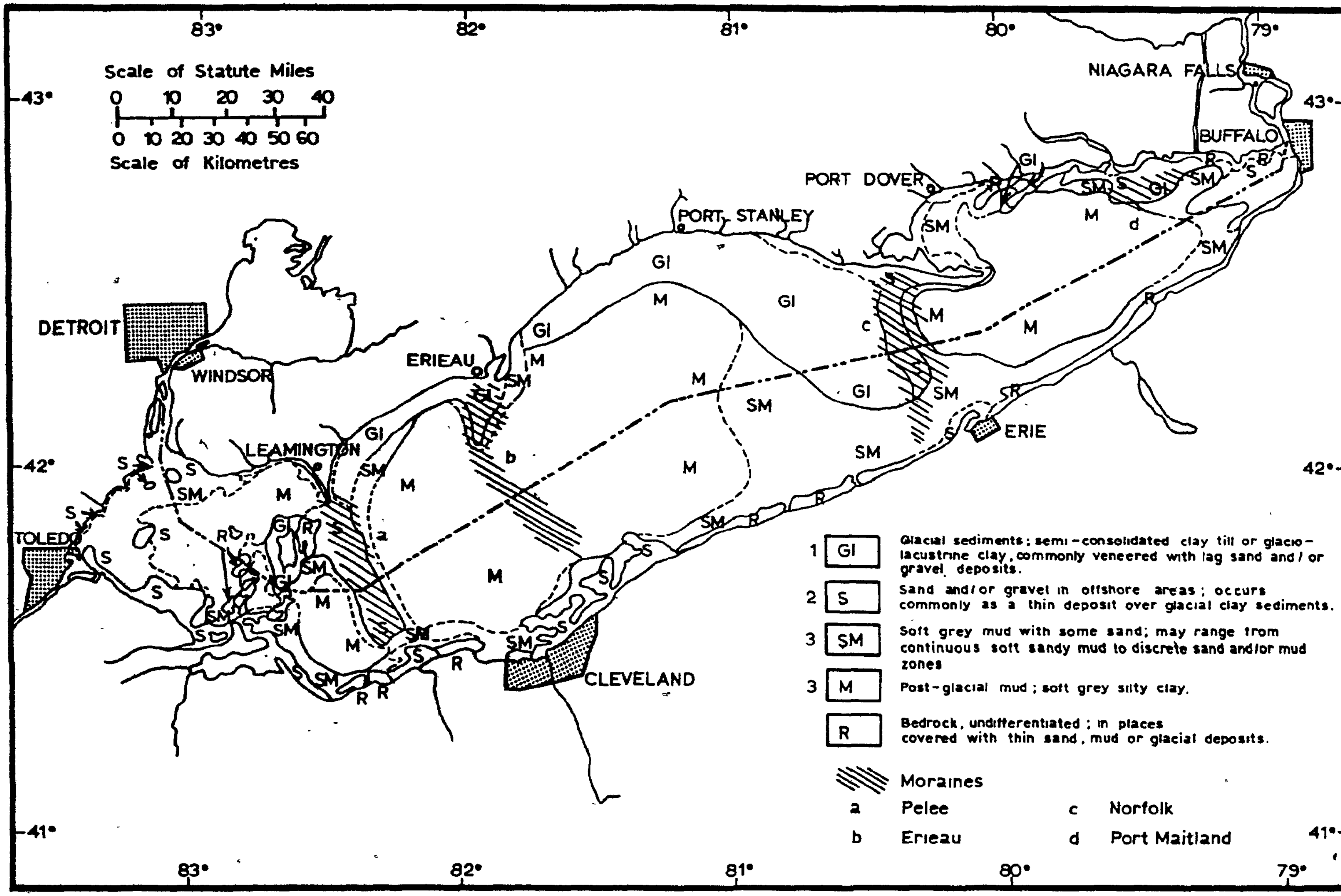


Fig.5 Lake Erie bottom sediments (adapted from Sly and Lewis, 1972).

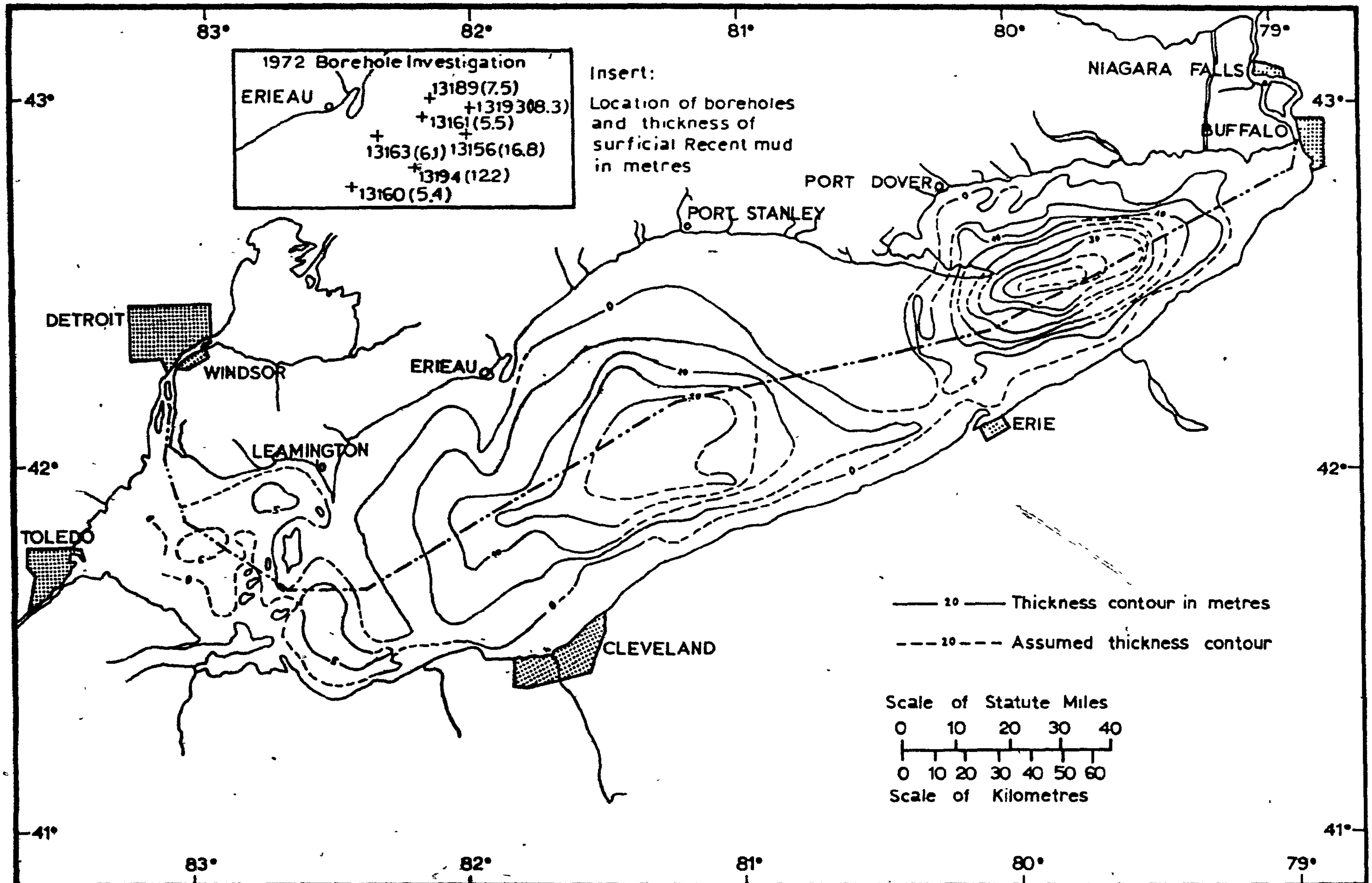


Fig.6 Isopach map of surficial Recent mud (adapted from Lewis, 1966 and 1972 borehole investigation).

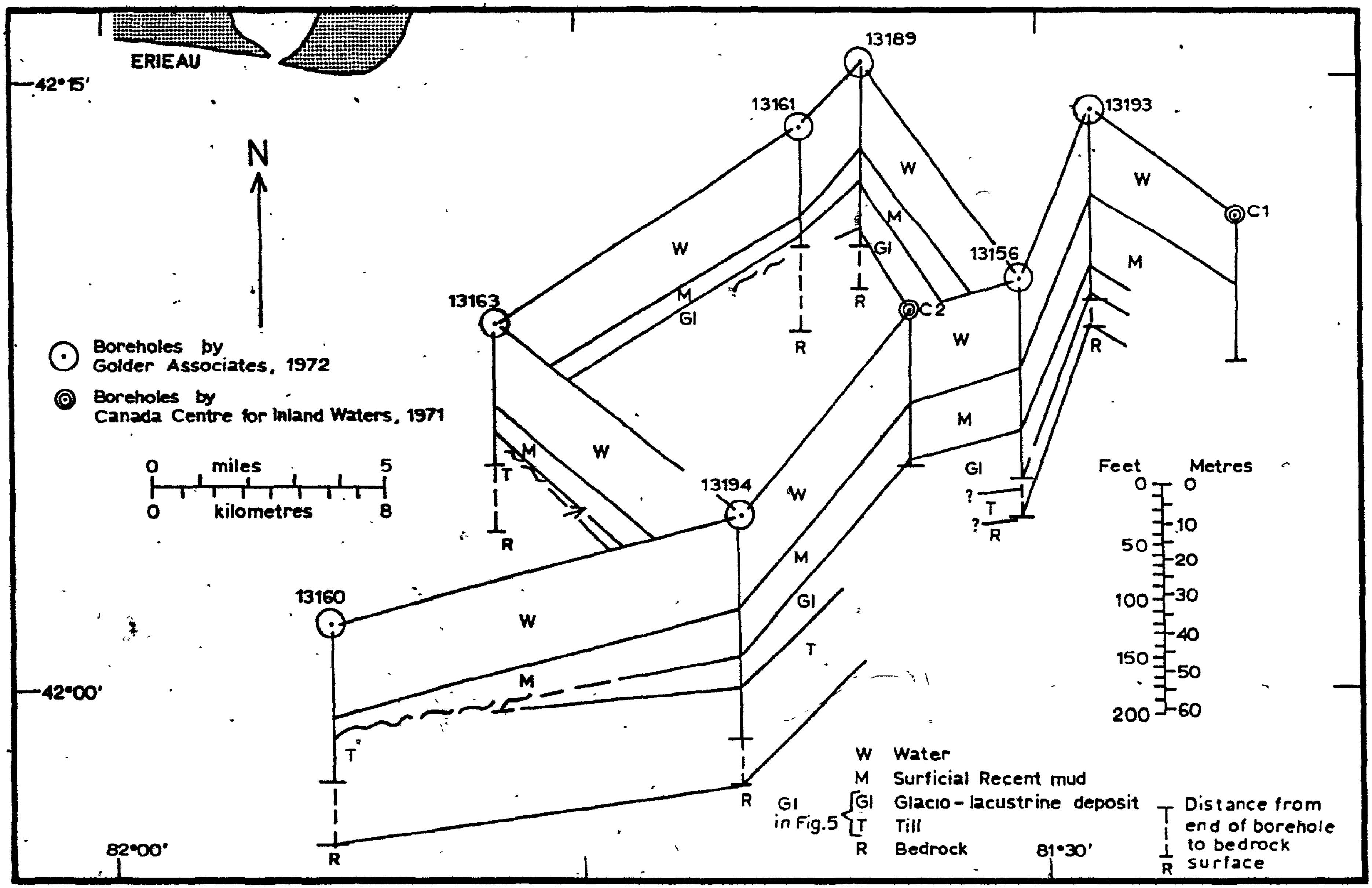


Fig.7 Site plan, Central Lake Erie near Erieau, Ont. (adapted from Lewis, 1972).

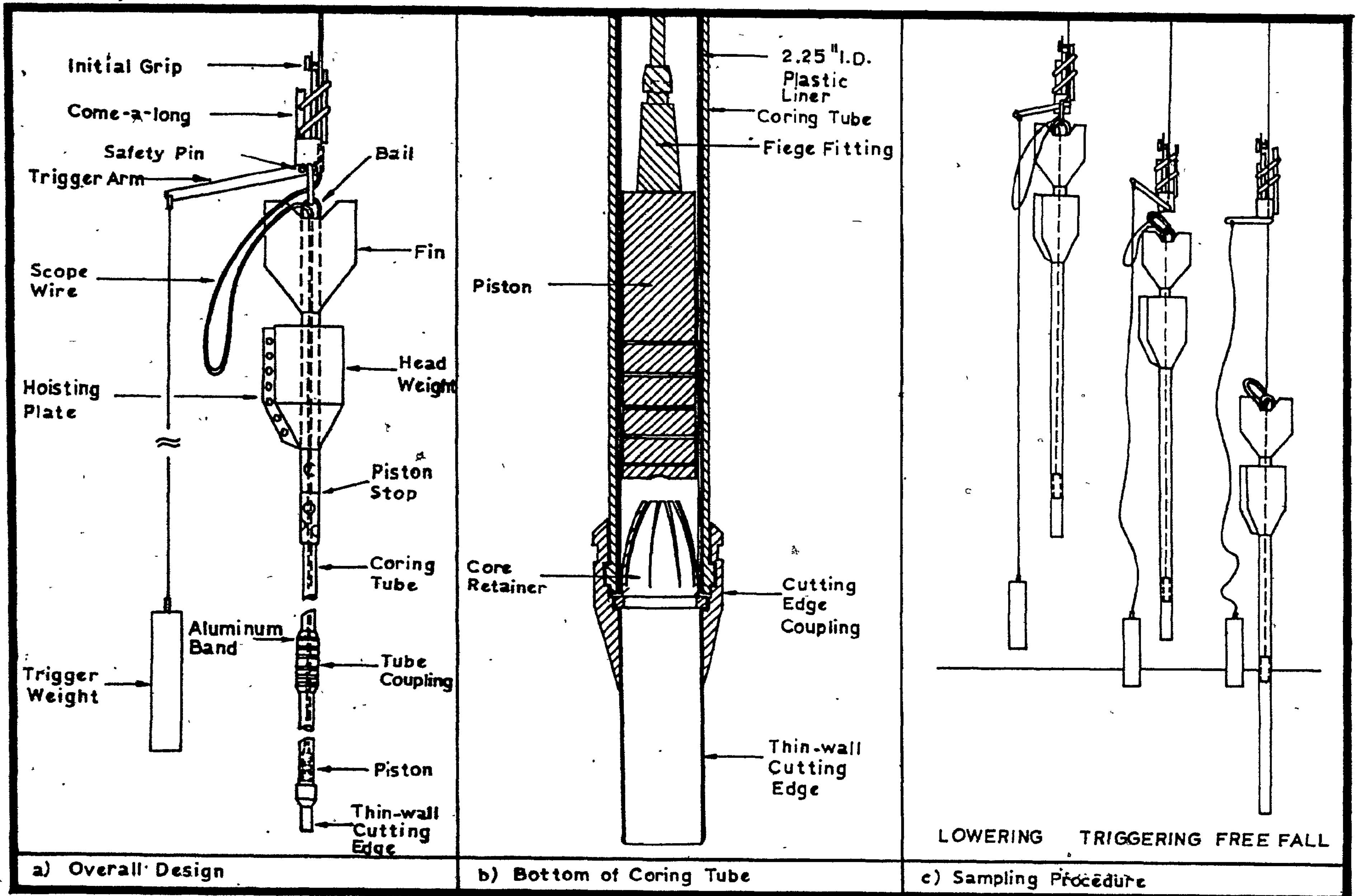


Fig. 8.1 Alpine 1200-lb. free-falling piston sampler.

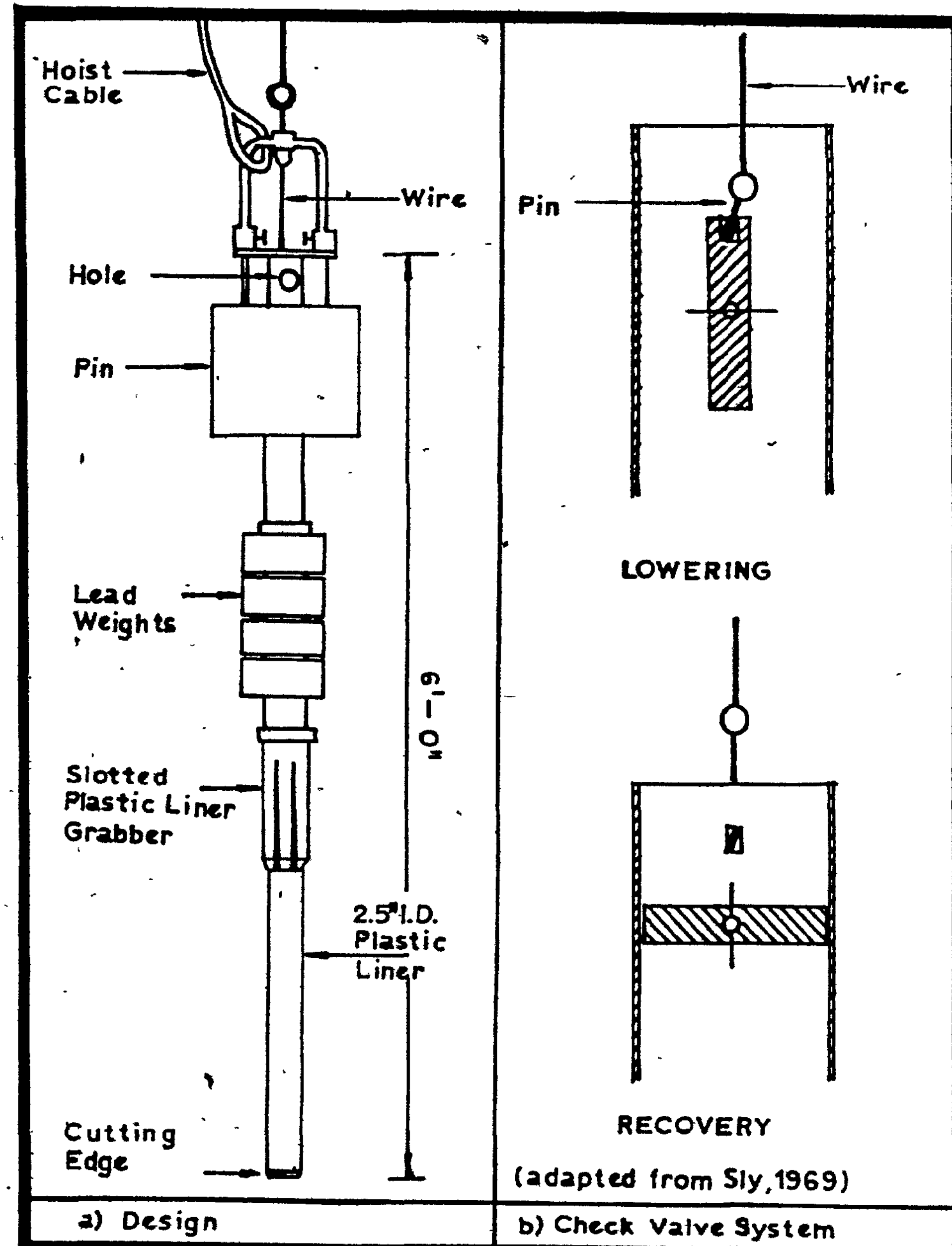


Fig. 8. 2 Benthos gravity sampler.

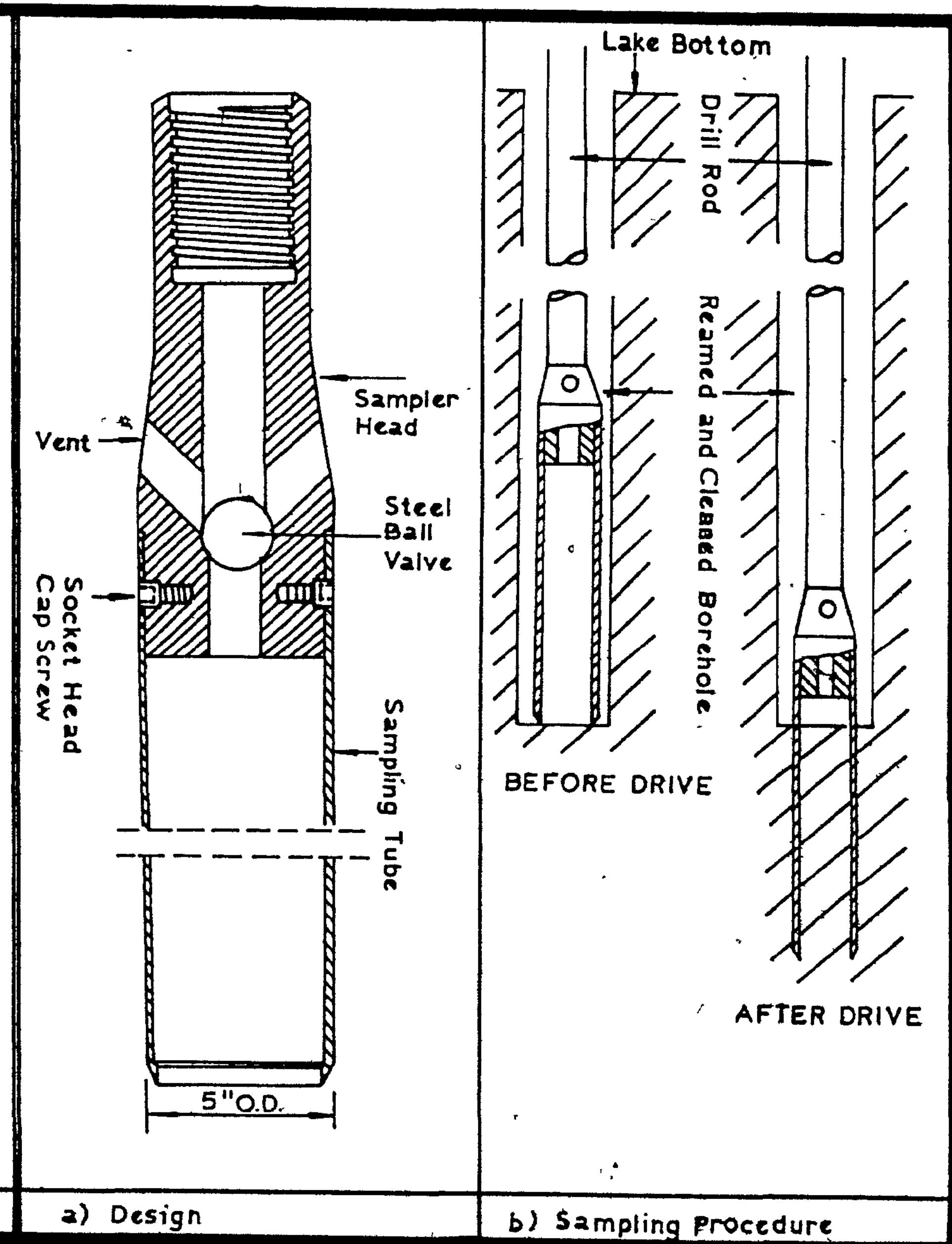


Fig. 8 .3 Thin-wall open drive (Shelby) sampler (adapted from the USBR Earth Manual, 1963).

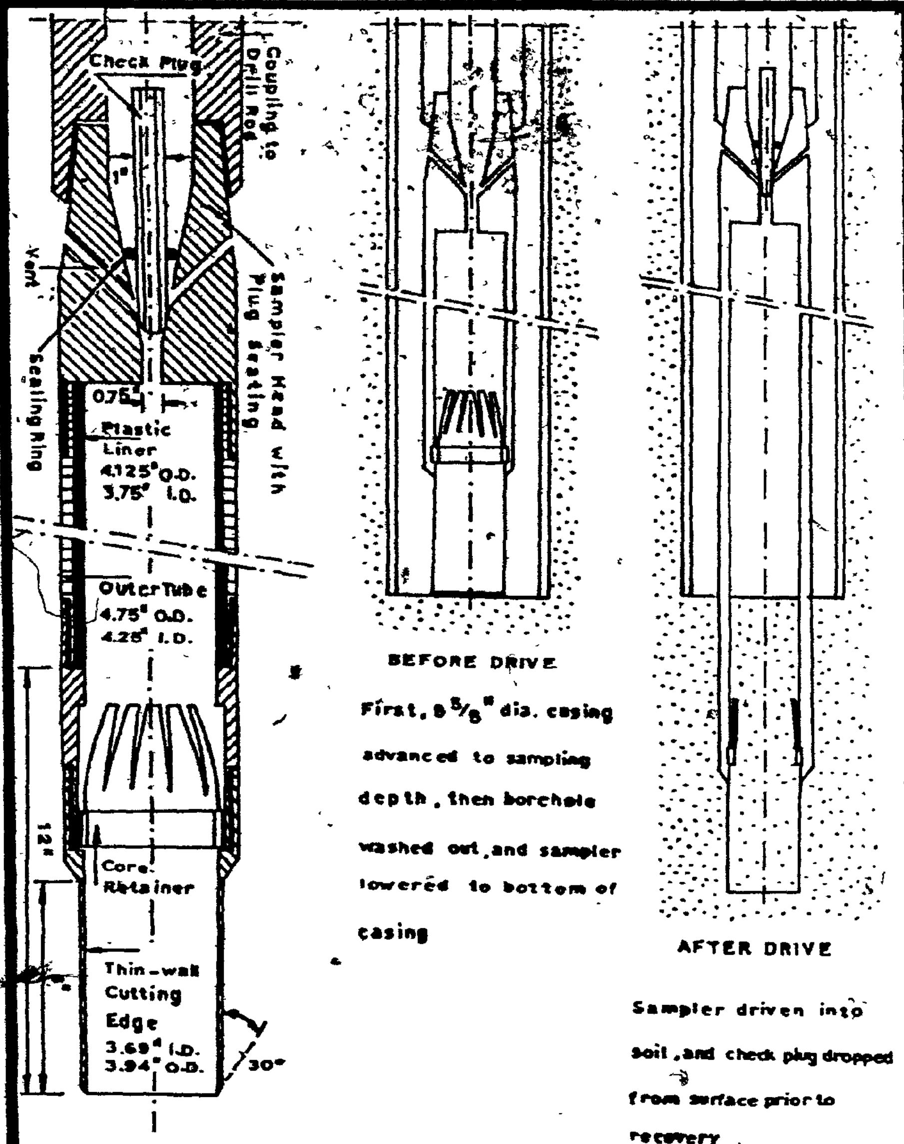


Fig. 8.4 Christensen thin-wall sleeve sampler.

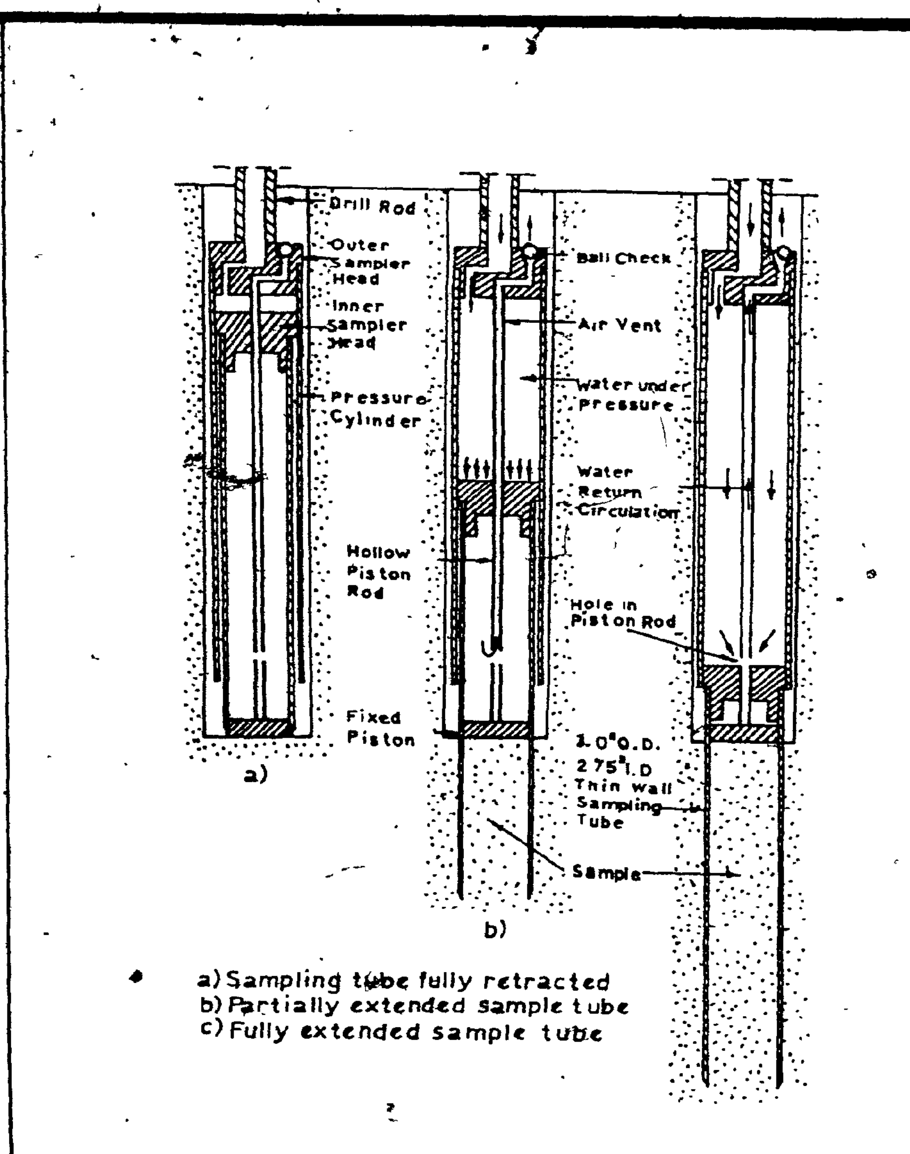


Fig. 8.5 Thin-wall fixed-piston sampler, Osterberg type (adapted from the USBR Earth Manual, 1963).

BOREHOLE LOCATION: 81° - 47' - 40" W 42 - 09' - 00" N

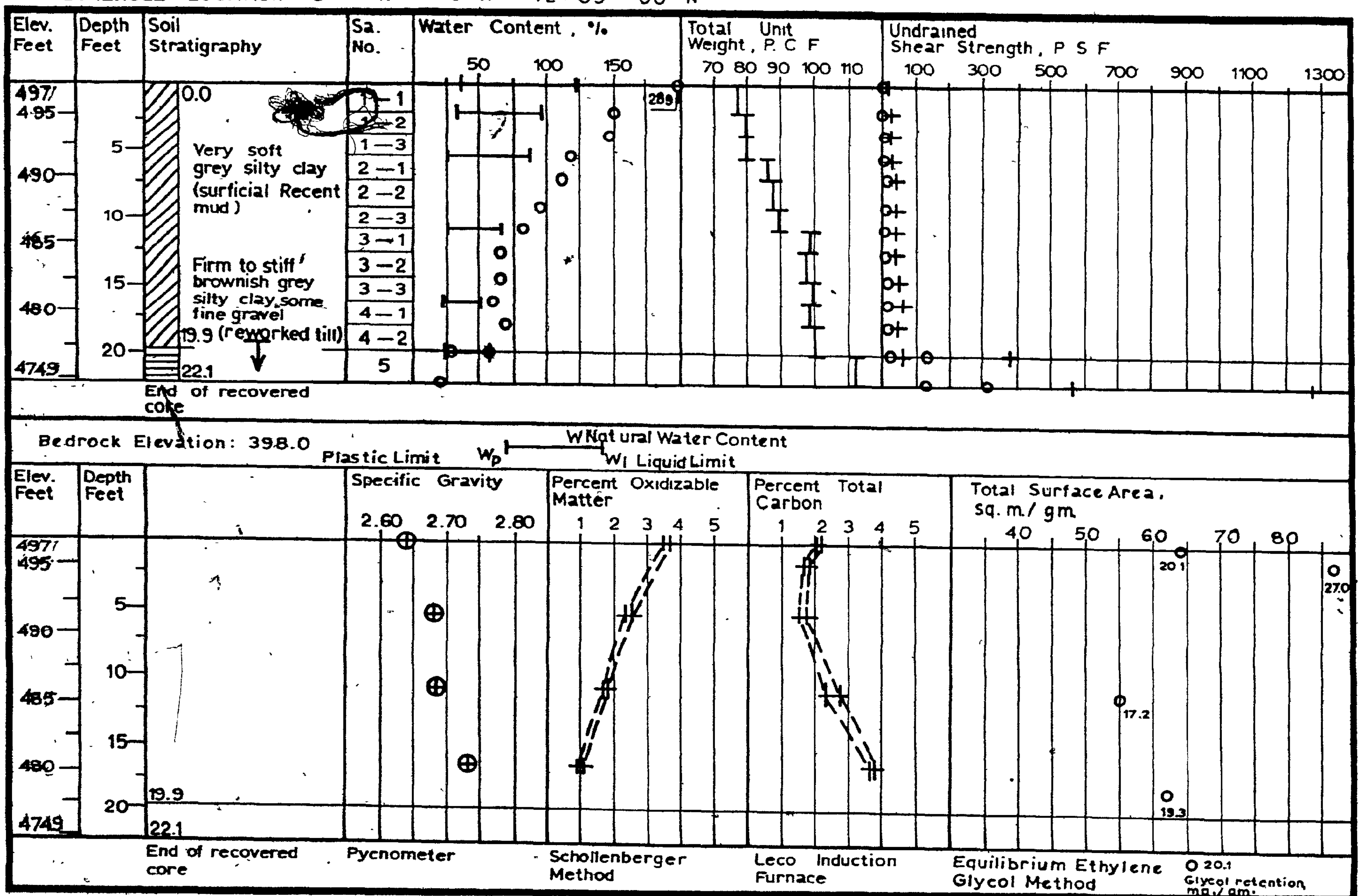


Fig. 9.1.1 Summary plot of geotechnical properties, Borehole No. 13163, Alpine Sampler

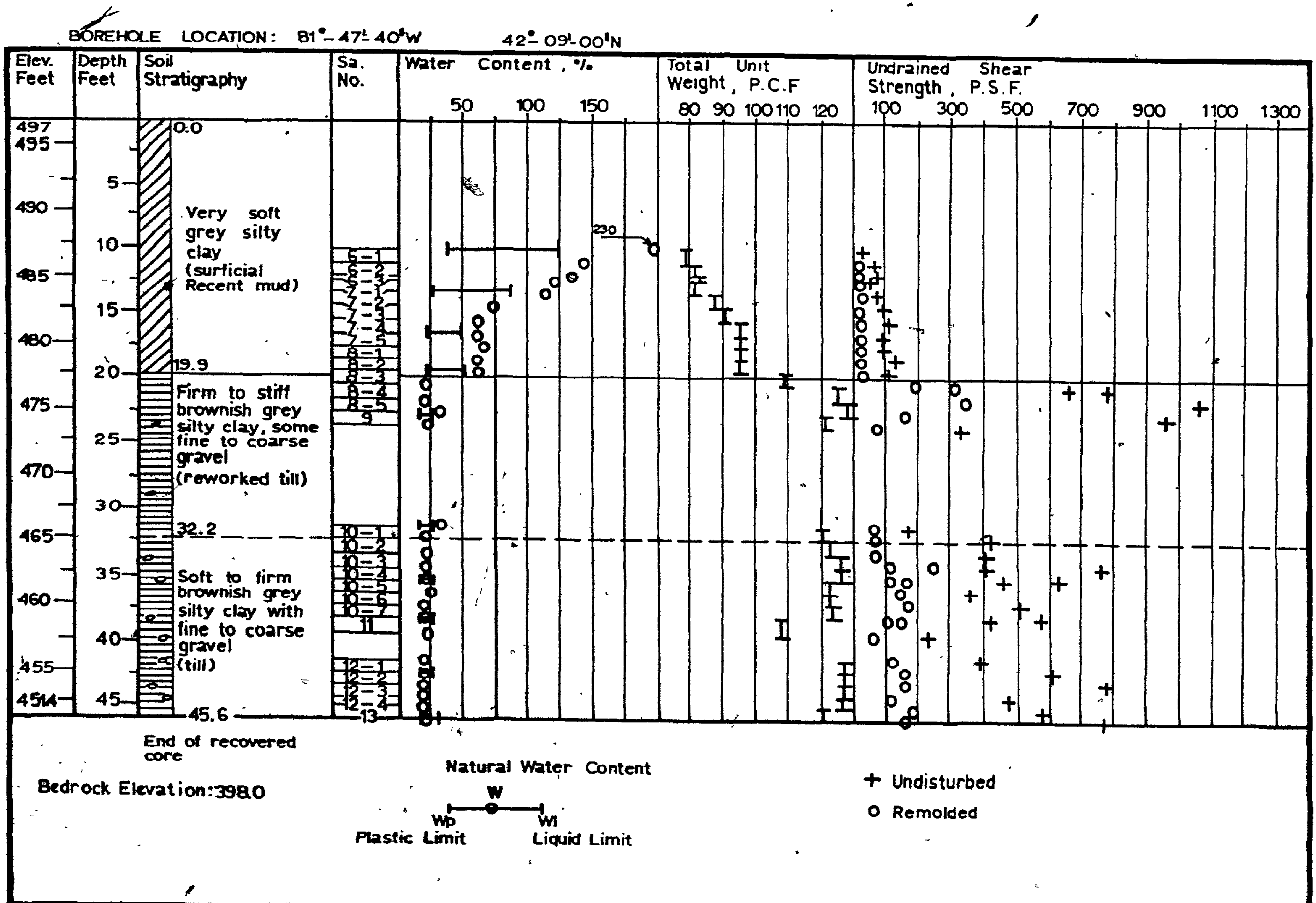


Fig. 9.1.2 Summary plot of geotechnical properties, Borehole No. 13163, Christensen Sampler

BOREHOLE LOCATION: 81°- 47'- 40" W 42°- 09'- 00" N

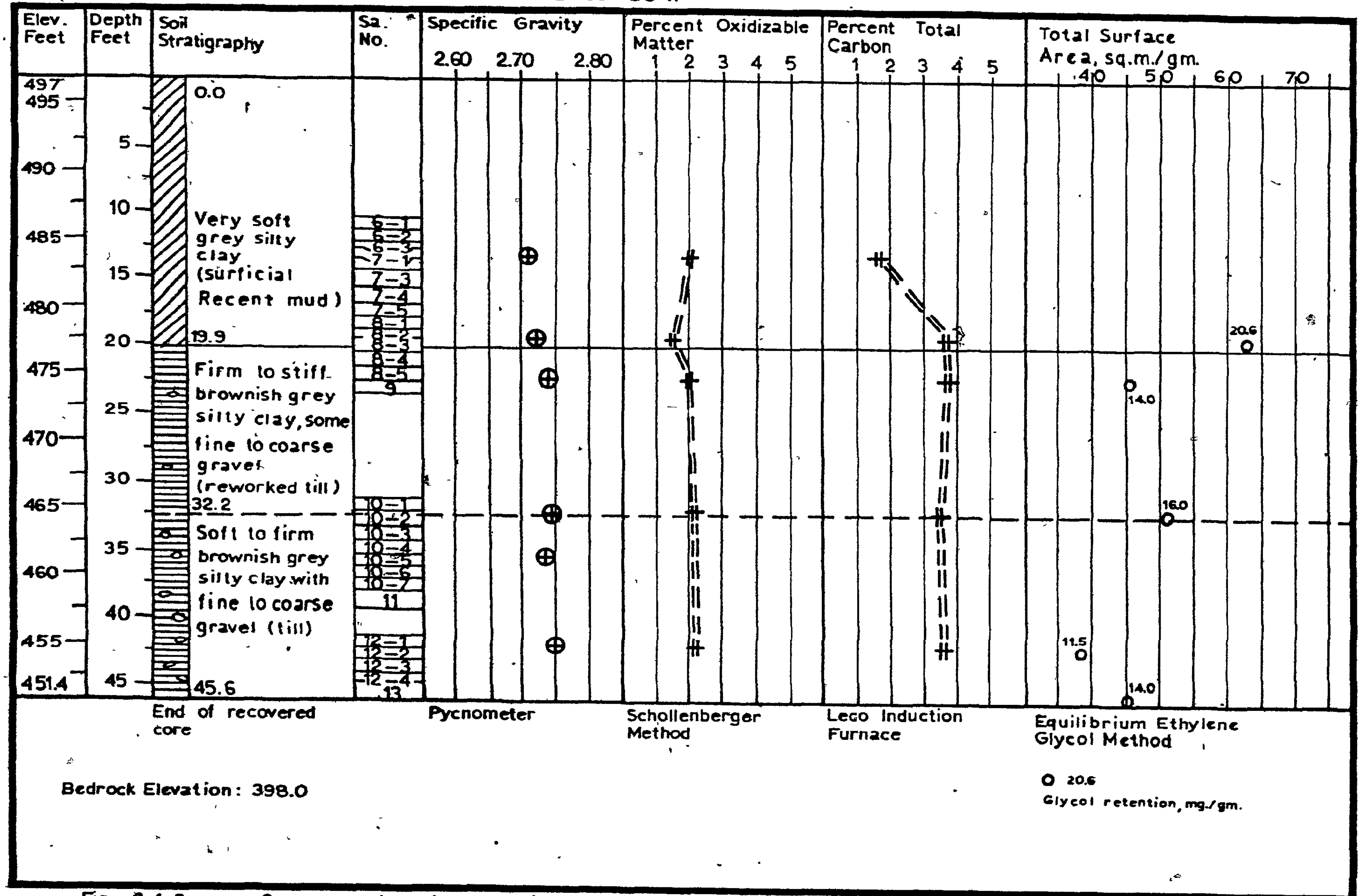


Fig. 9.1.3 Summary plot of geotechnical properties, Borehole No. 13163, Christensen Sampler

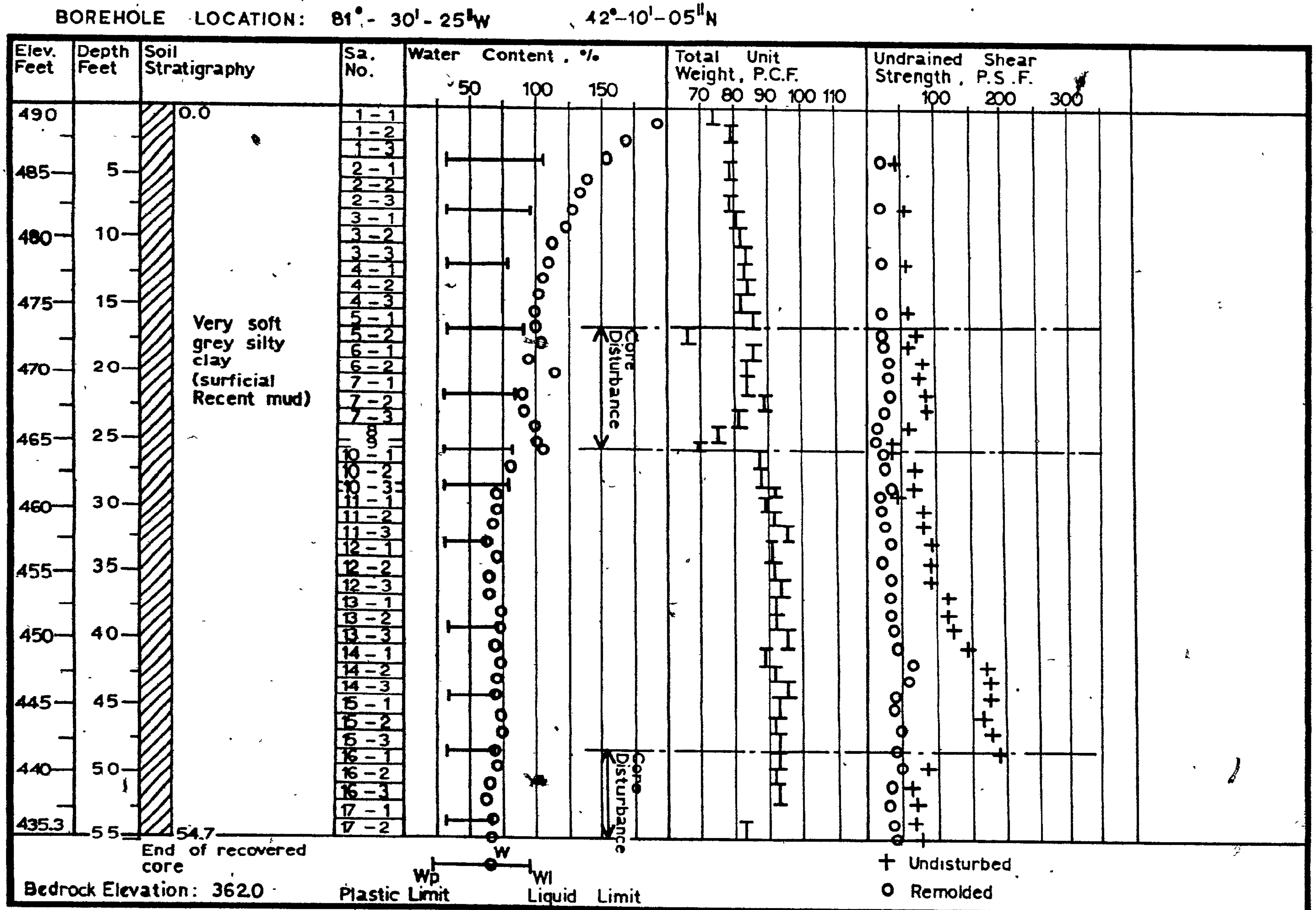


Fig. 9.2.1 Summary plot of geotechnical properties, Borehole No 13156, Alpine Sampler.

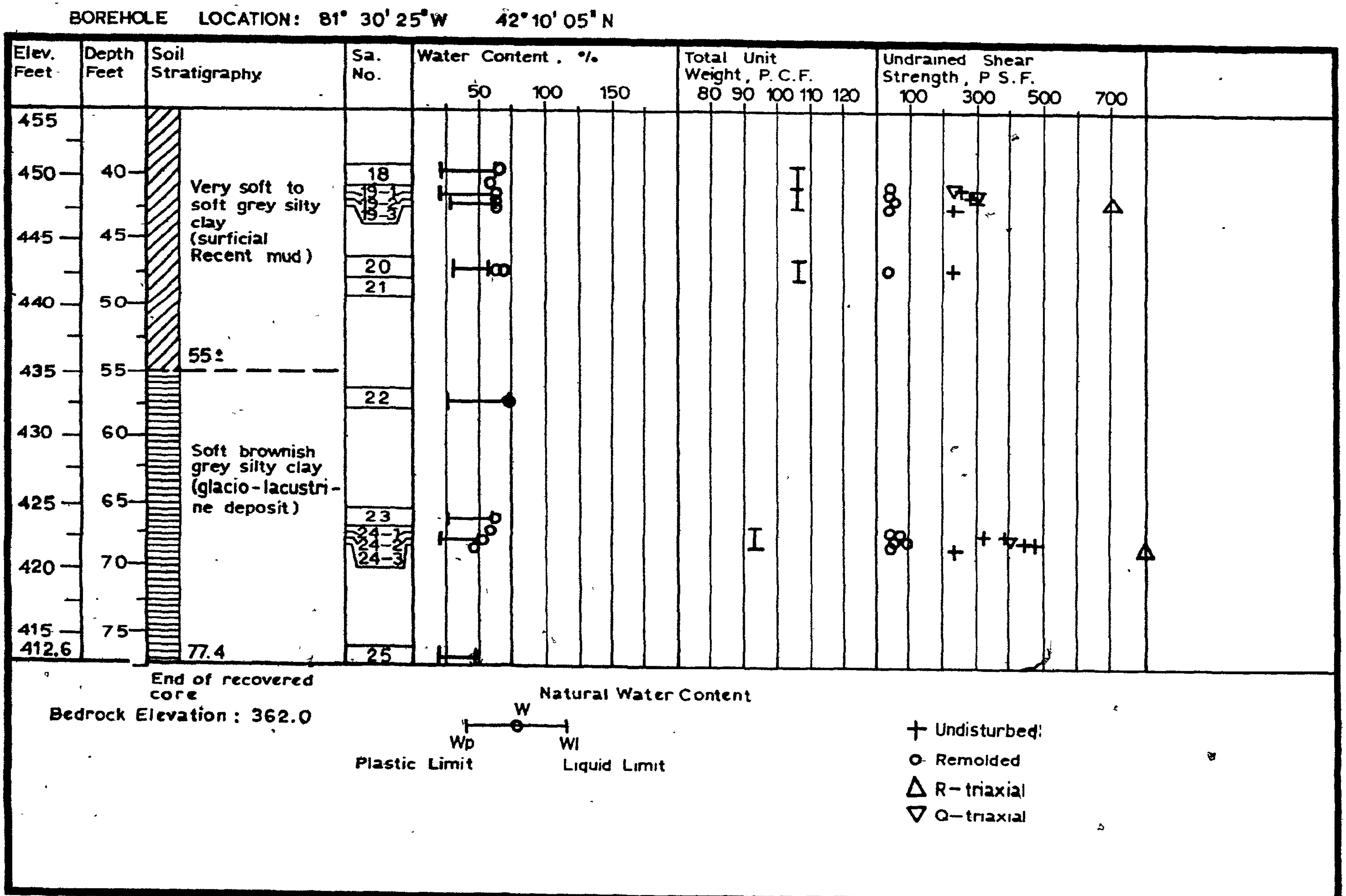


Fig. 9.2.2 Summary plot of geotechnical properties, Borehole No. 13156, Osterberg Sampler and Shelby Sampler.

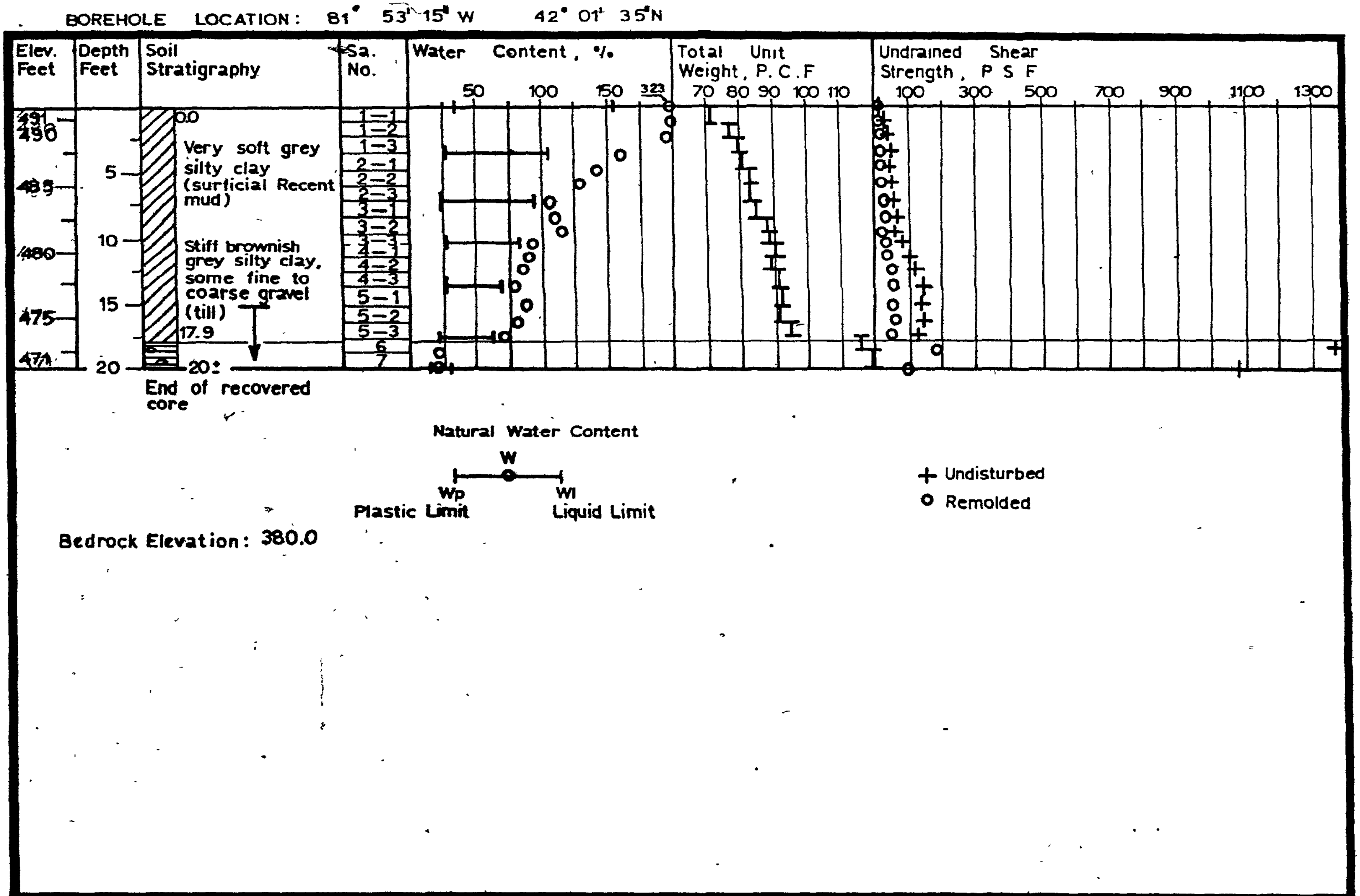


Fig. 9.3.1 Summary plot of geotechnical properties, Borehole No. 13160, Alpine Sampler.

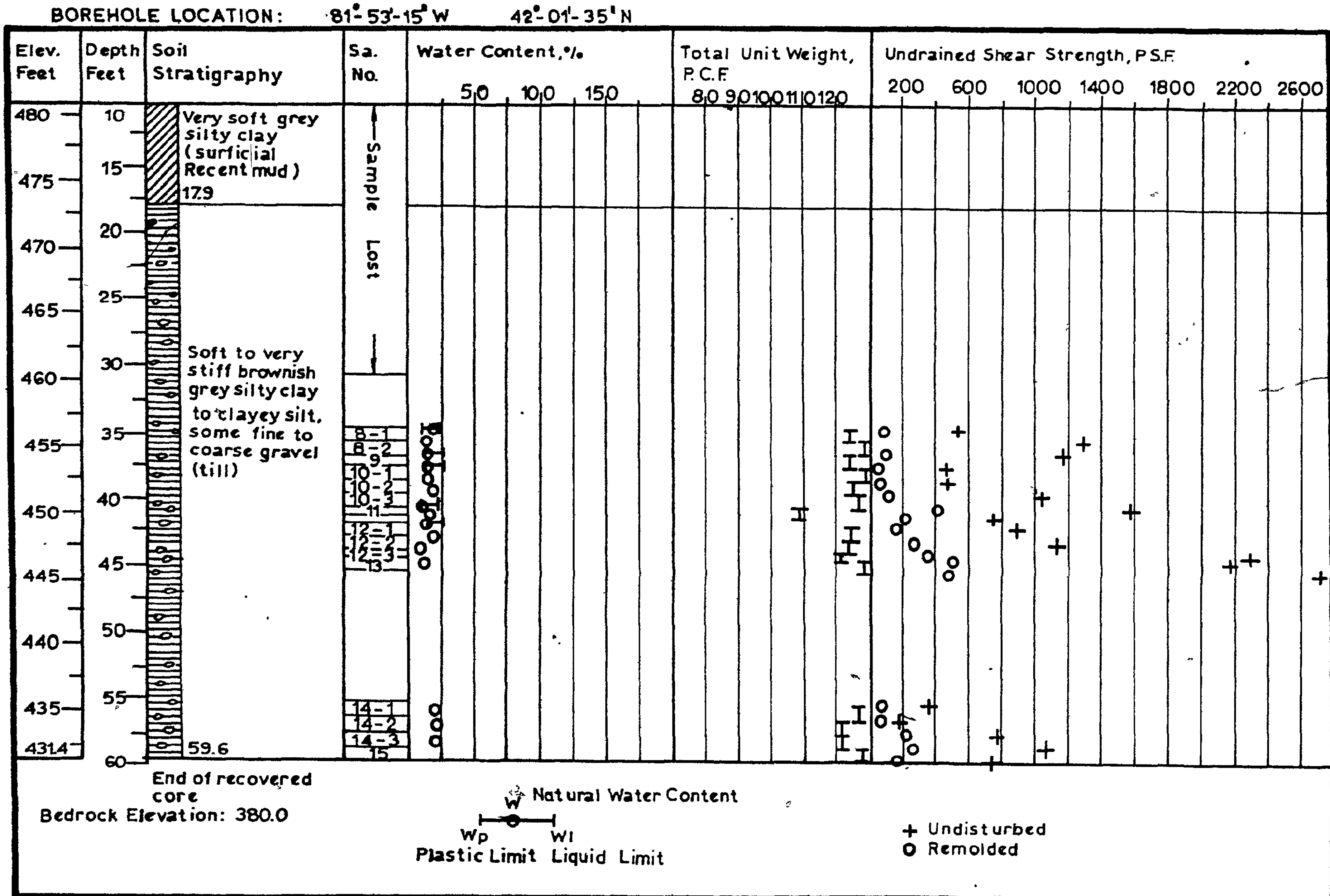


Fig. 9.3.2 Summary plot of geotechnical properties, Borehole No 13160, Christensen Sampler.

BOREHOLE LOCATION: 81°-37'-45"W 42°-13'-45"N

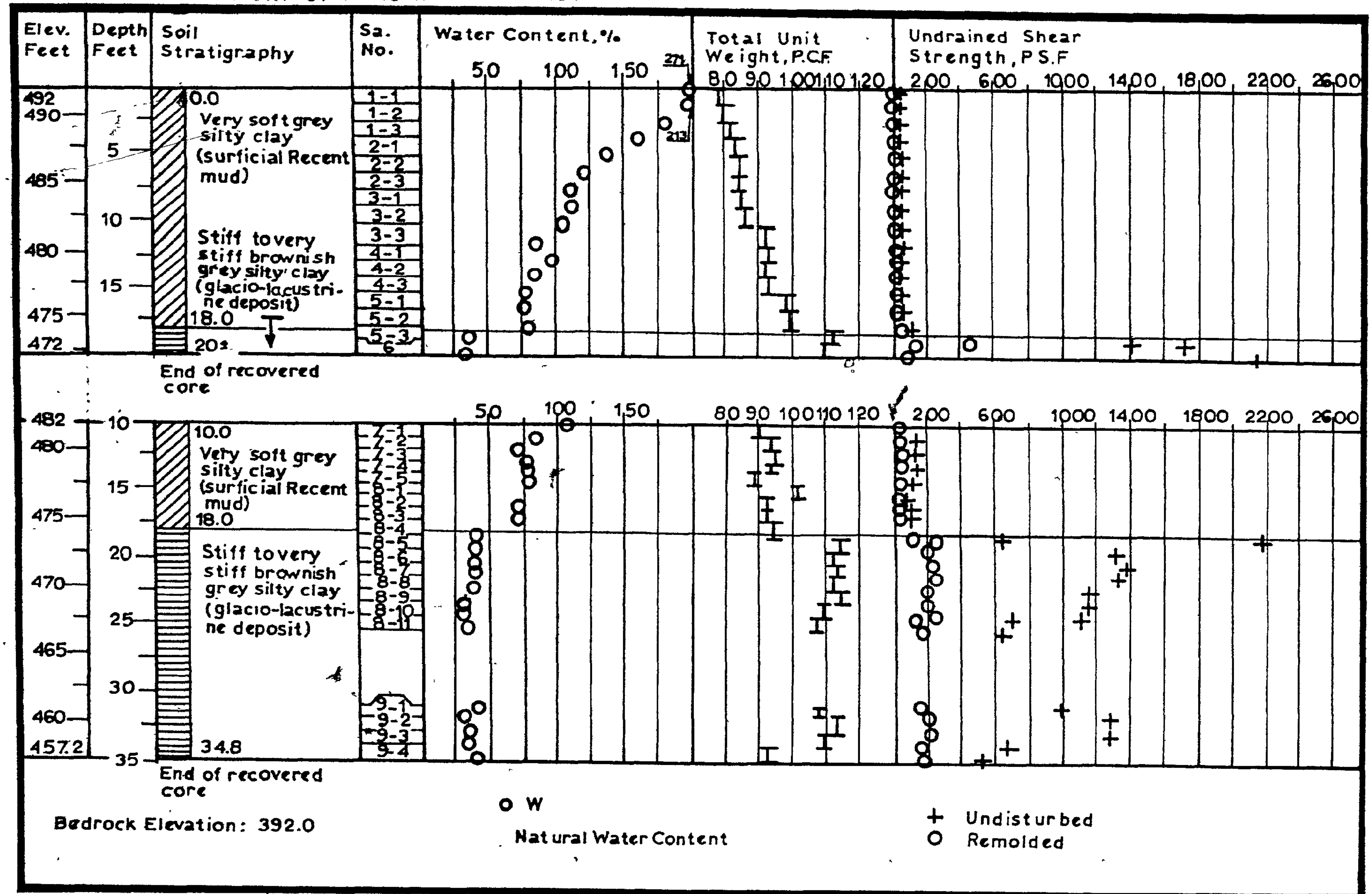


Fig. 9.4 Summary plot of geotechnical properties, Borehole No. 13161, Alpine Sampler (above) and Christensen Sampler (below).

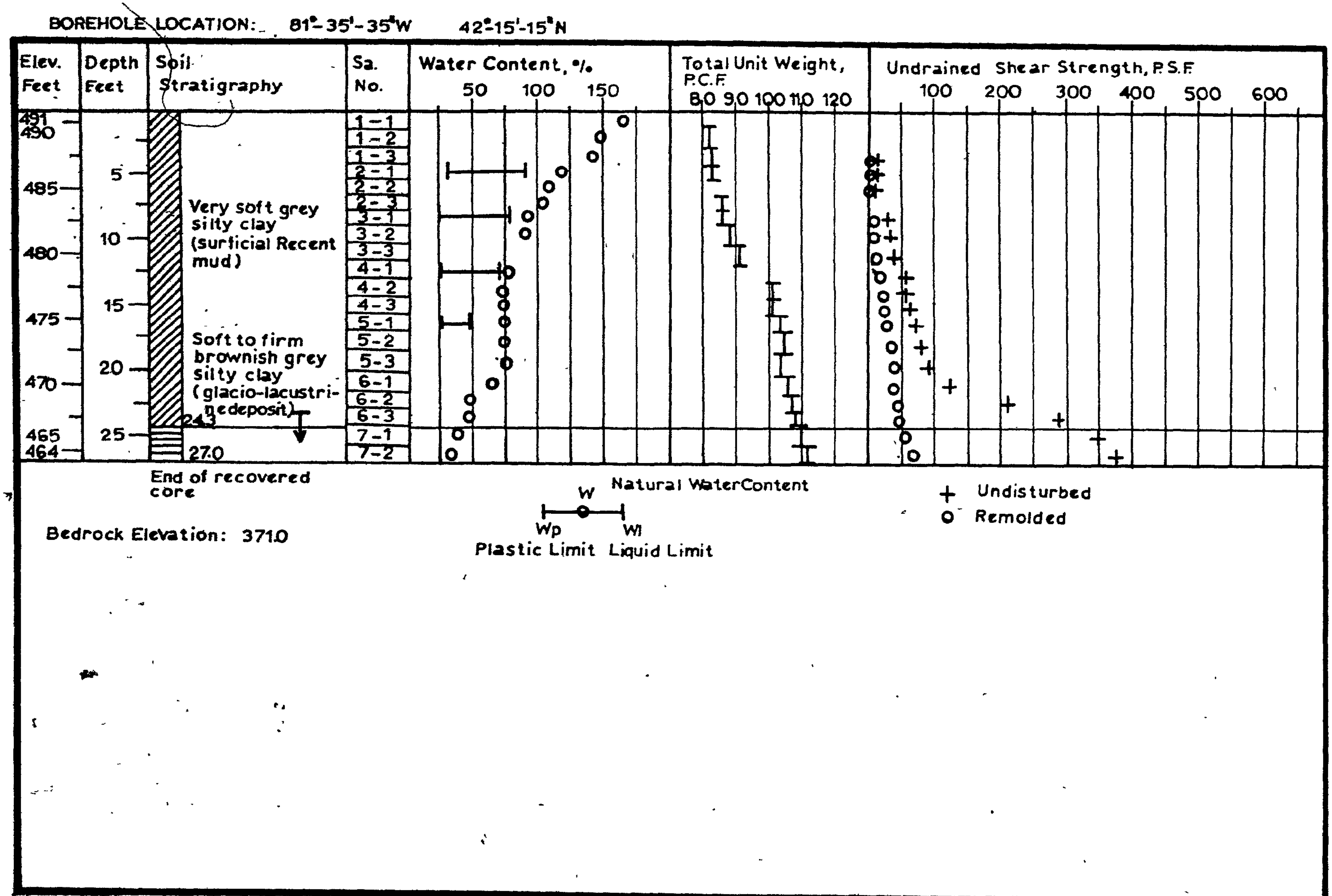


Fig. 9.5.1 Summary plot of geotechnical properties, Borehole No.13189, Alpine Sampler.

BOREHOLE LOCATION : 81°-35'-35" W 42°-15'-15" N

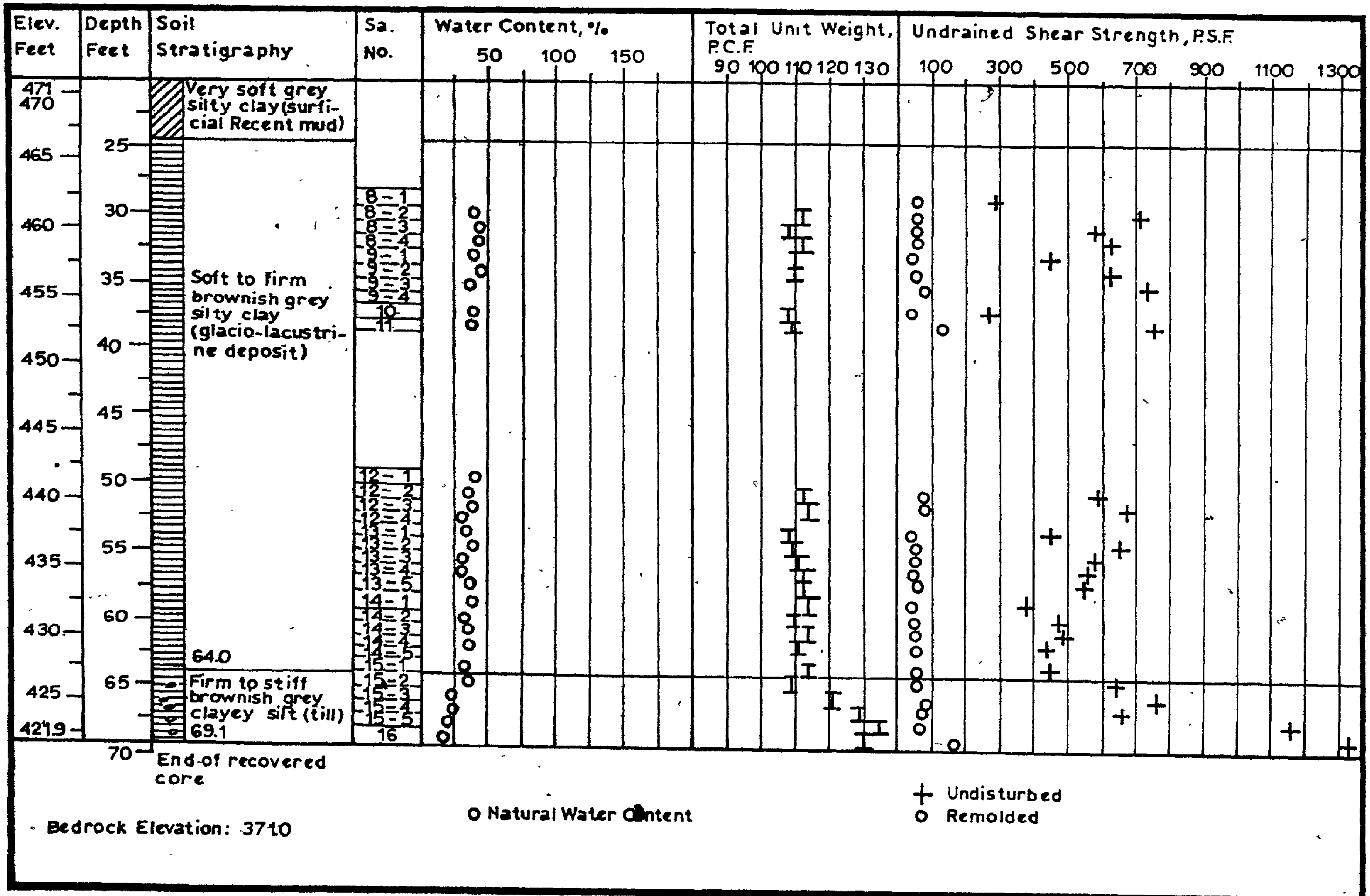


Fig. 9.5.2 Summary plot of geotechnical properties, Borehole No.13189, Christensen Sampler.

BOREHOLE LOCATION: 81°-28'-20" W 42°-14'-15" N

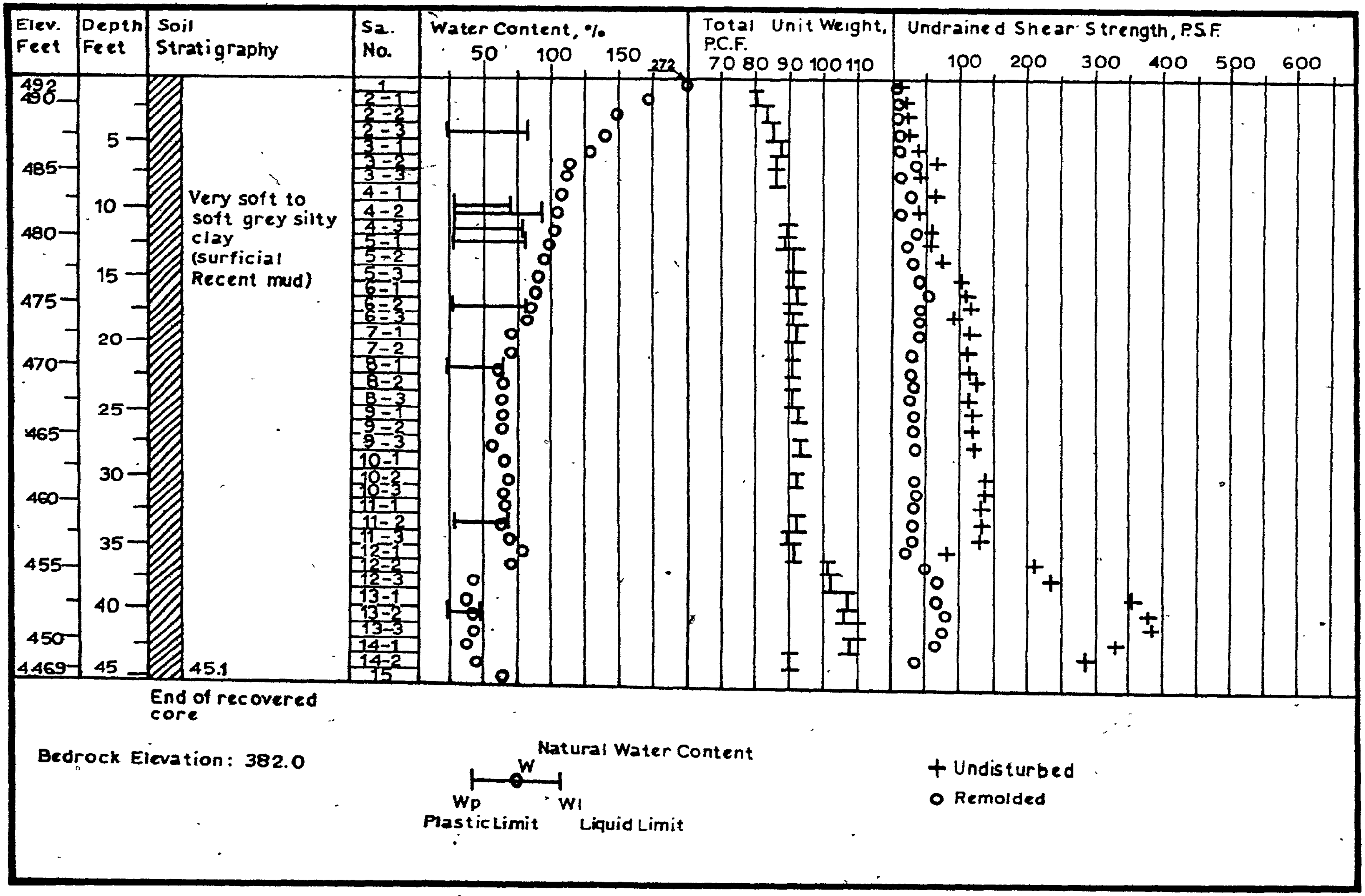


Fig. 9.6.1 Summary plot of geotechnical properties, Borehole No. 13193, Alpine Sampler.

BOREHOLE LOCATION: 81°- 28'- 20"W 42°- 14'-15"N

Bedrock Elevation: 382.0

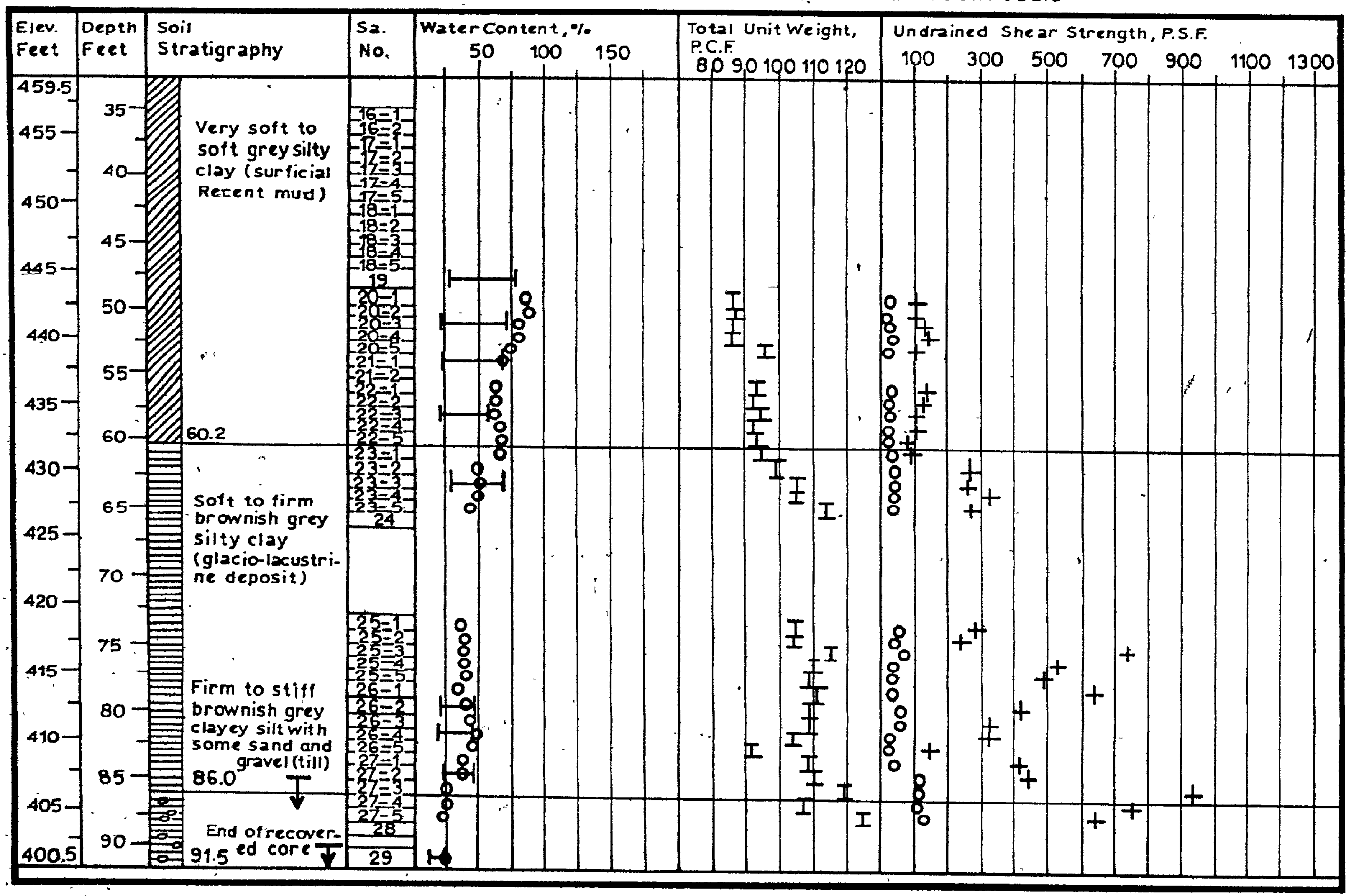


Fig. 9.6.2 Summary plot of geotechnical properties, Borehole 13193, Christensen Sampler.

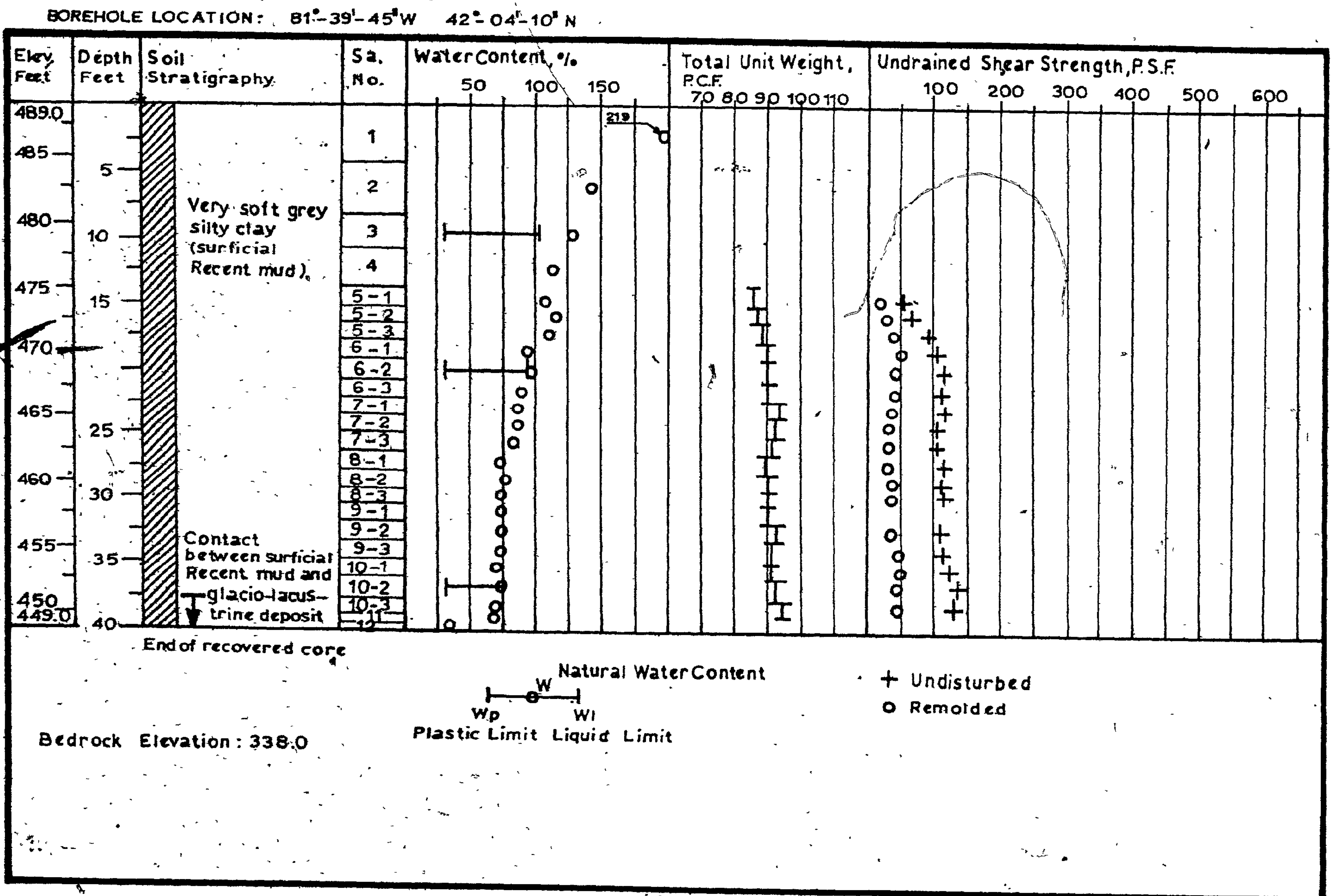


Fig. 9.7.1 Summary plot of geotechnical properties, Borehole No. 13194, Alpine Sampler.

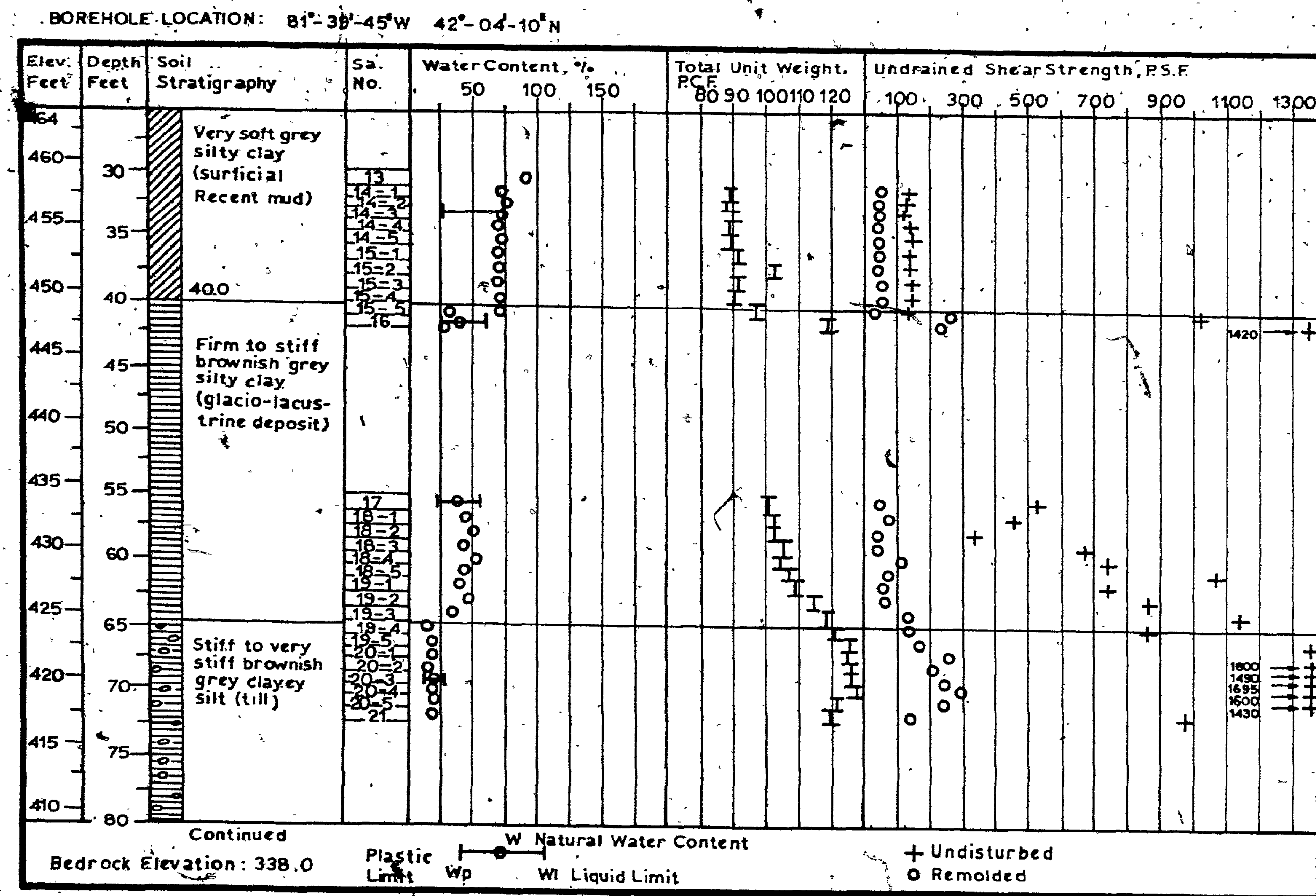


Fig. 9.7.2 Summary plot of geotechnical properties, Borehole No. 13194, Christensen Sampler.

BOREHOLE LOCATION: 81°-39'-45"W 42°-04'-10"N

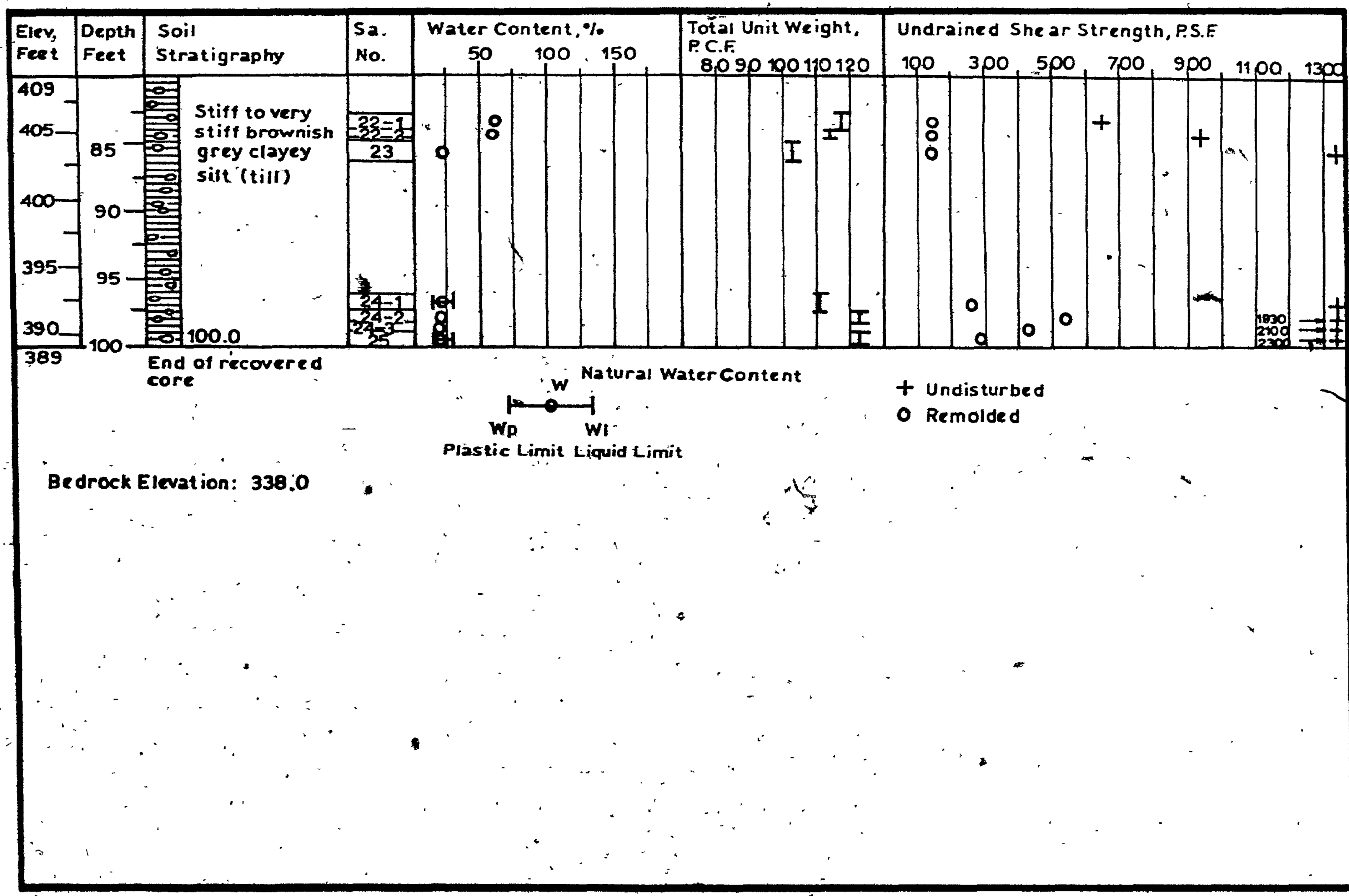
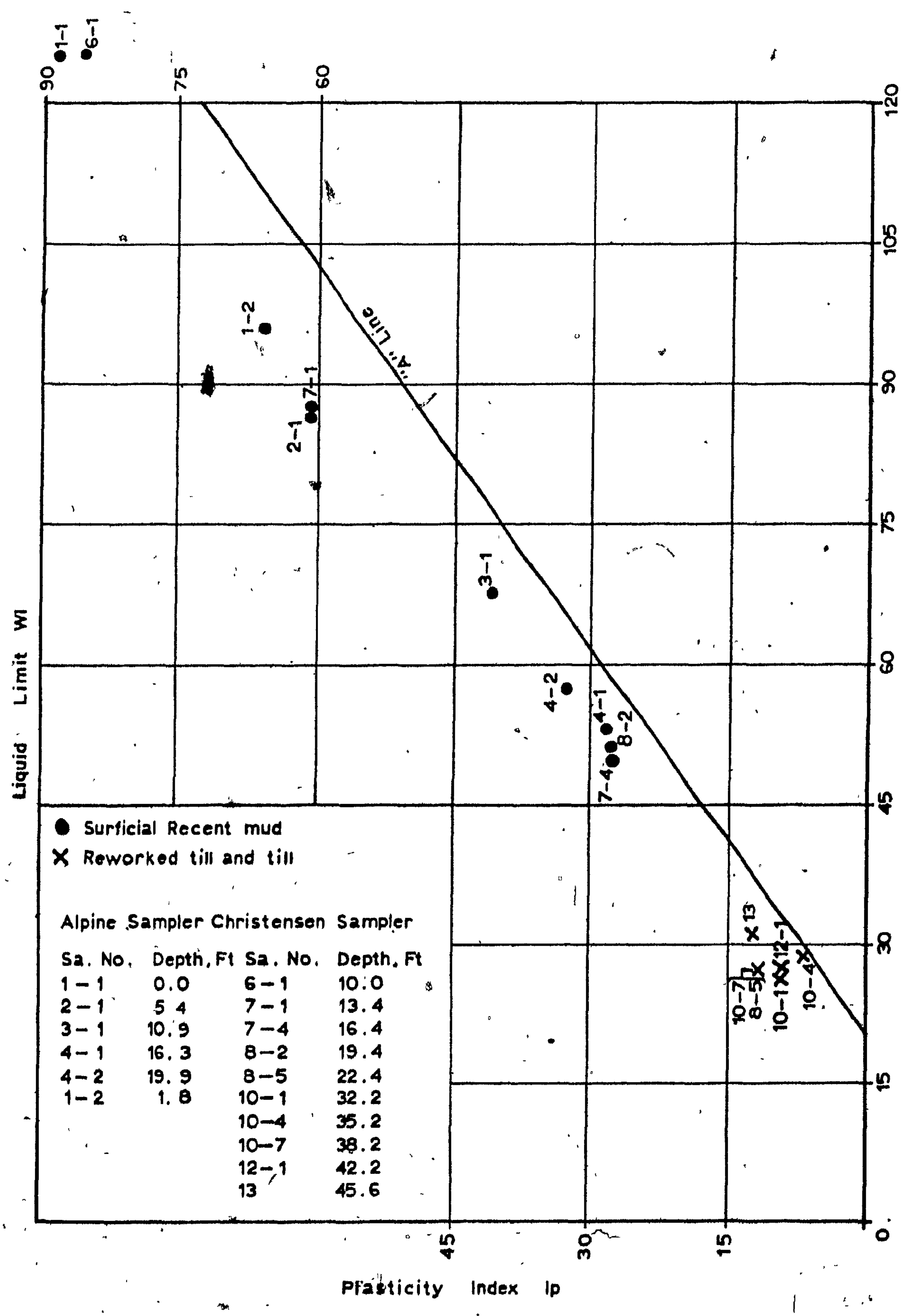


Fig. 9.7.3 Summary plot of geotechnical properties, Borehole No. 13194, Christensen Sampler.

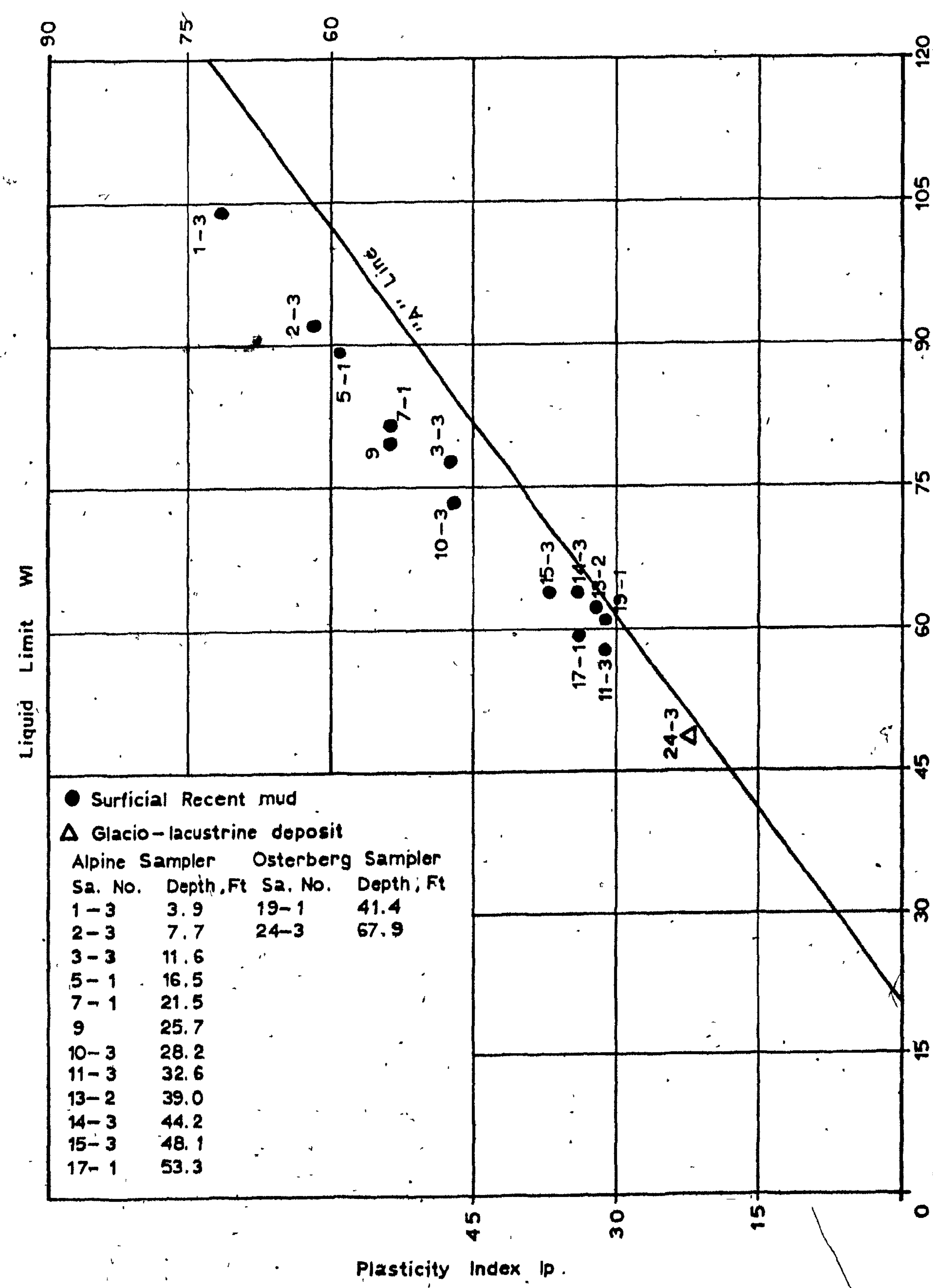
Casagrande plasticity chart, Borehole No. 13163

Figure 10. 1



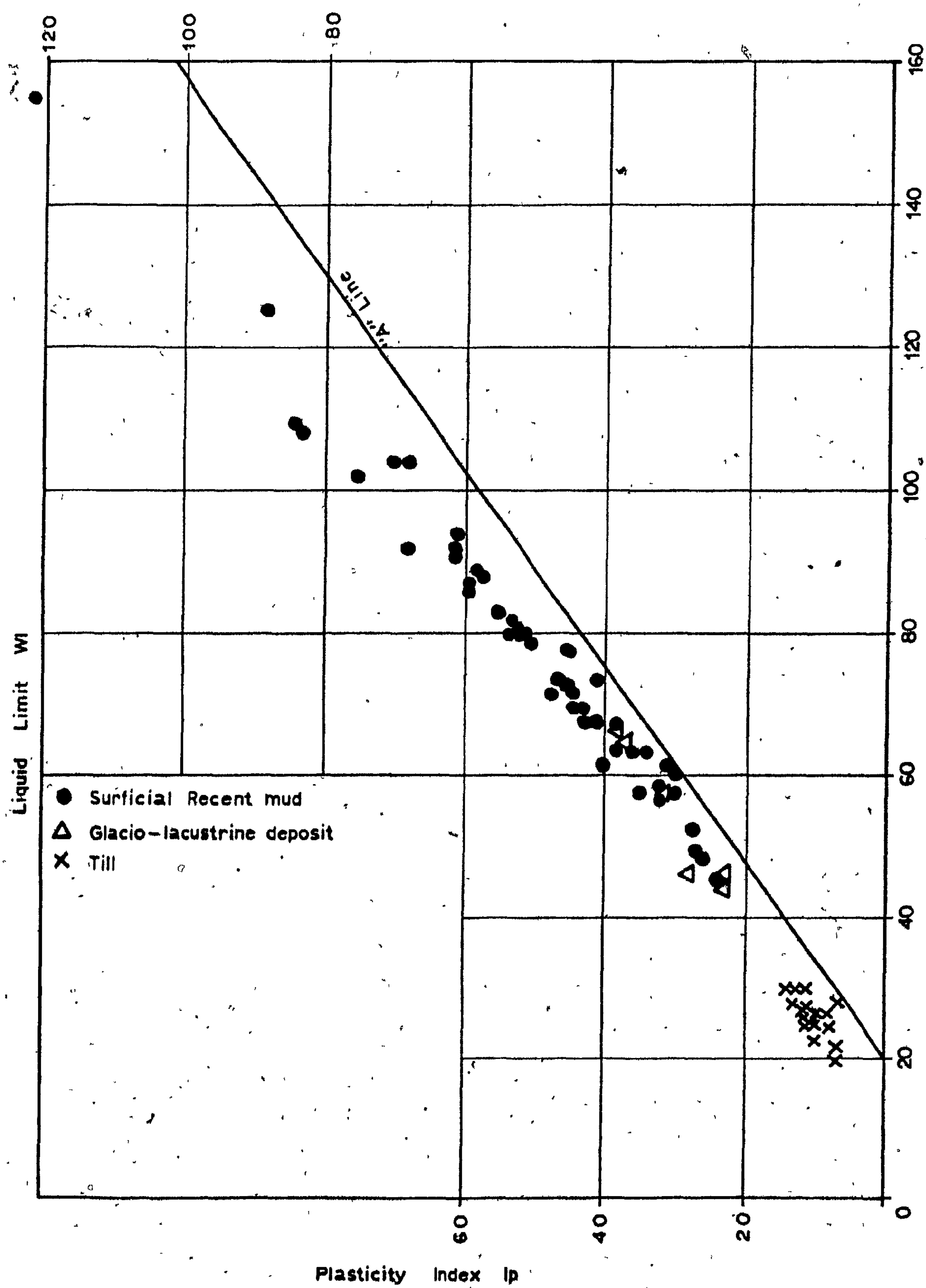
Casagrande plasticity chart, Borehole No.13156

Figure 10. 2



Casagrande plasticity chart, all boreholes

Figure 10.3



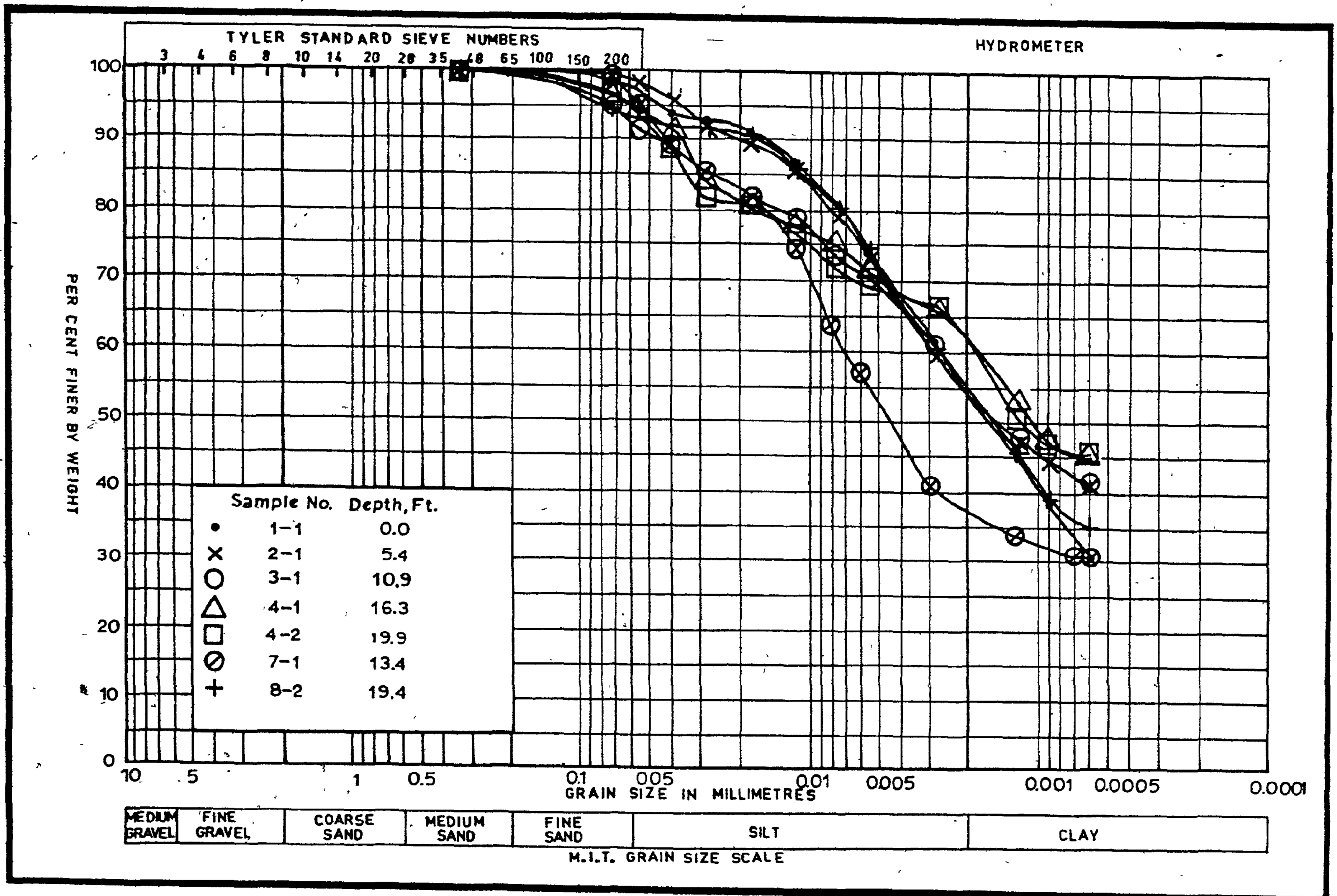


Fig. 11.1 Grain size distribution, Borehole No. 13163, surficial Recent mud.

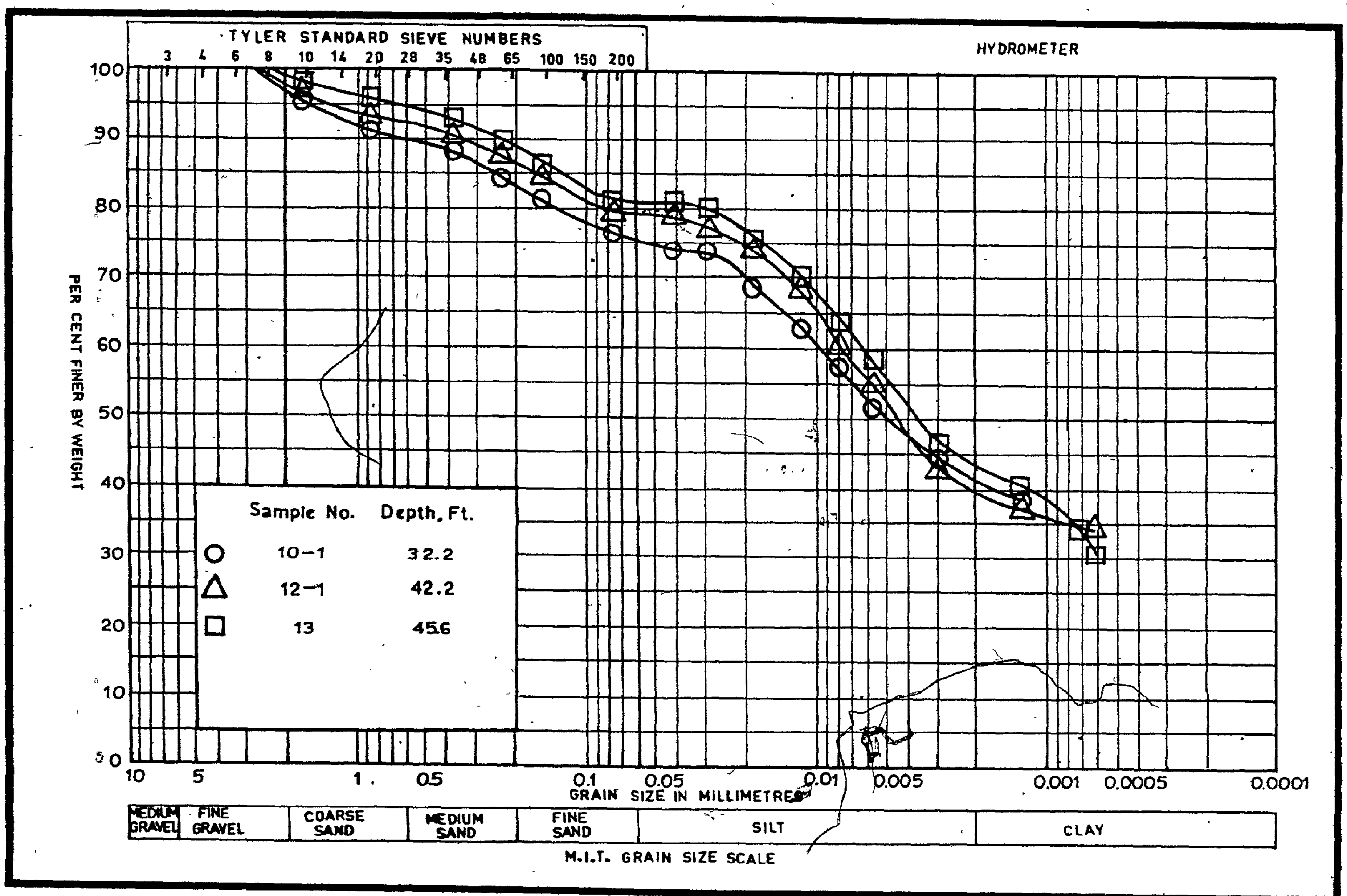


Fig. 11.2 Grain size distribution, Borehole No.13163, reworked till and till.

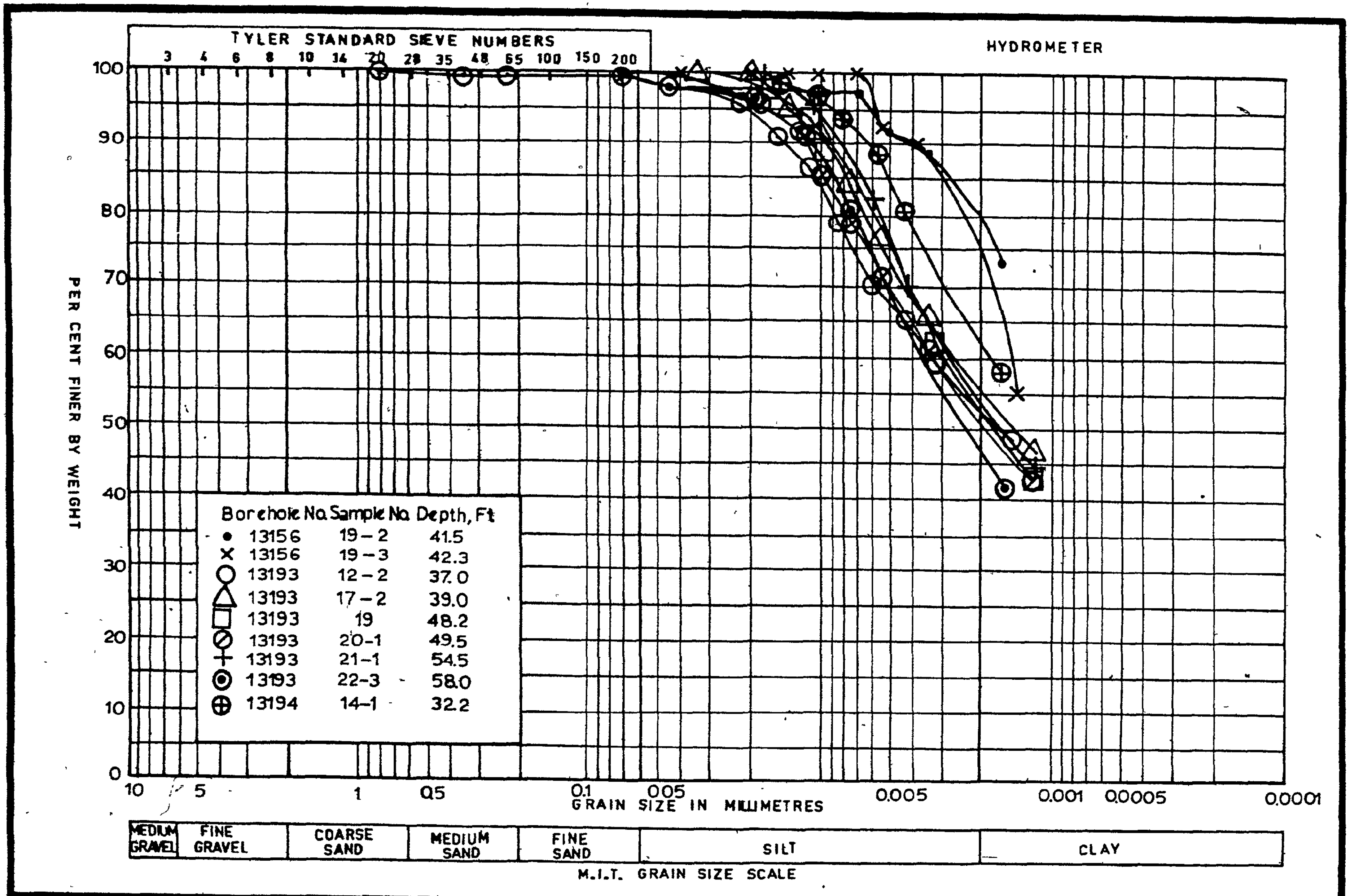


Fig. 11.3 Grain size distribution, surficial Recent mud (tests by H.Q.G.A.).

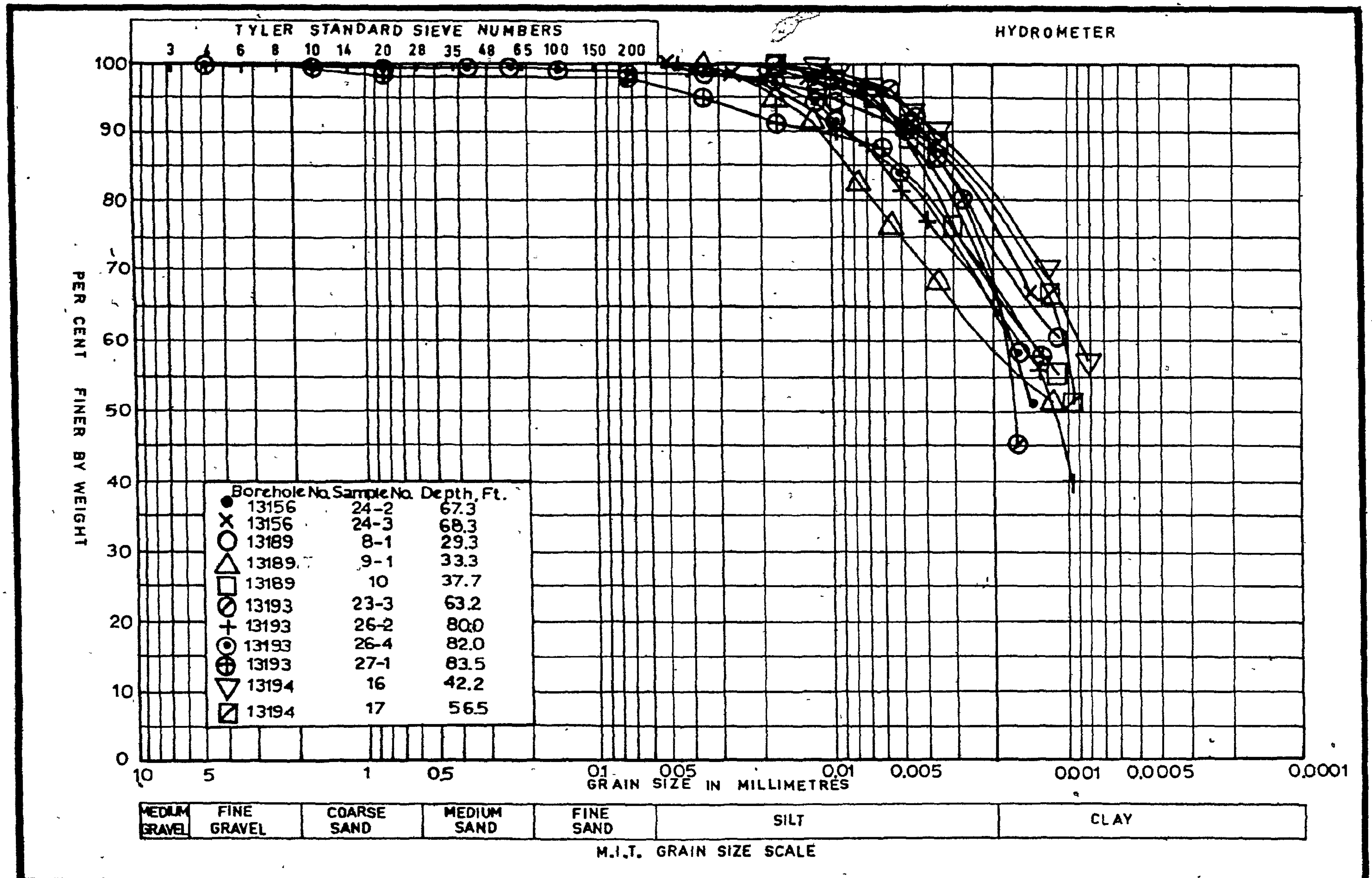


Fig. 11.4 Grain size distribution, glacio-lacustrine deposit (tests by H.Q.G.A.).

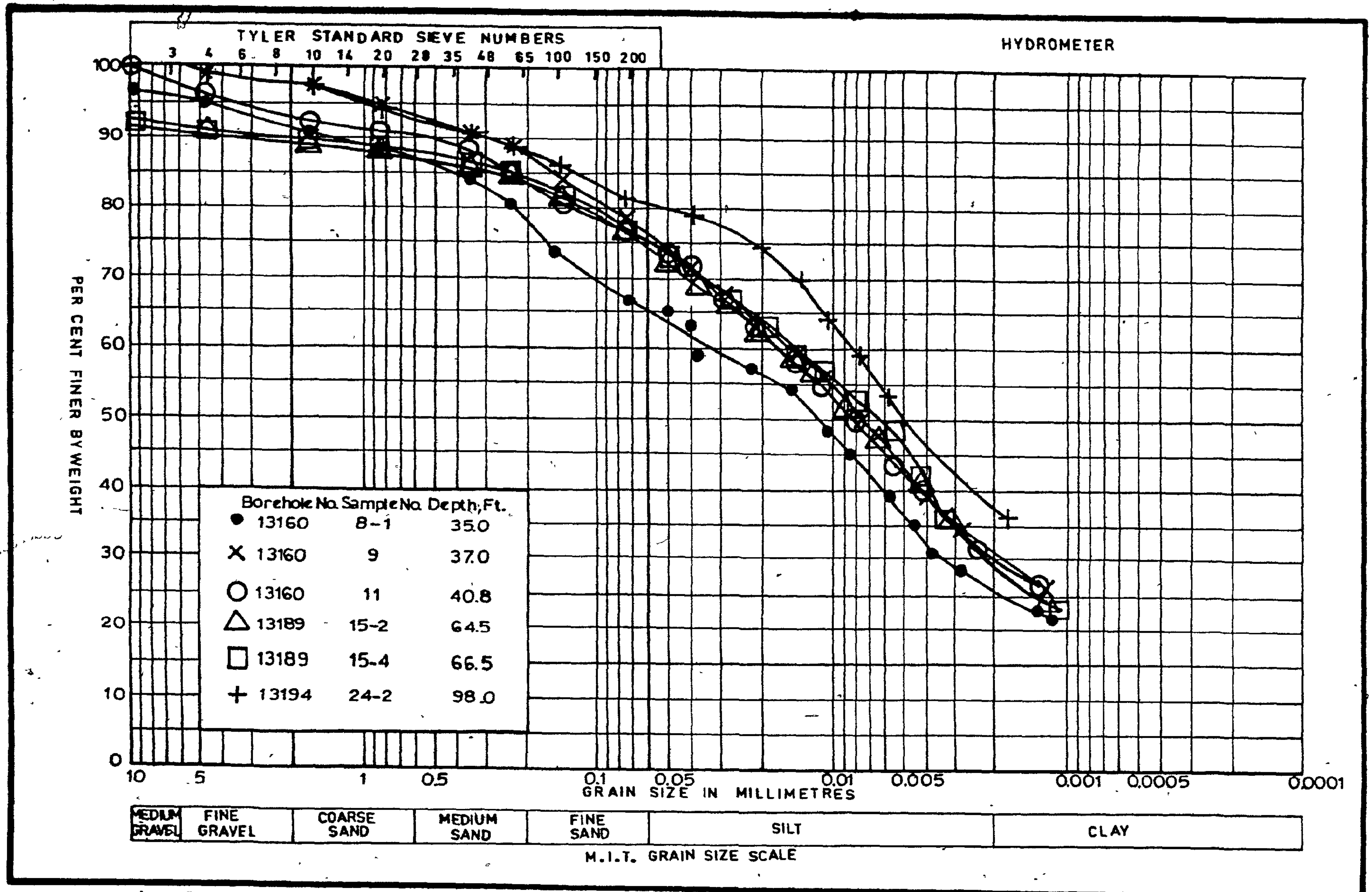
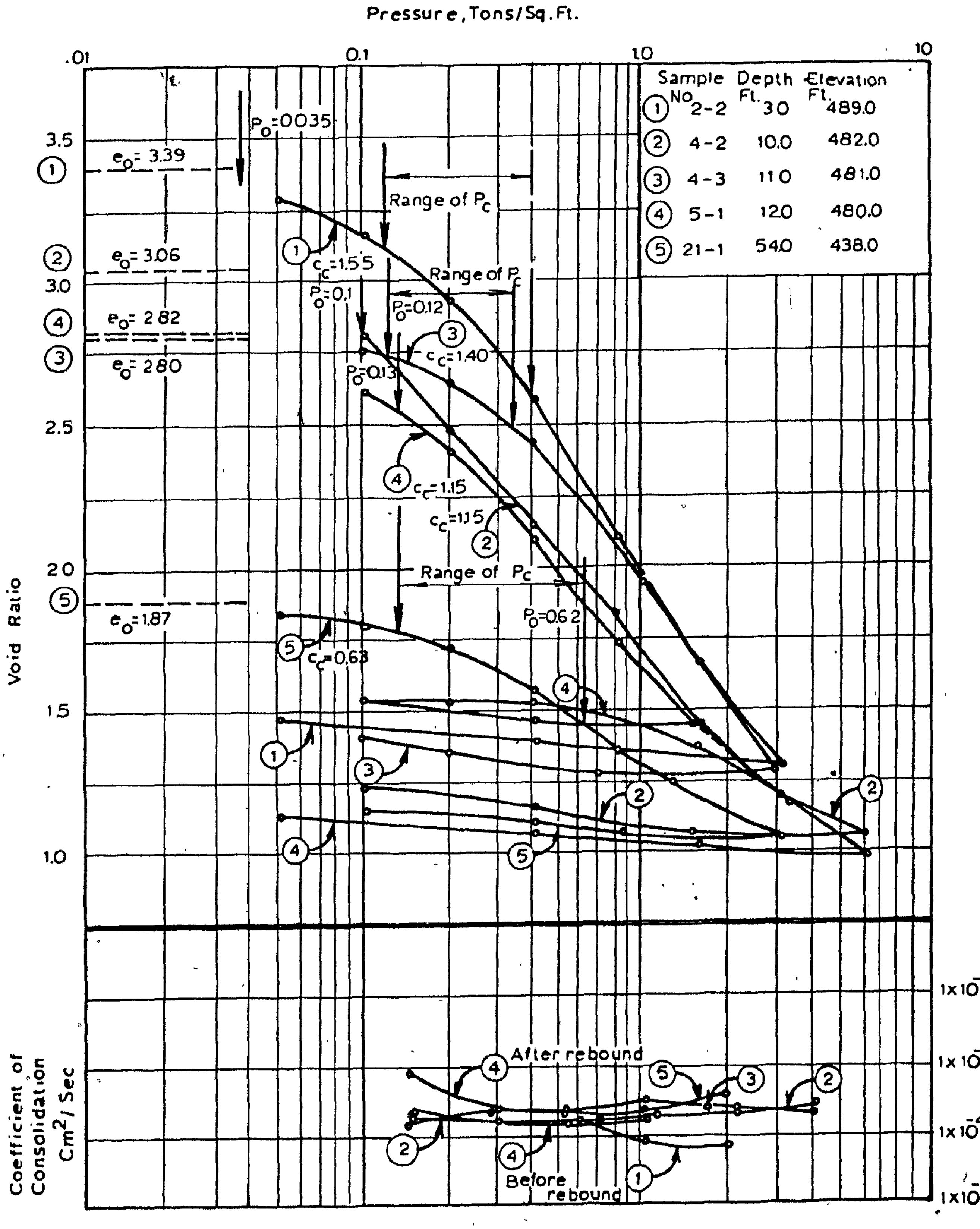


Fig. 11.5 Grain size distribution, till (tests by H.Q.G.A.).



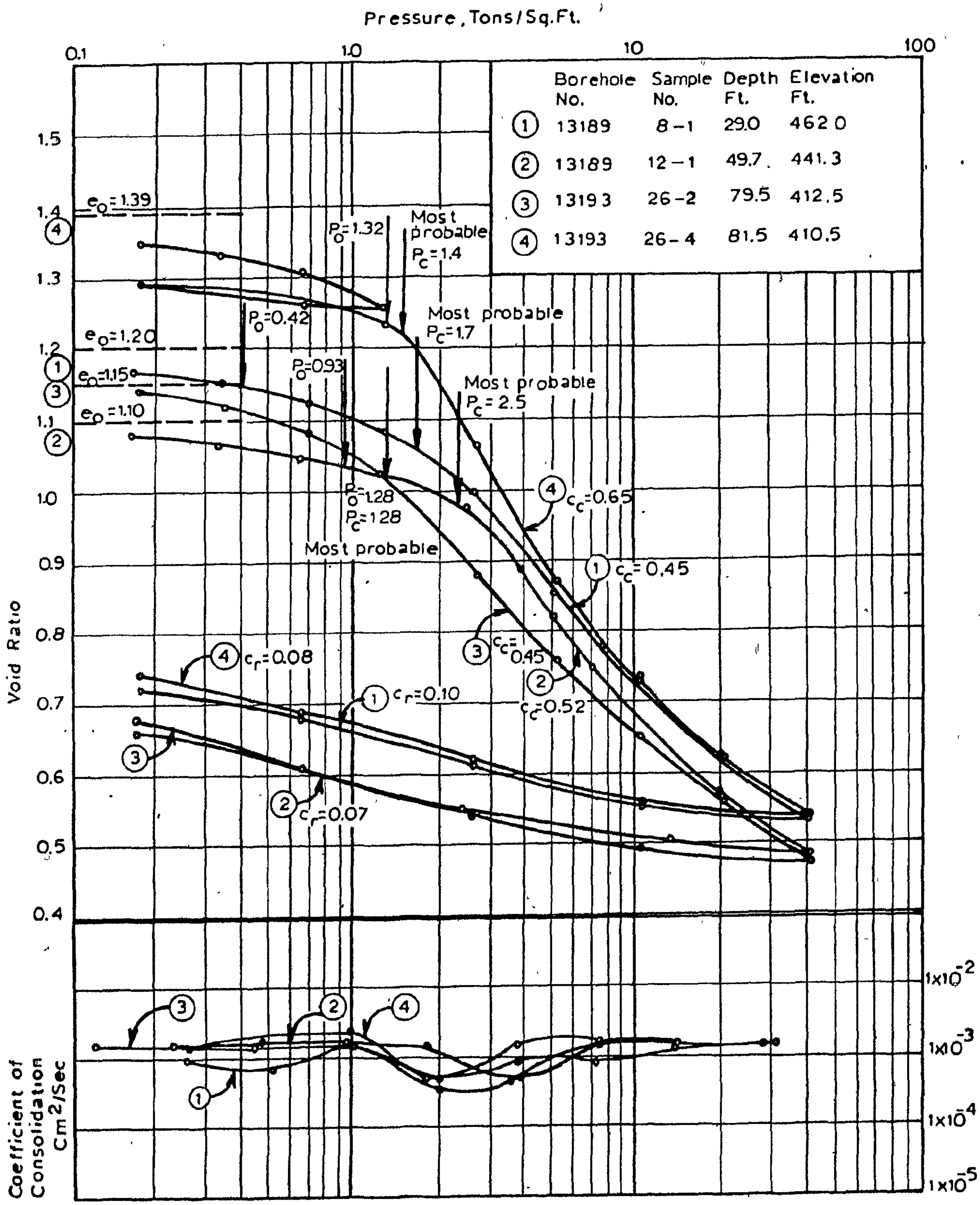
P_o = Effective overburden pressure

P_c = Preconsolidation pressure

e_o = Natural void ratio

c_c = Compression index

Fig.12.1 Consolidation curves (e - log p) for surficial Recent mud, Borehole 13193 (tests by H.Q.G.A.).



P_o = Effective overburden pressure

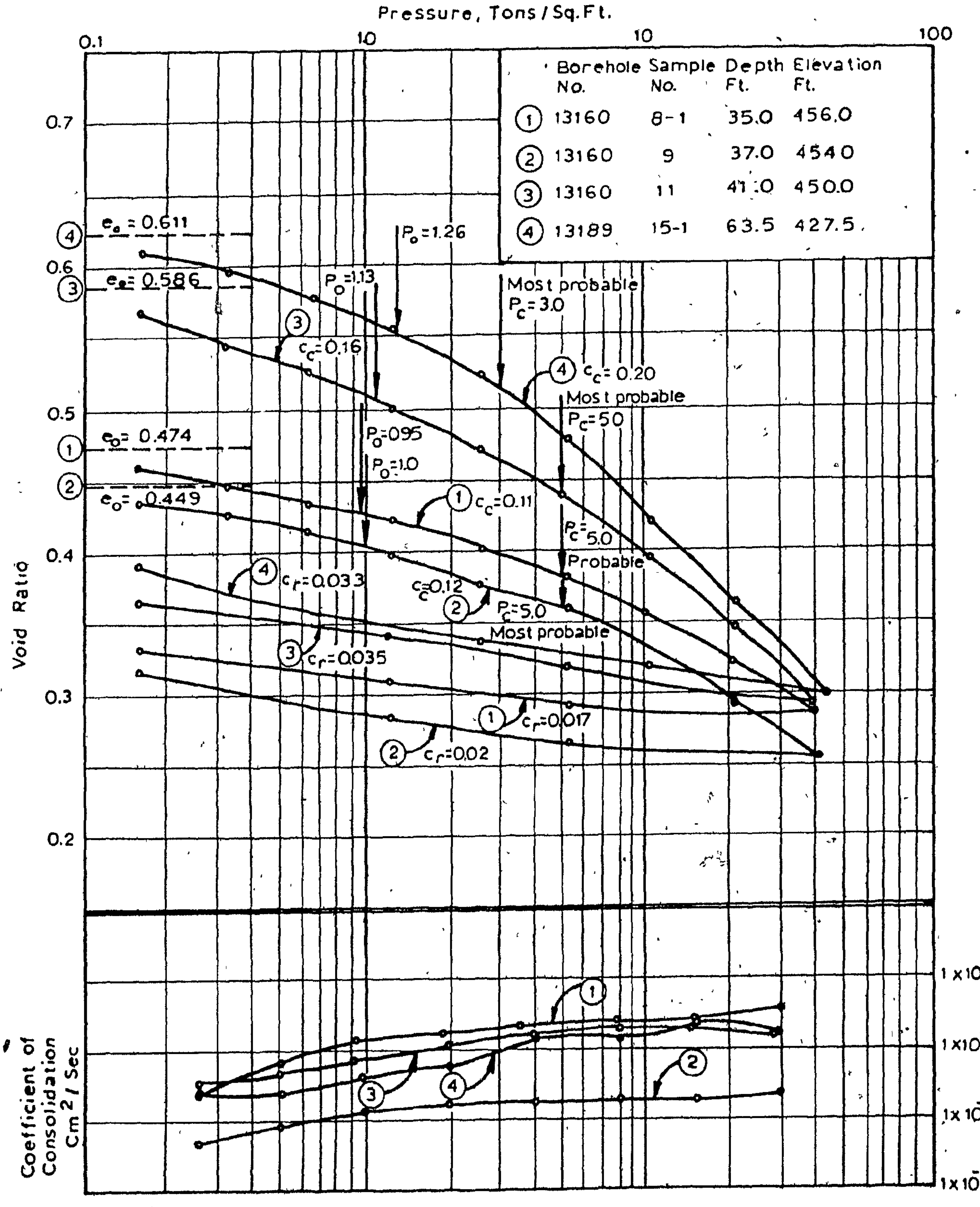
P_c = Preconsolidation pressure

e_o = Natural void ratio

c_c = Compression index

c_r = Rebound index

Fig. 12.2 Consolidation curves (e - log p) for glacio-lacustrine deposit (tests by H.O.G.A.).



P_o = Effective overburden pressure

P_c = Preconsolidation pressure

e_o = Natural void ratio

c_c = Compression index

c_r = Rebound index

Fig.12.3 Consolidation curves (e - log p) for till deposit (tests by H.Q.G.A.).

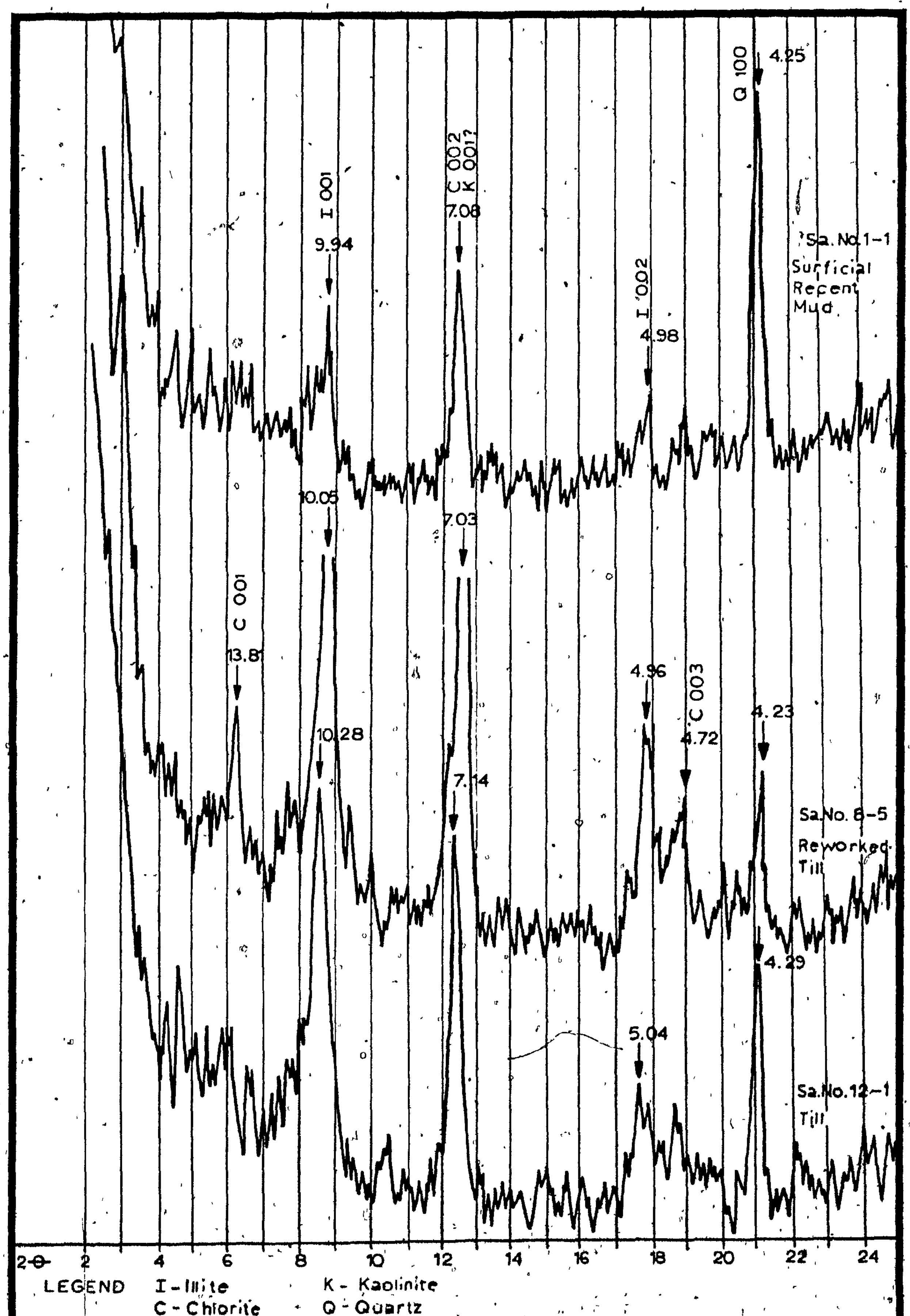
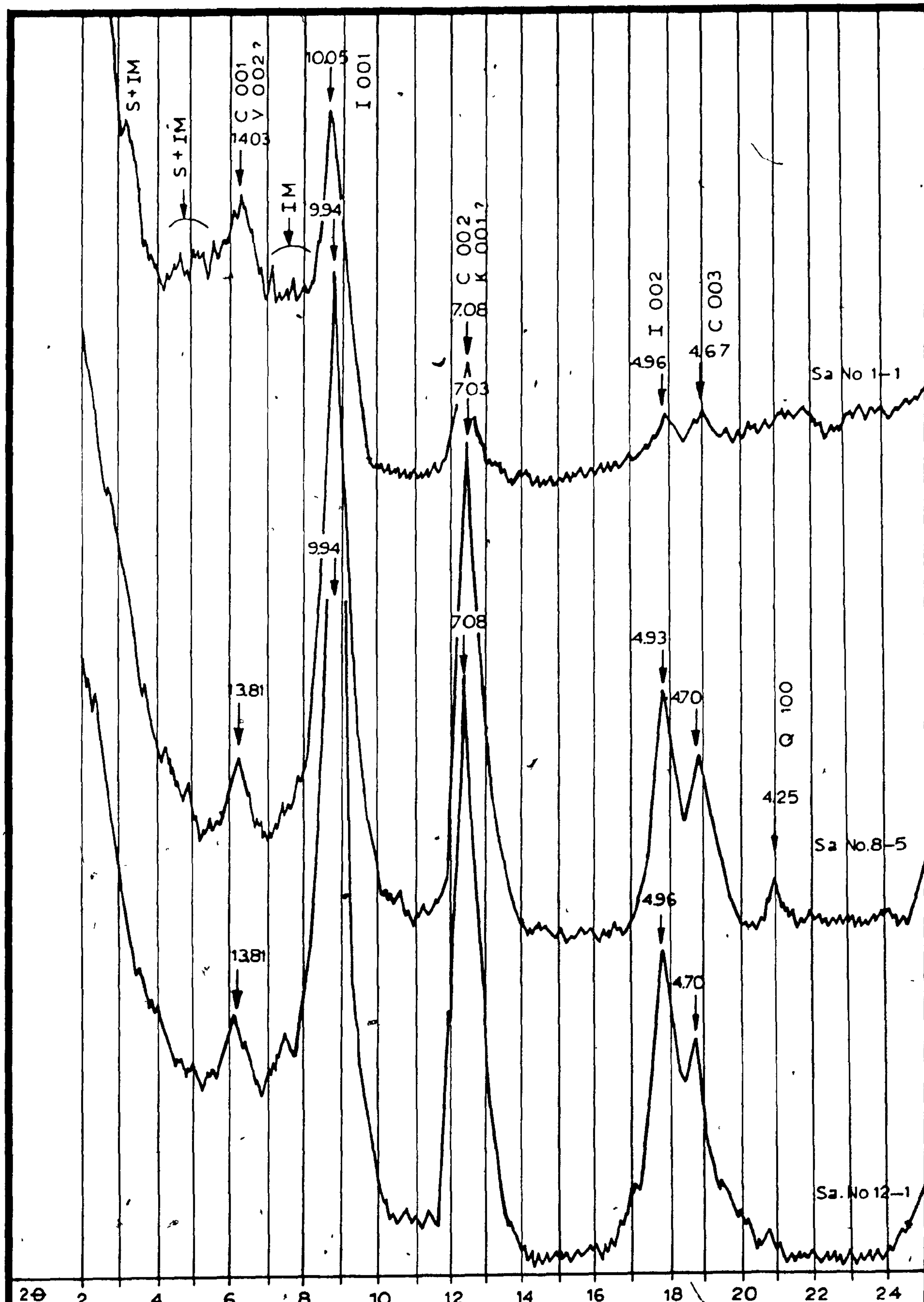


Fig. 13.1 X-ray diffraction traces, untreated bulk specimens, Borehole 13163.



LEGEND I - Illite K - Kaolinite IM - Interlayered Mineral Q - Quartz
C - Chlorite V - Vermiculite S - Smectite

Fig. 13 2 X-ray diffraction traces, untreated -2 micron fraction, Borehole 13163.

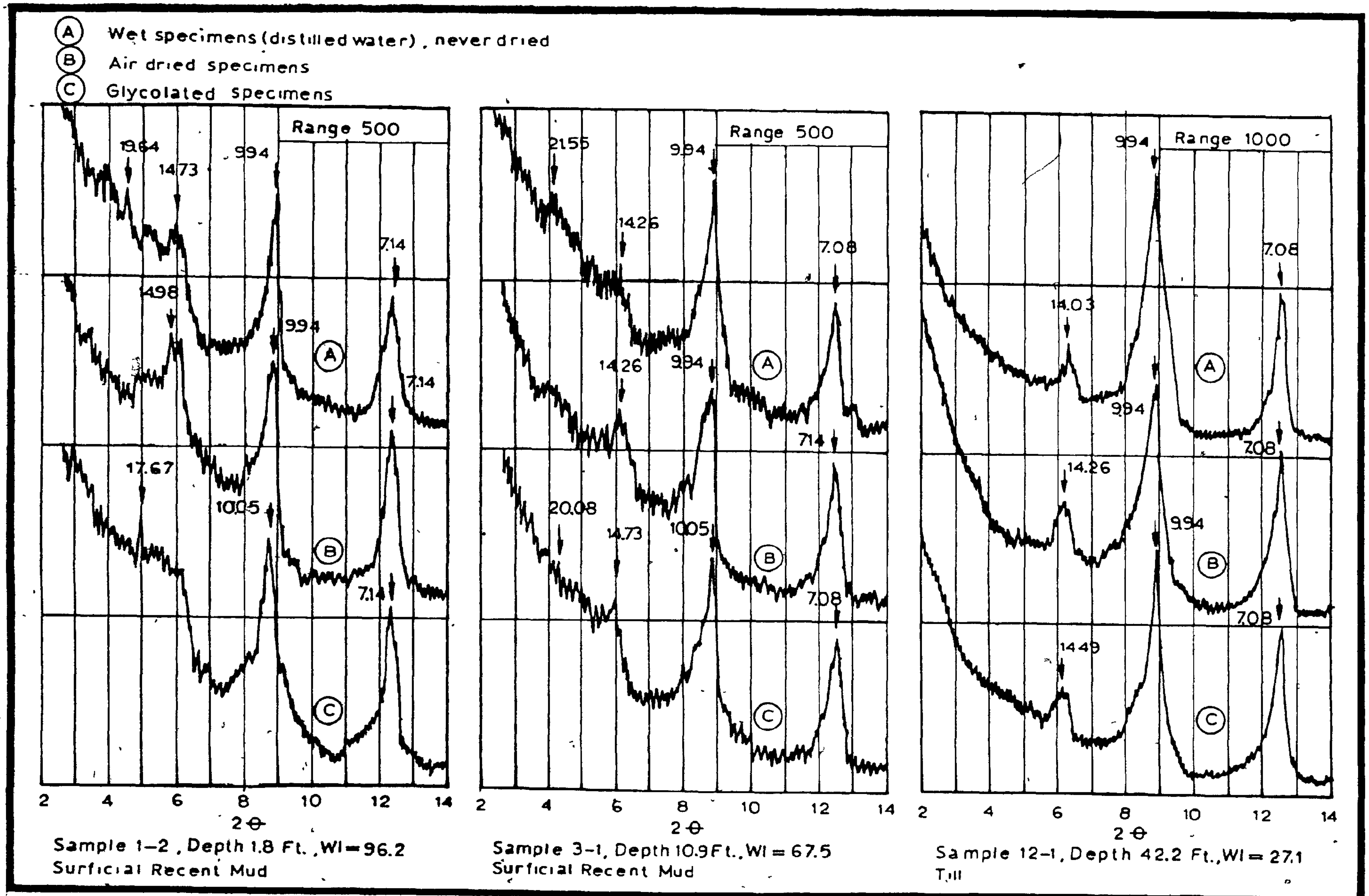


Fig. 13.3 Effect of air drying and glycolation on X-ray diffraction traces, Borehole 13163, -2 micron fraction, centrifuge oriented (tests by Soil Mechanics Laboratory, University of Western Ontario).

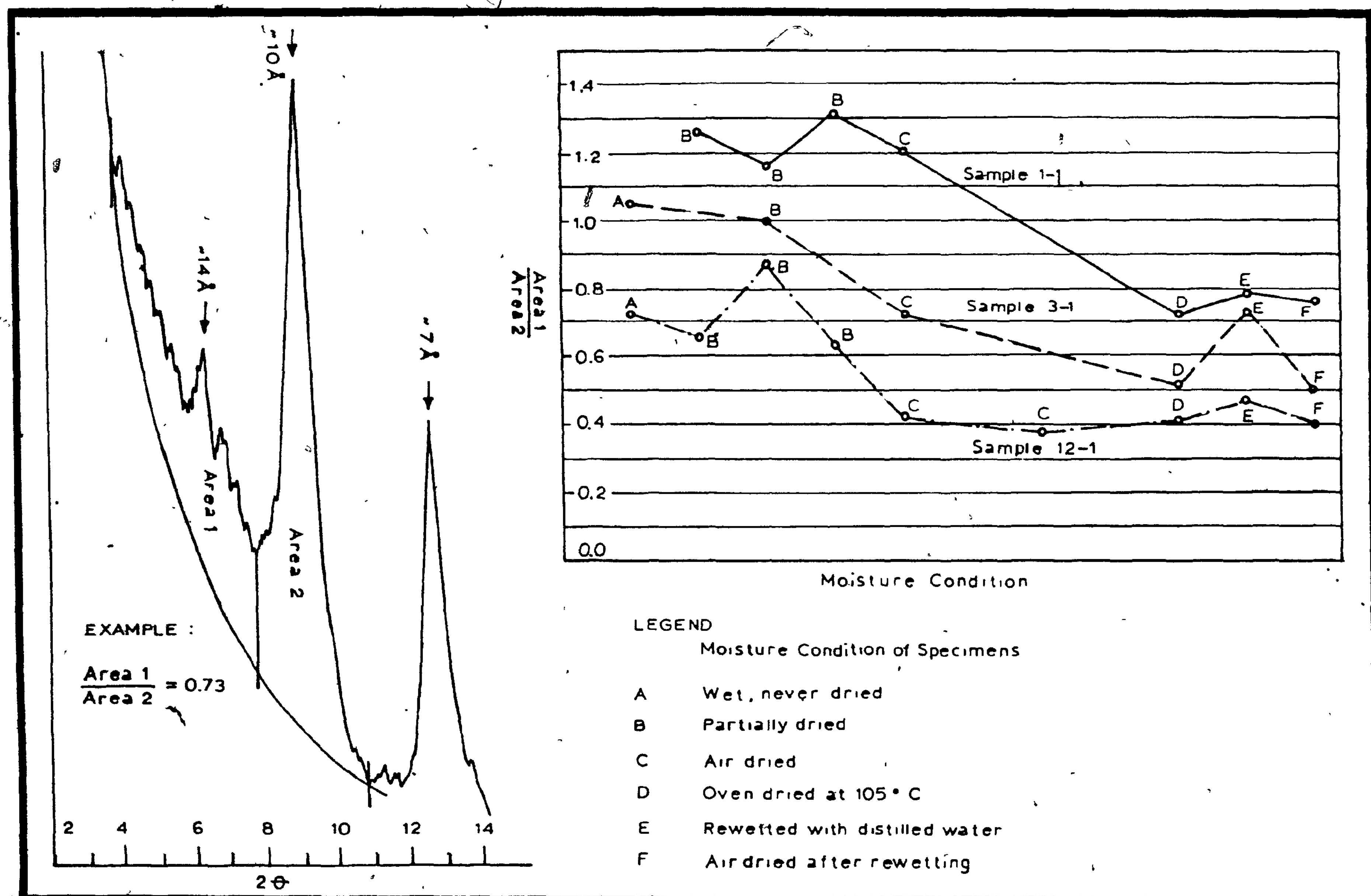


Fig. 13.4 Effect of air drying, oven drying, and rewetting on the 14 Å and 10 Å peak areas, Borehole 13163, untreated -2 micron fraction.

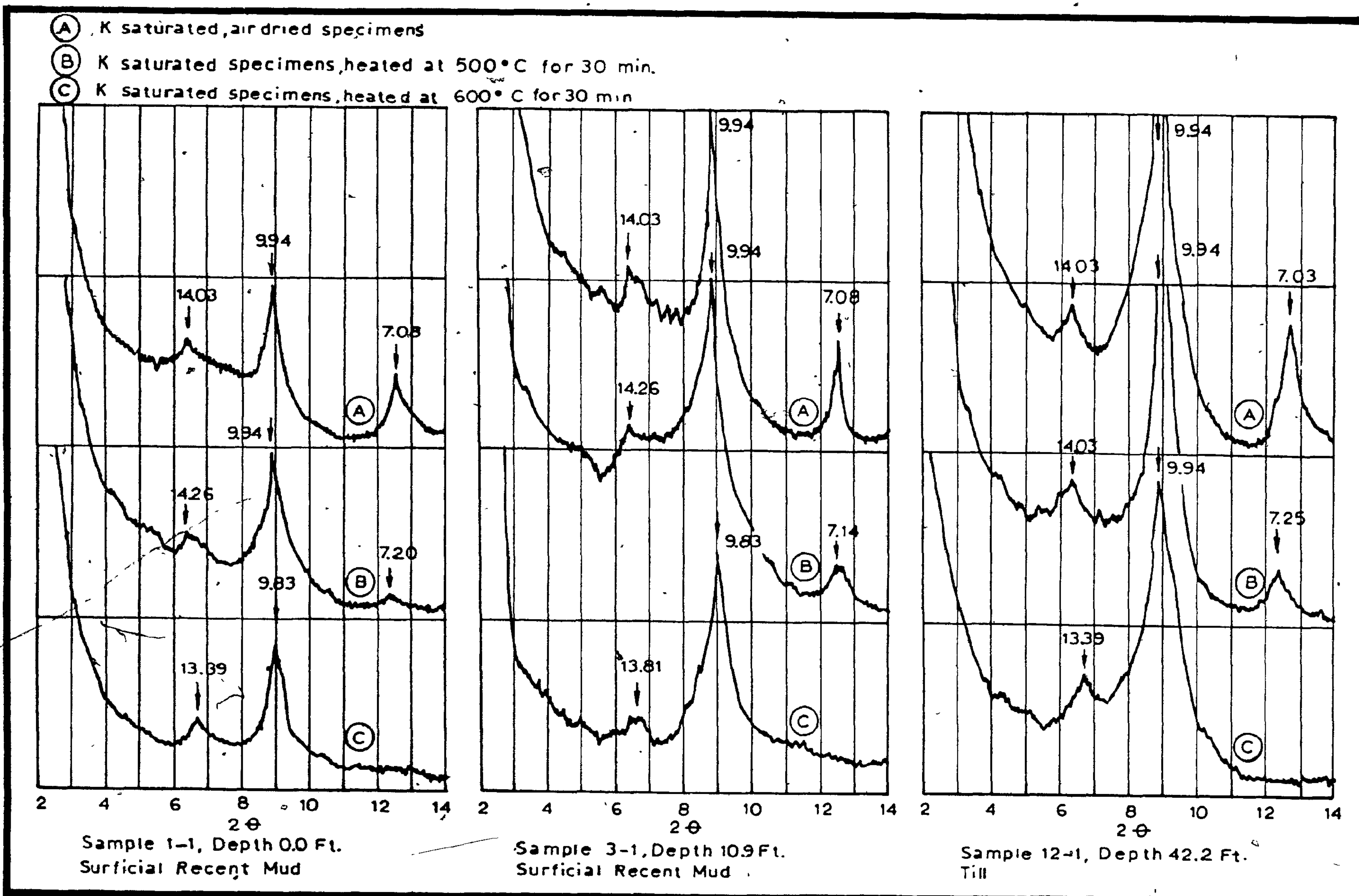


Fig. 13.5 · Effect of potassium saturation and furnace heating on X-ray diffraction traces, Borehole 13163, -2 micron fraction.

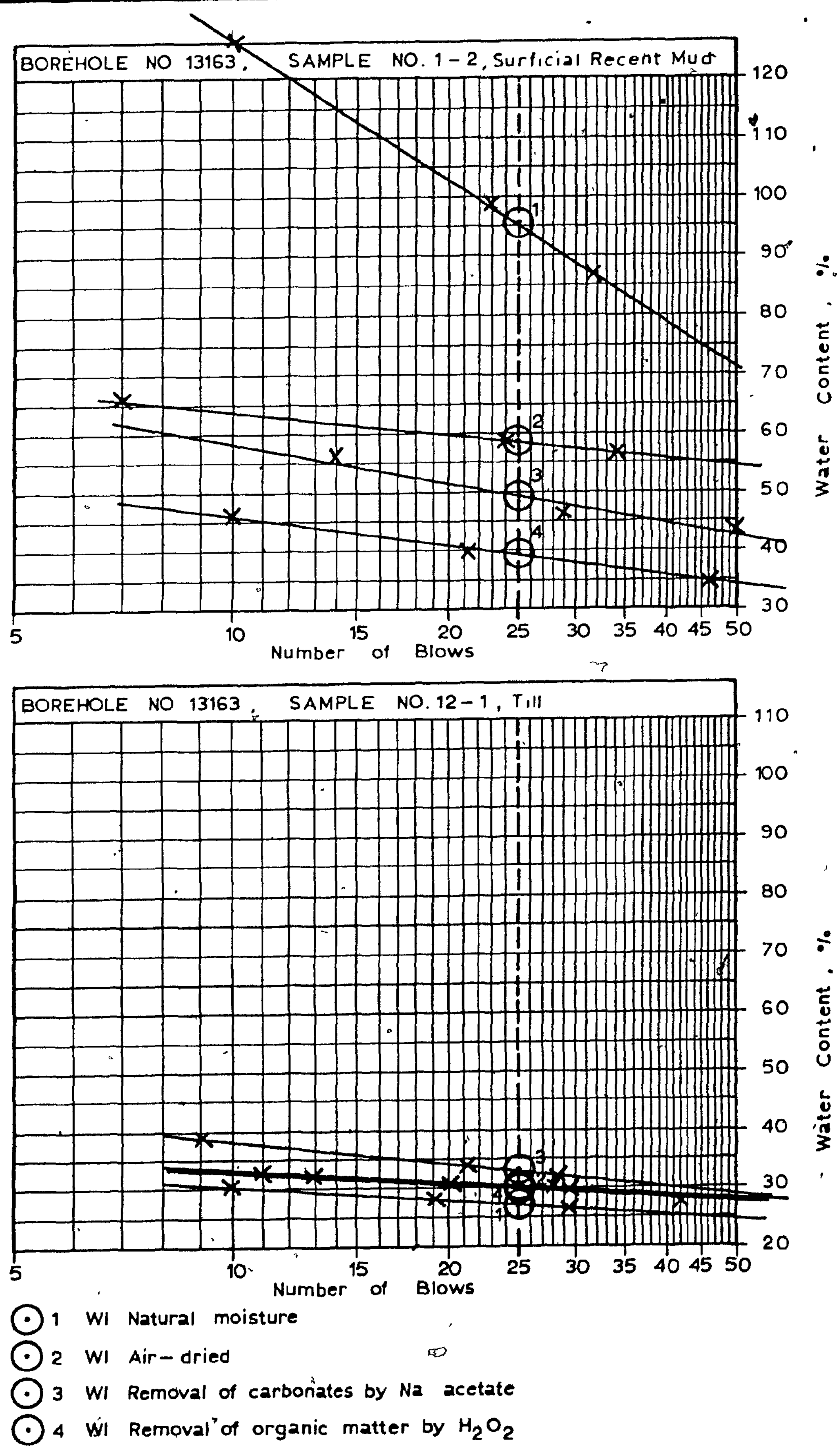
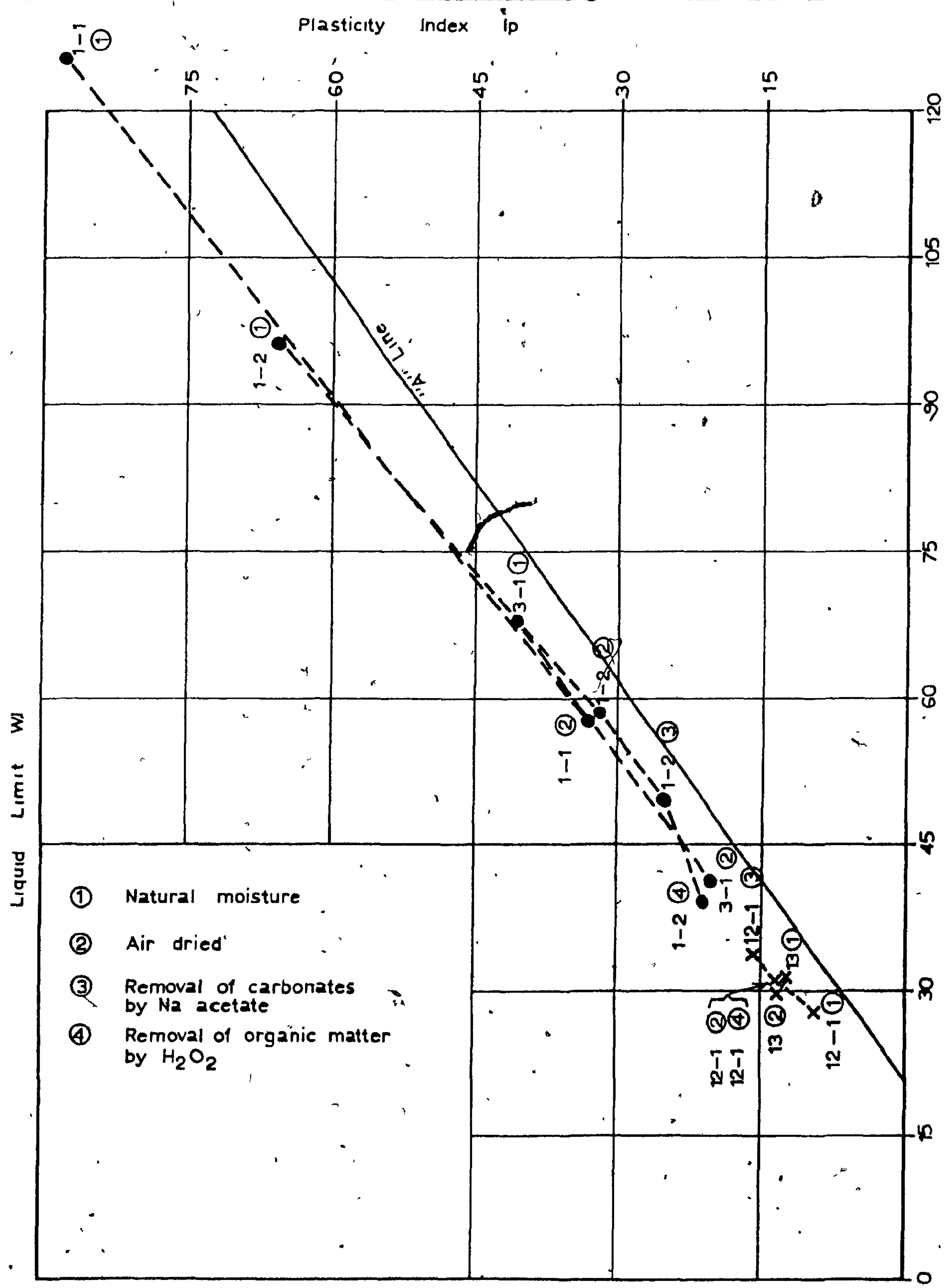


Fig. 14.1 Change in liquid limit due to air drying and pretreatment for mineralogical analysis

BOREHOLE 13163

Figure 14.2



Change in plasticity due to air drying and pretreatment for mineralogical analysis.

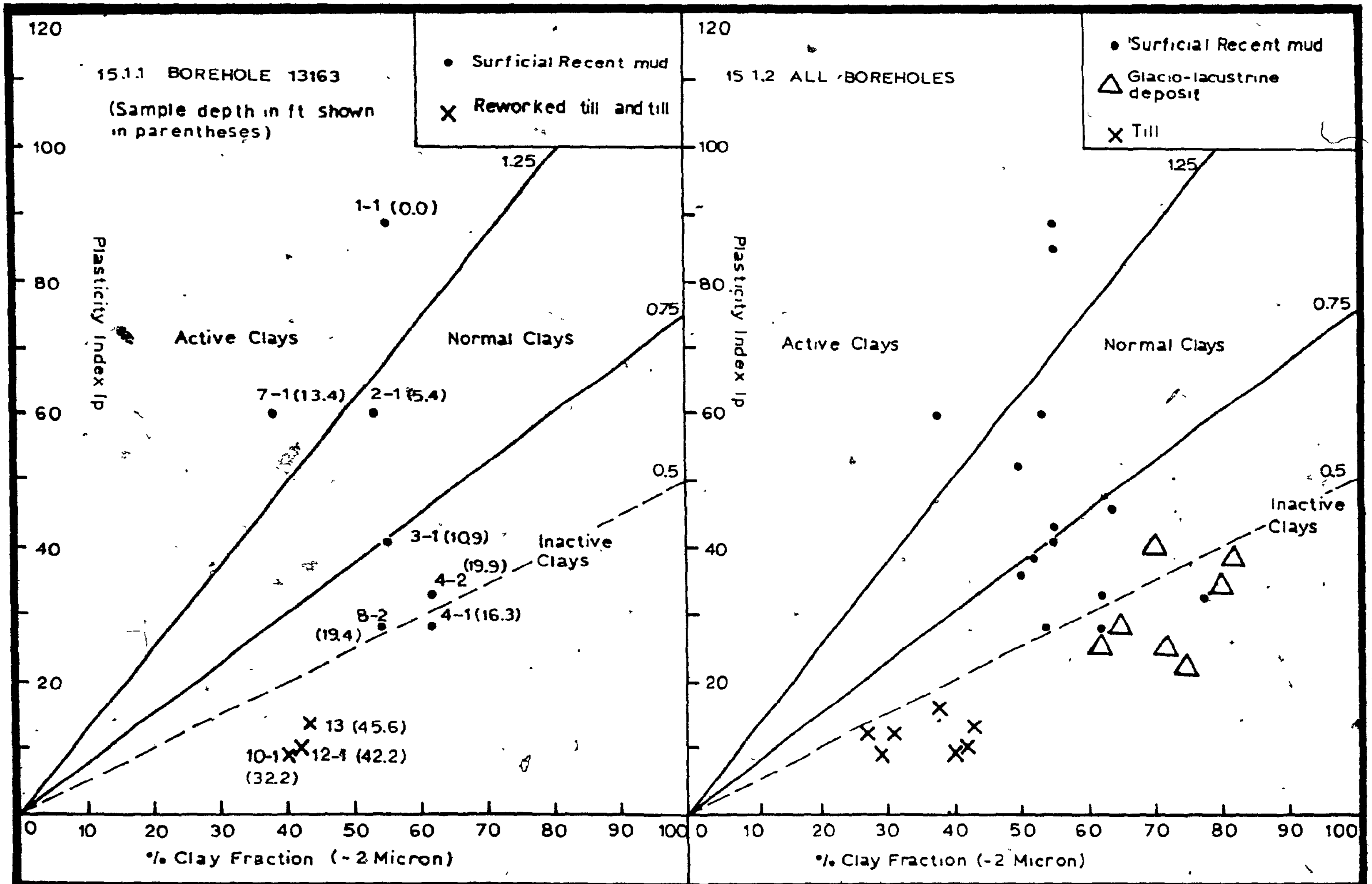


Fig. 15.1 Activity Chart - relationship between plasticity index and % clay fraction (activity groups after Skempton, 1953).

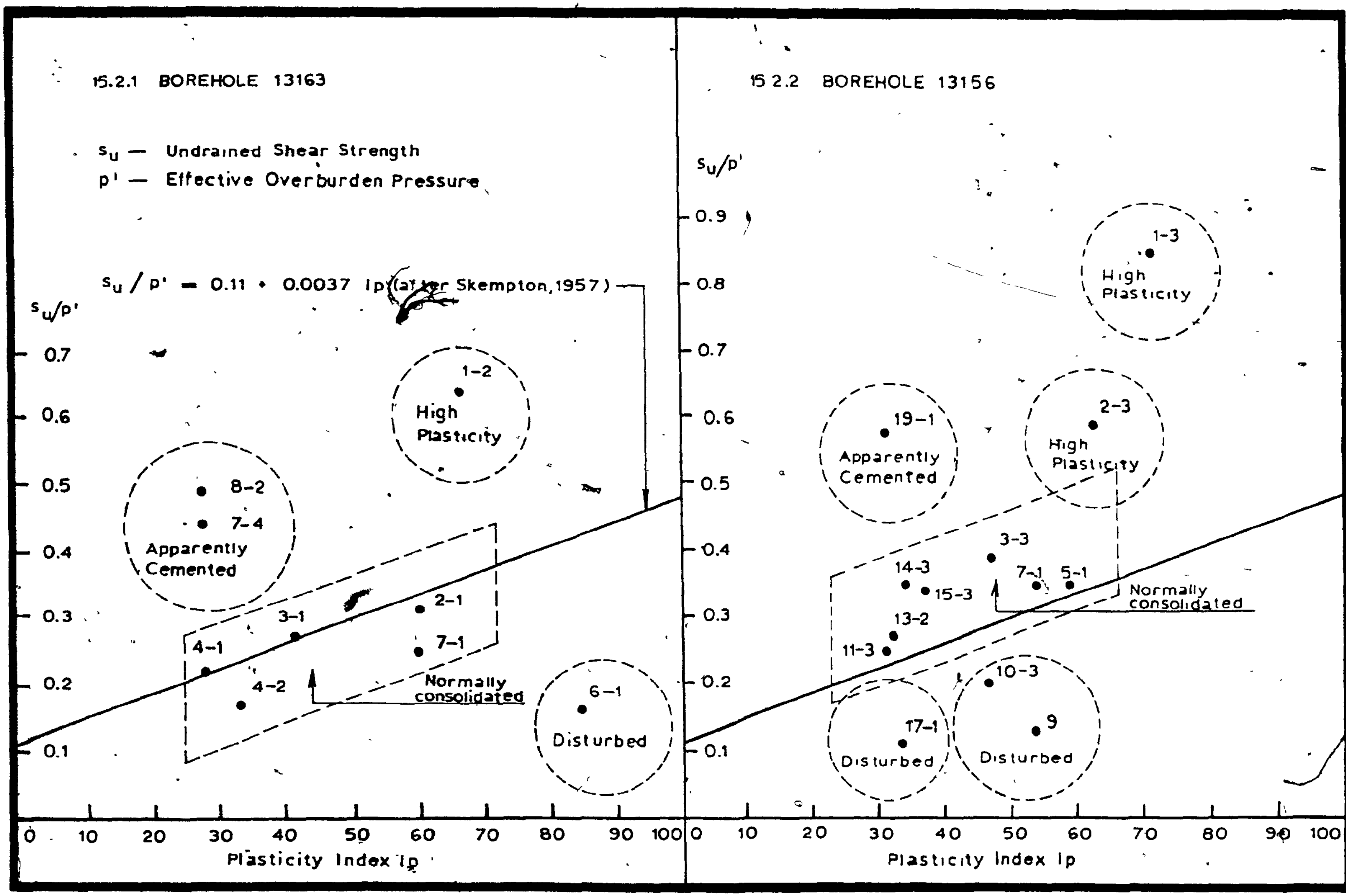


Fig. 15.2 Relationship between s_u/p' and plasticity index for the surficial Recent mud.

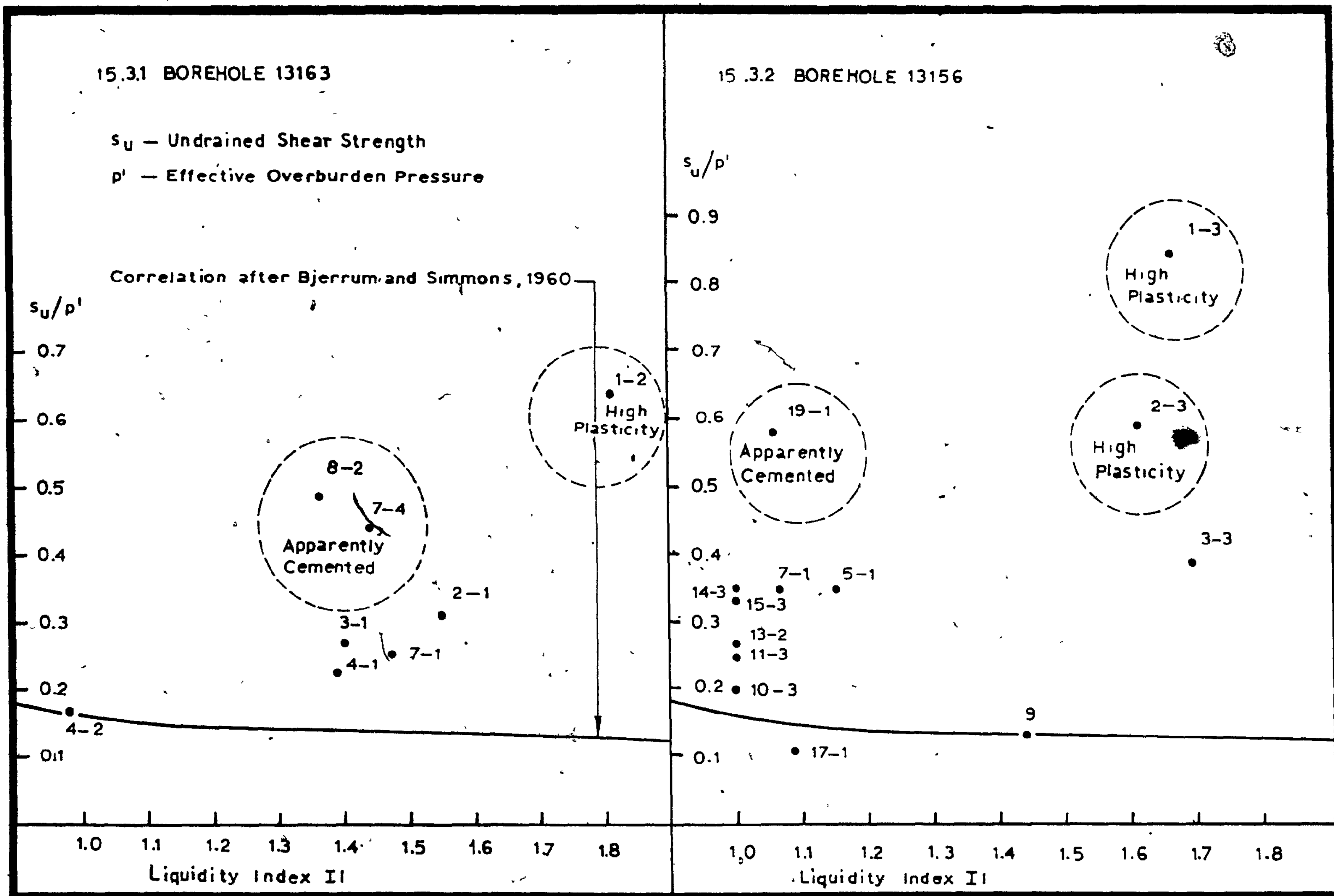


Fig.15.3 Relationship between s_u/p' and liquidity index for the surficial Recent mud.

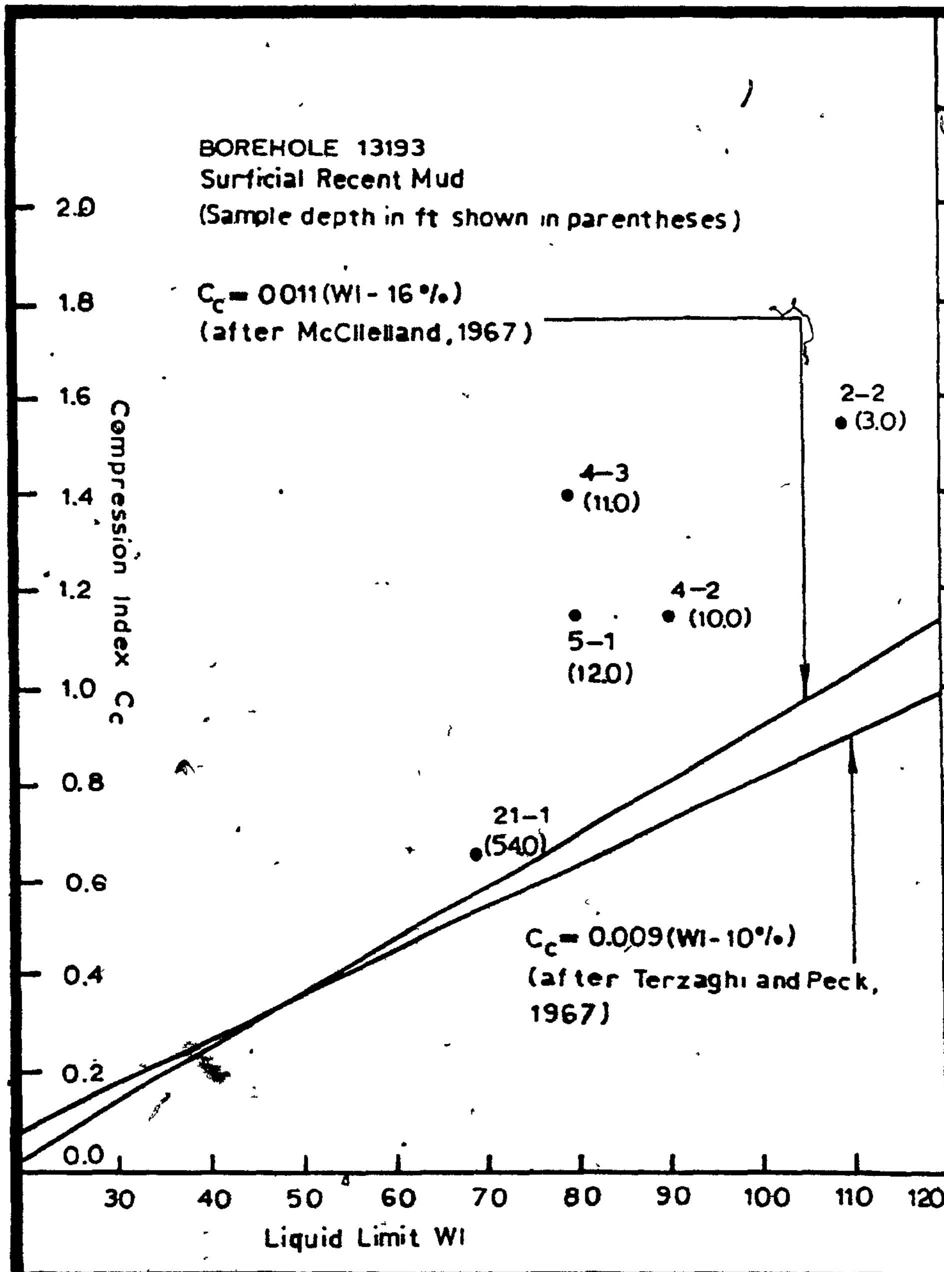


Fig. 15.4 Relationship between compression index and liquid limit.

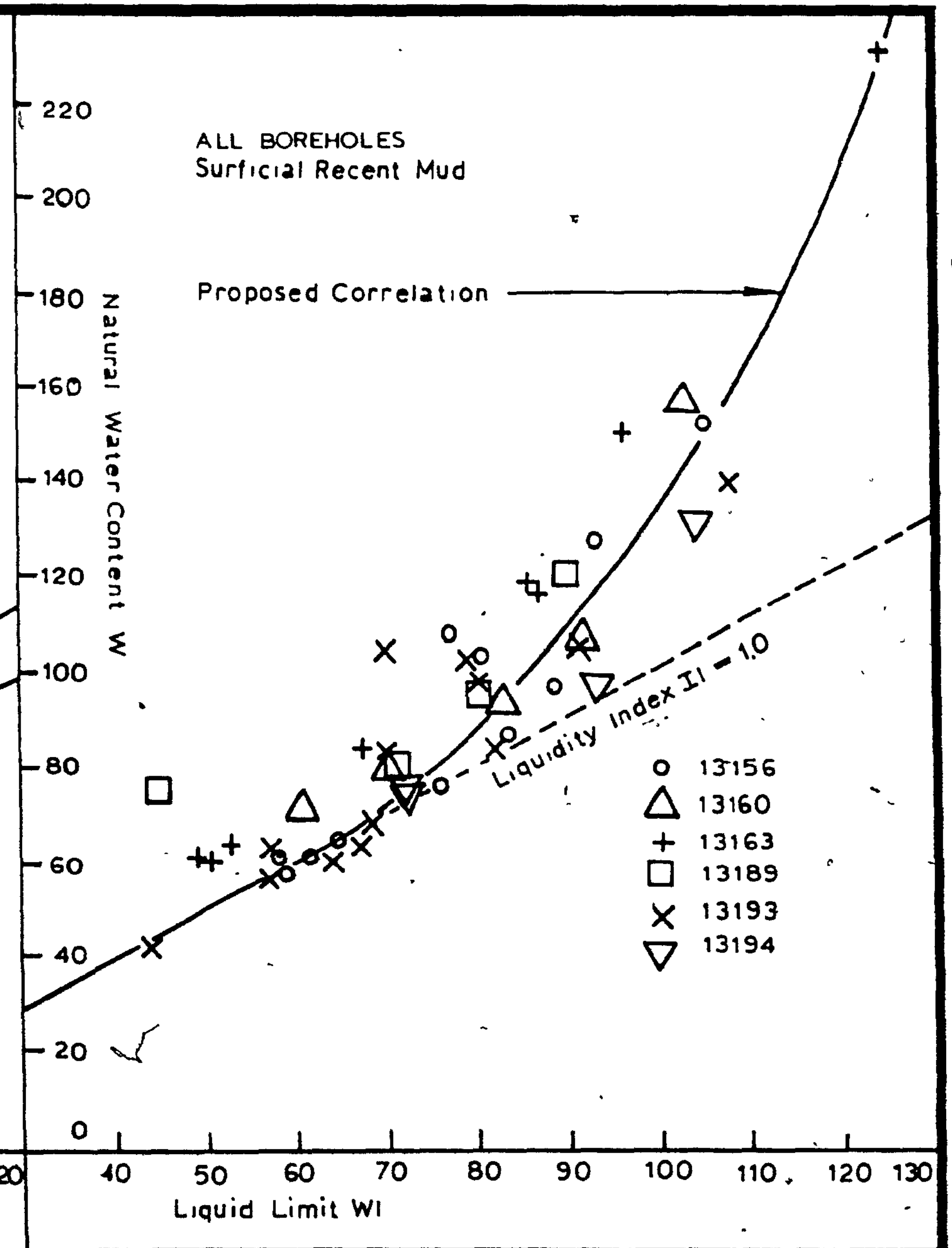


Fig. 15.5 Relationship between natural water content and liquid limit.

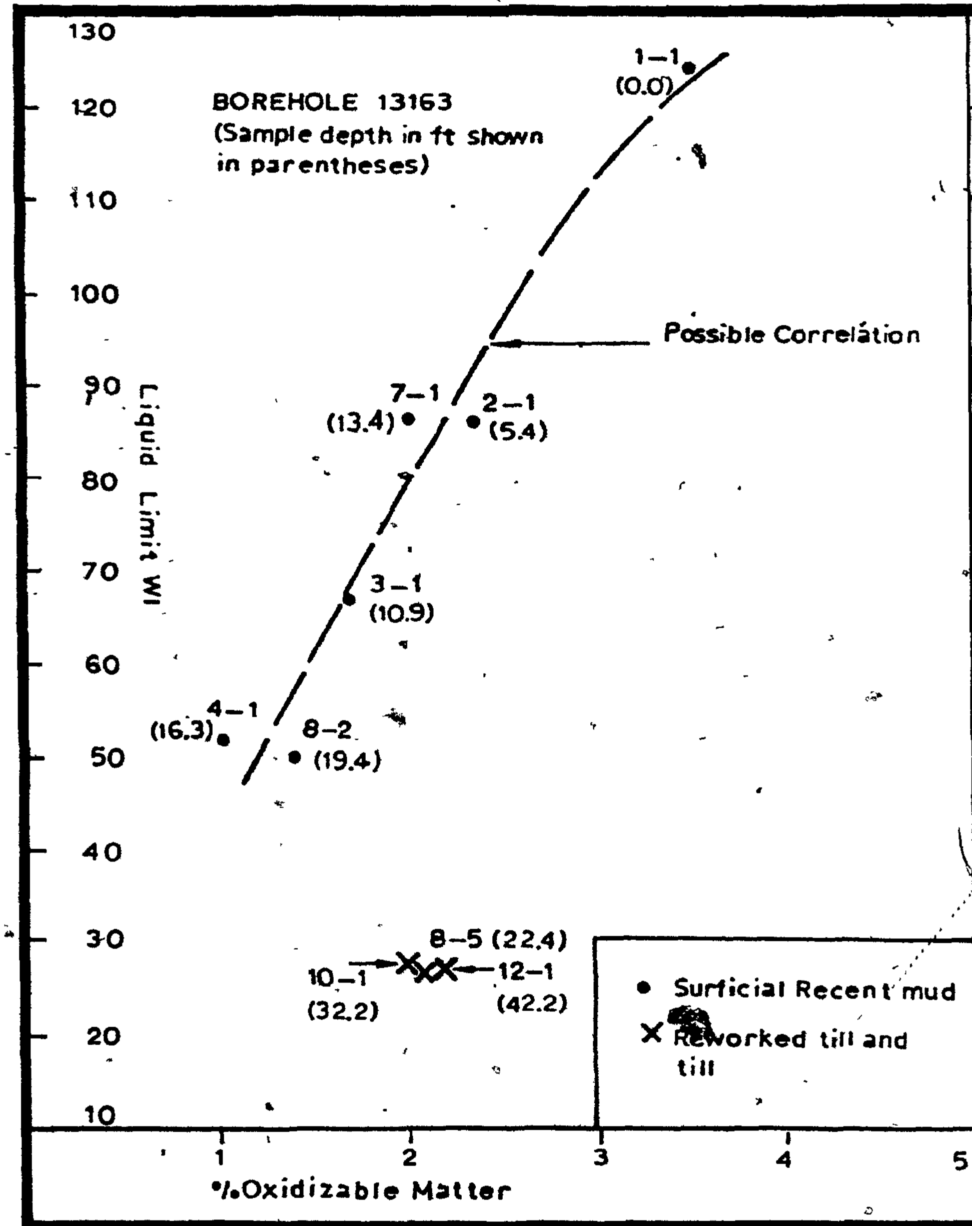


Fig. 15.6 Relationship between liquid limit and percent oxidizable matter.

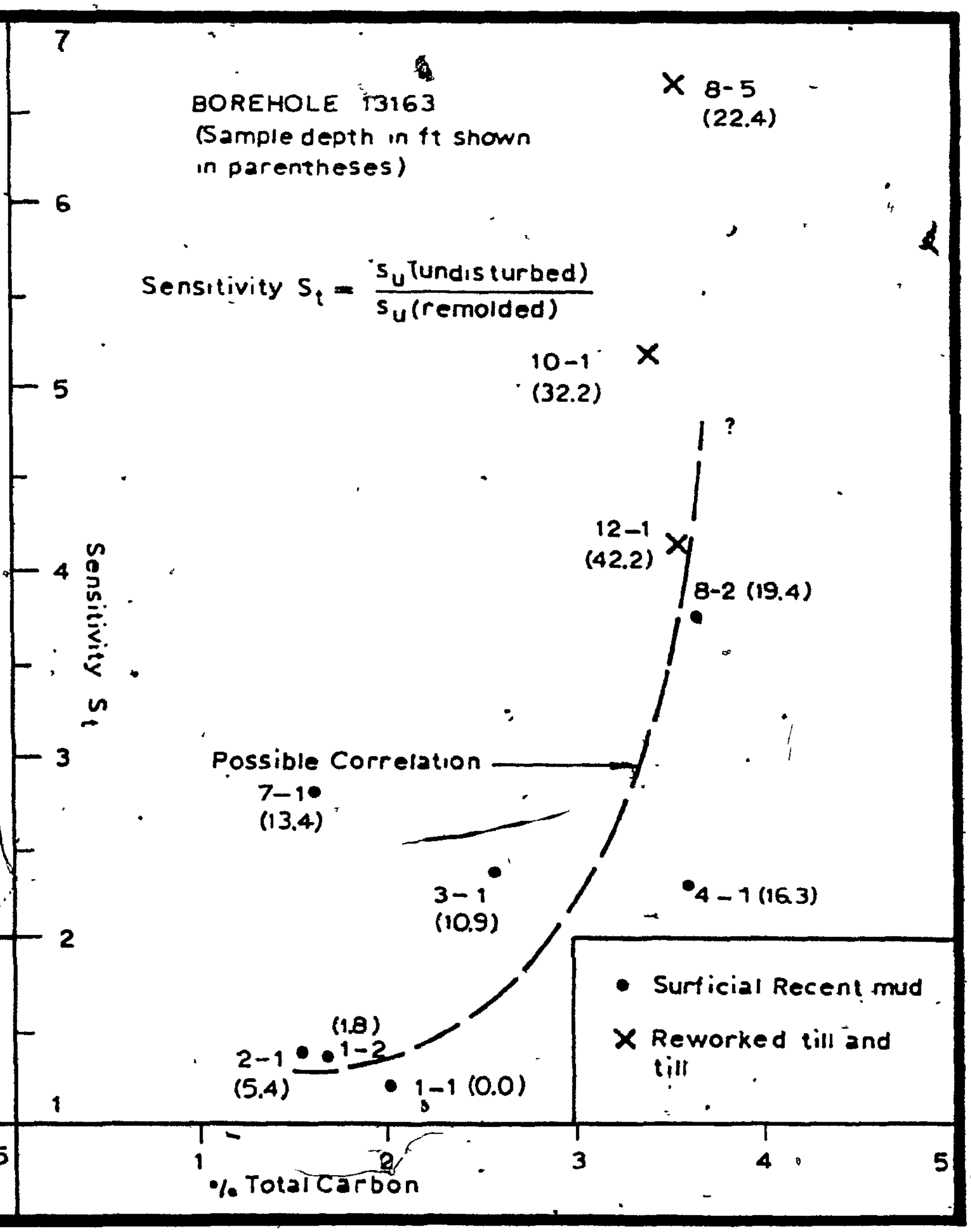


Fig. 15.7 Relationship between sensitivity and percent total carbon.

PLATE 1

PLATE 2

PLATE 3

PLATE 4

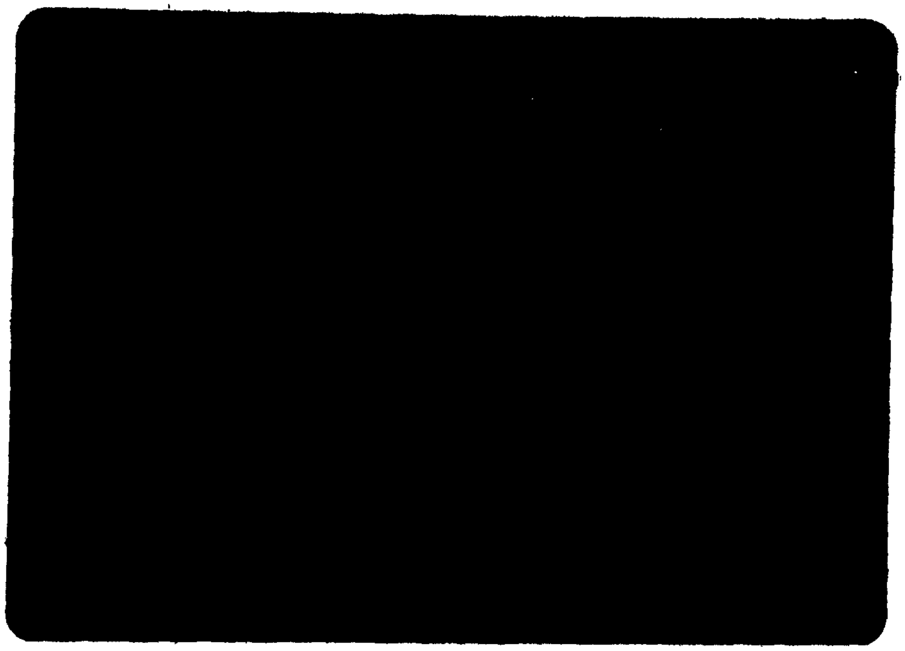


PLATE 5

PLATE 6

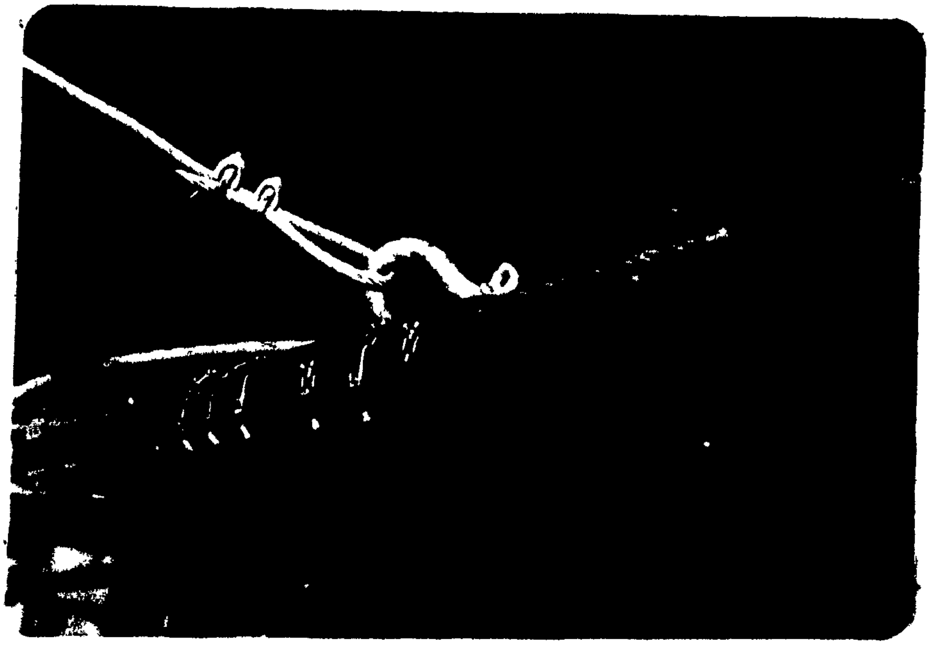
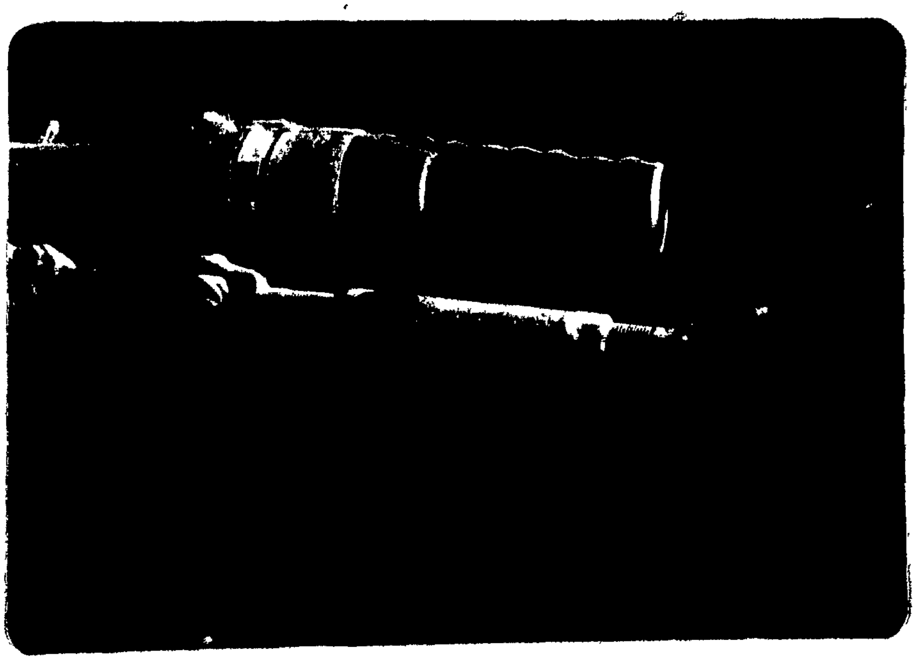


PLATE 7

PLATE 8

PLATE 9



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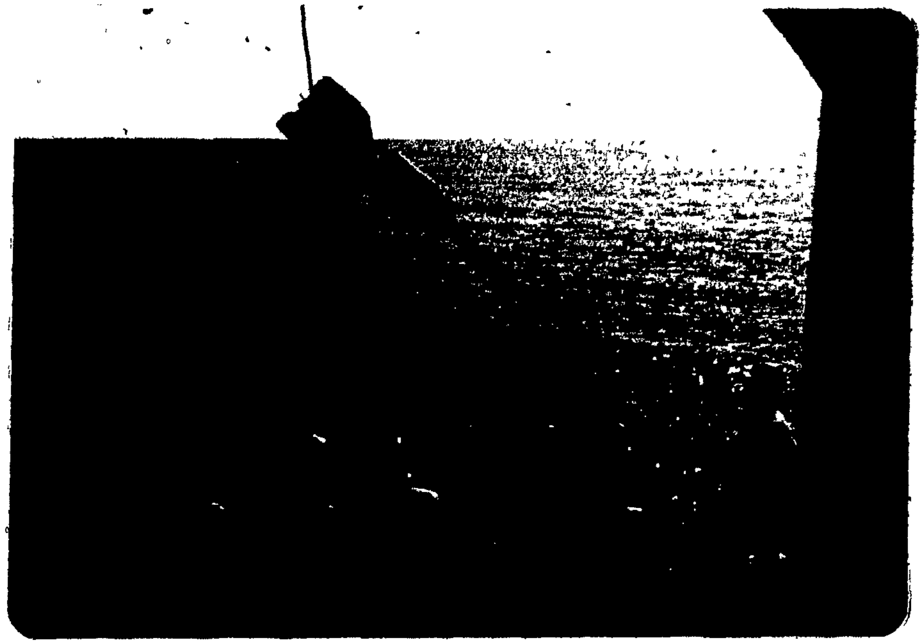

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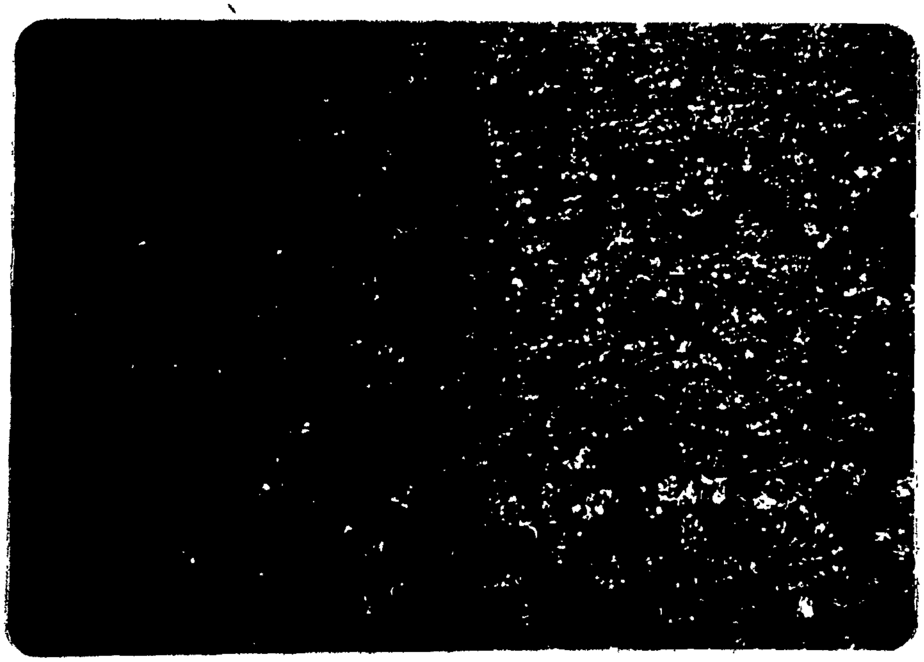


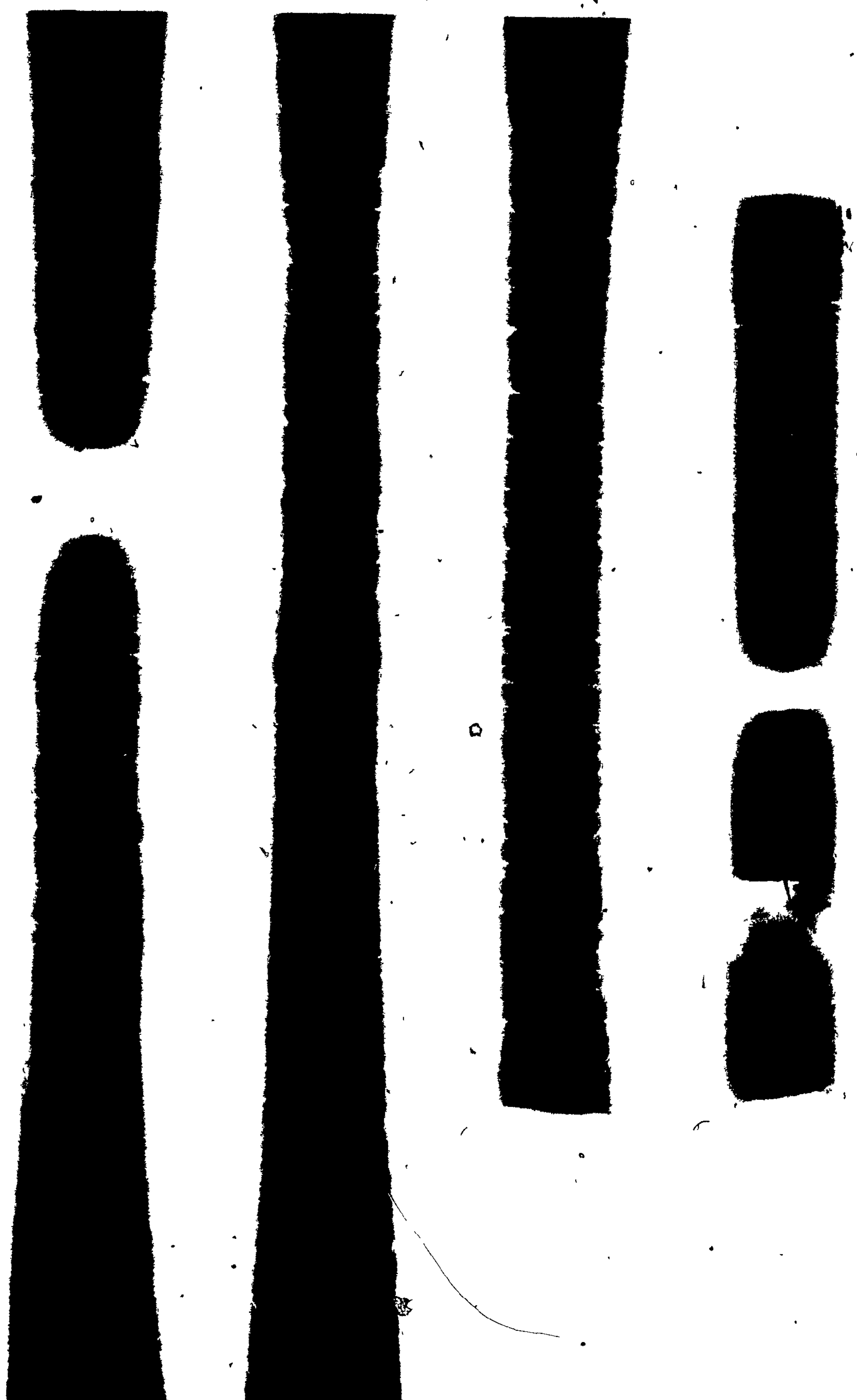
PLATE 12

PLATE 13

PLATE 14

PLATE 15

PLATE 16



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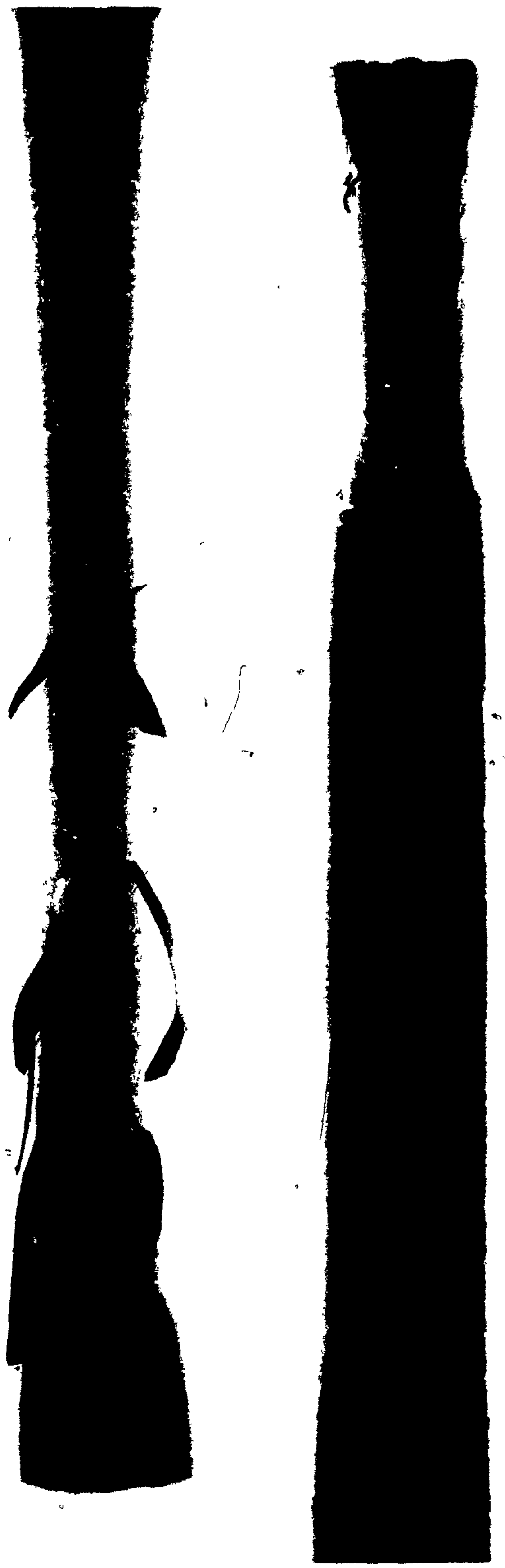

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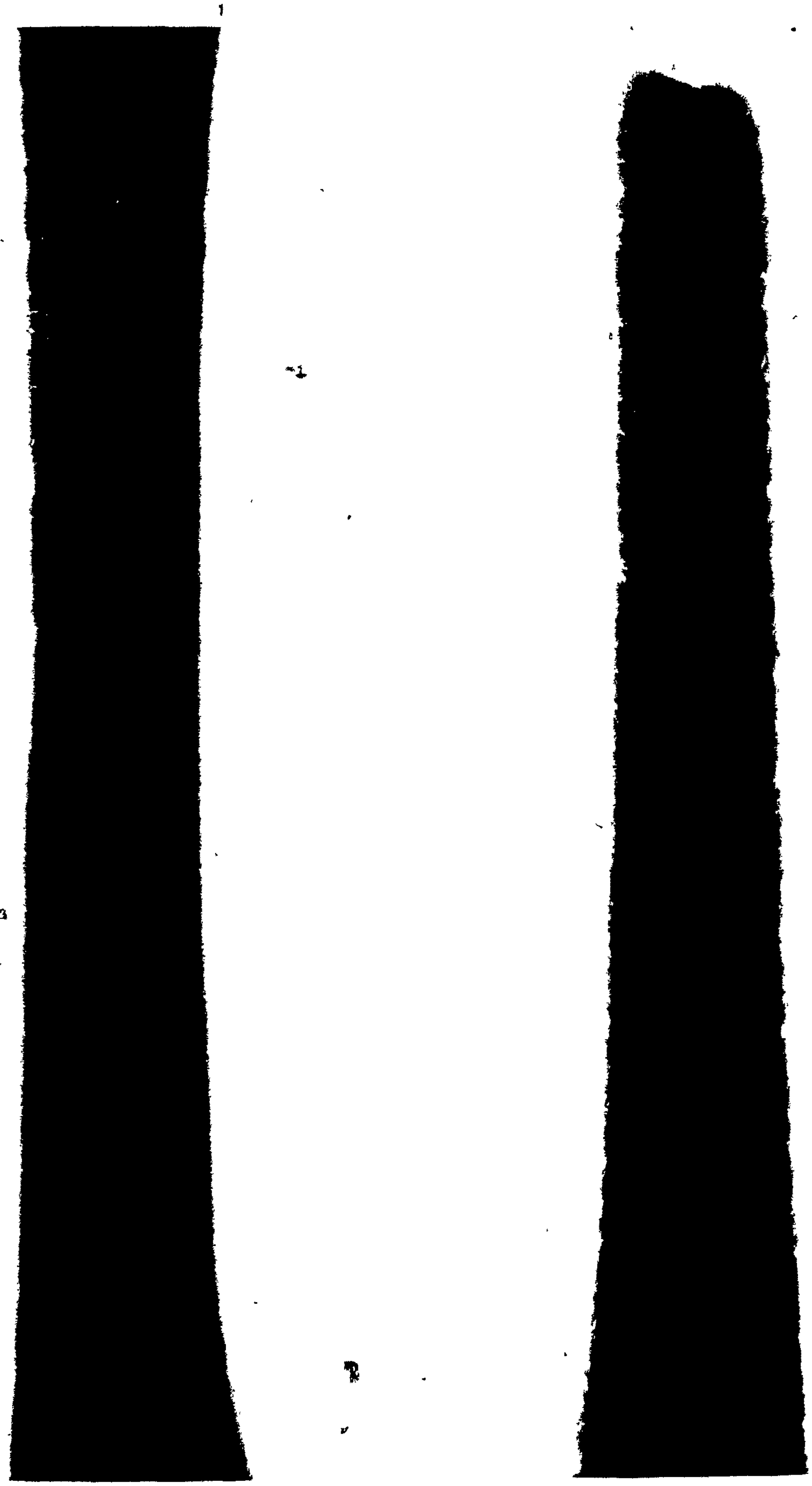

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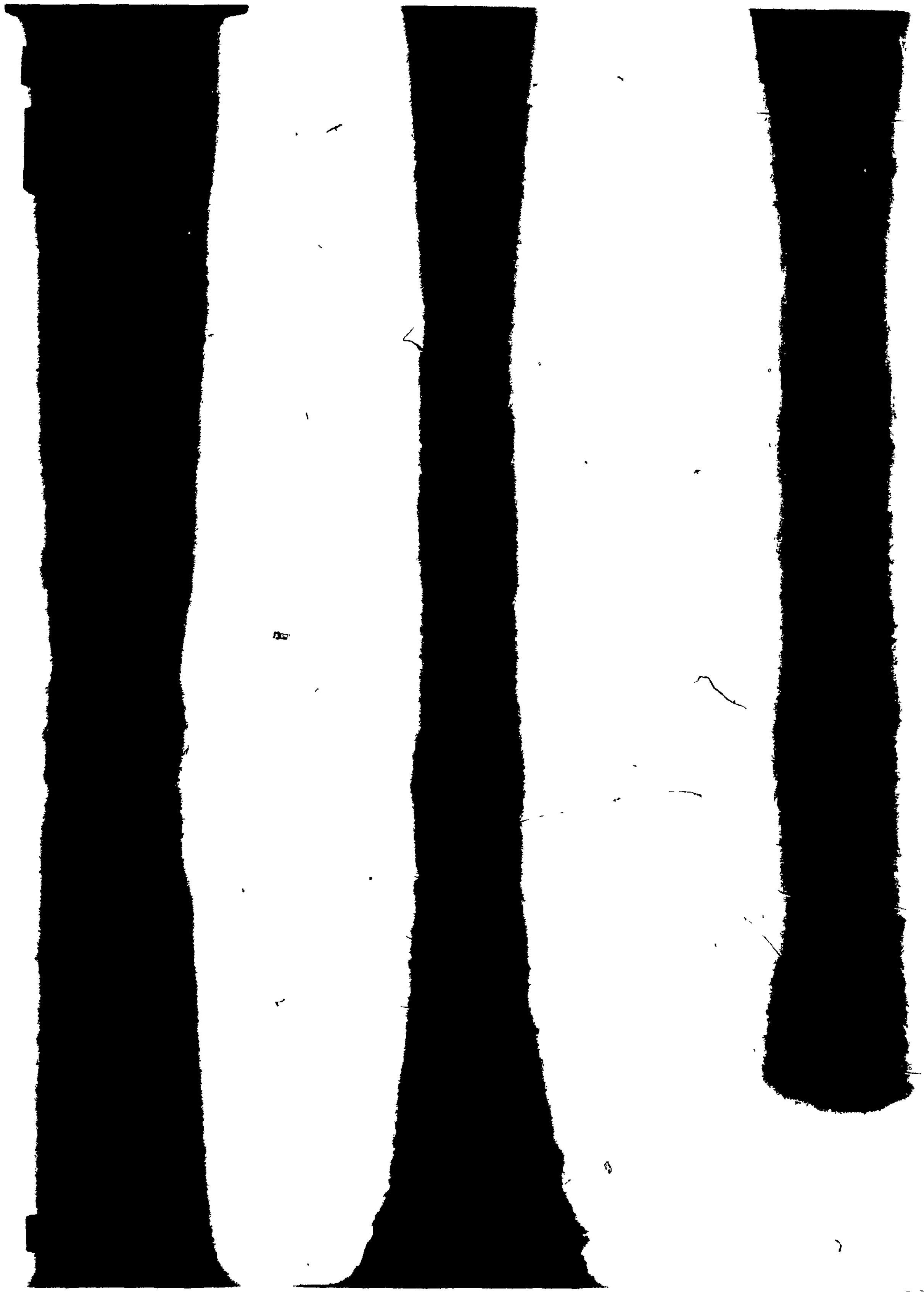


PLATE 20

PLATE 21

PLATE 22

PLATE 23

PLATE 24

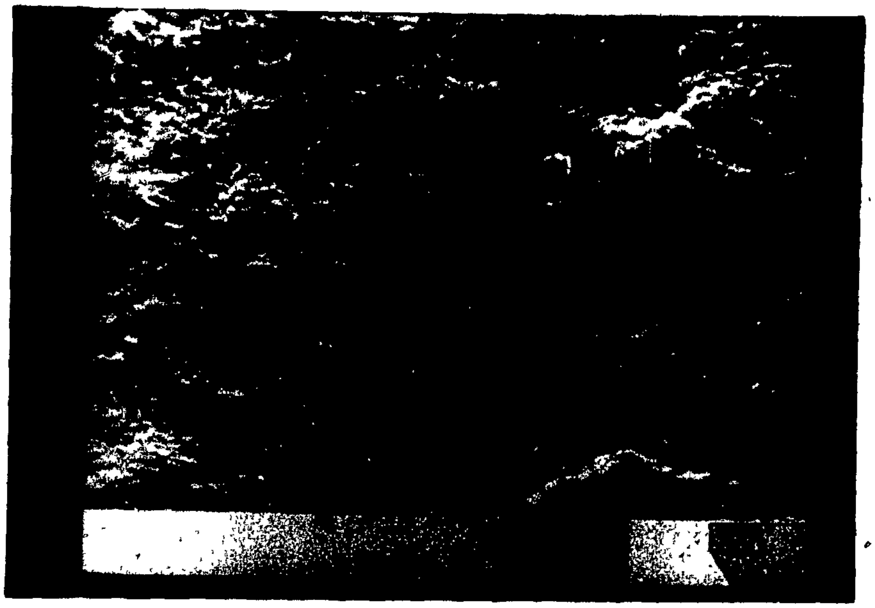
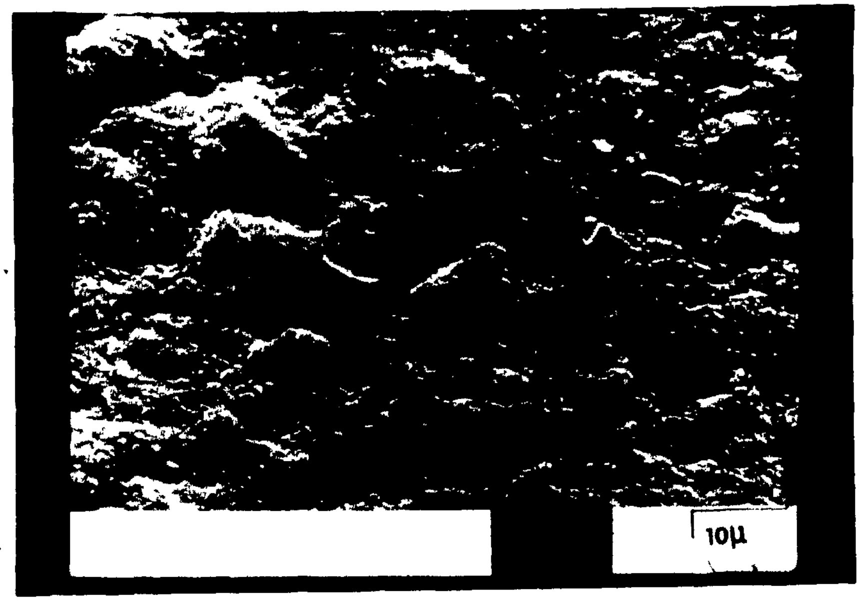


PLATE 25

PLATE 26

PLATE 27

PLATE 28



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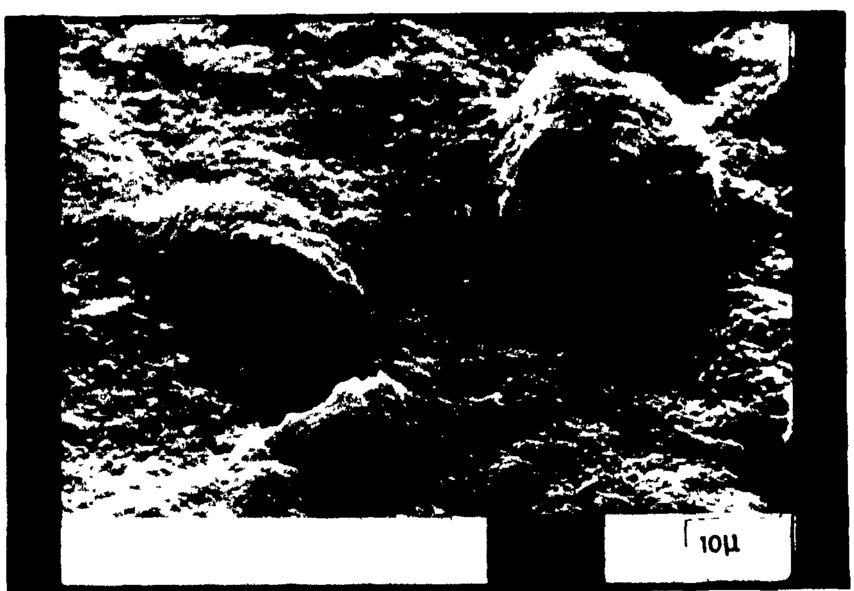

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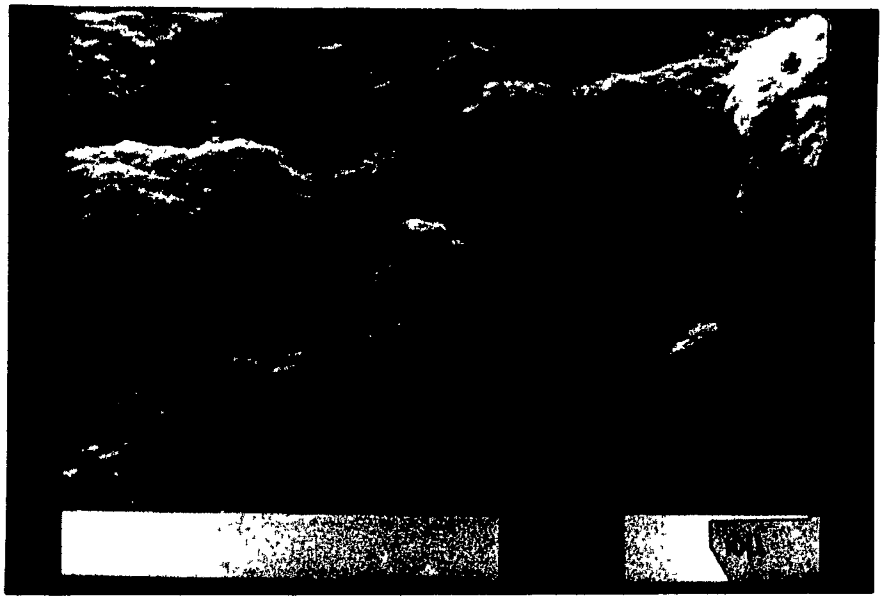


PLATE 31

PLATE 32

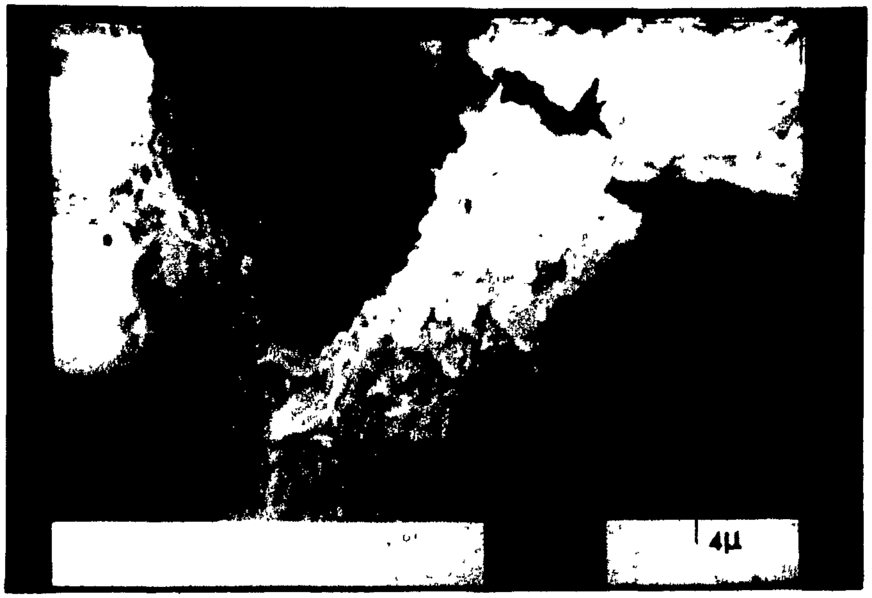
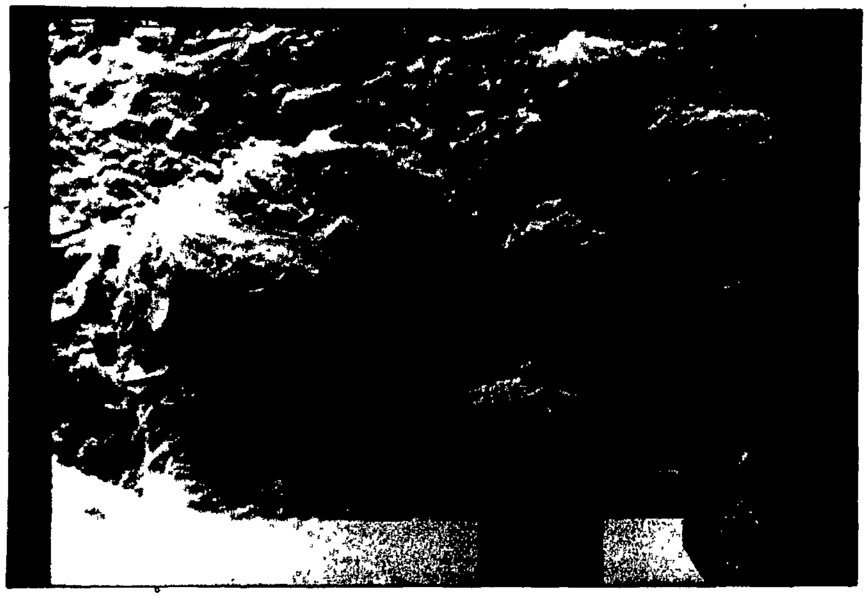


PLATE 33

PLATE 34



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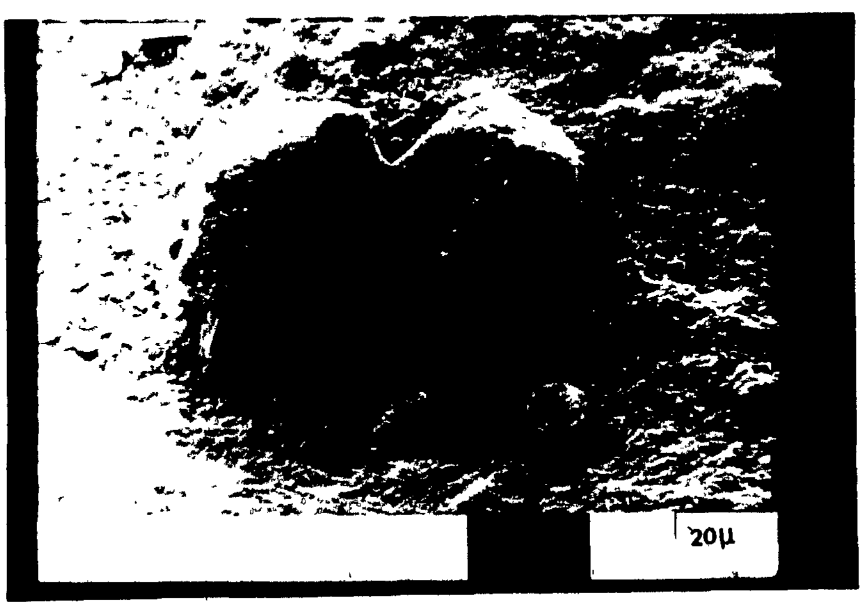
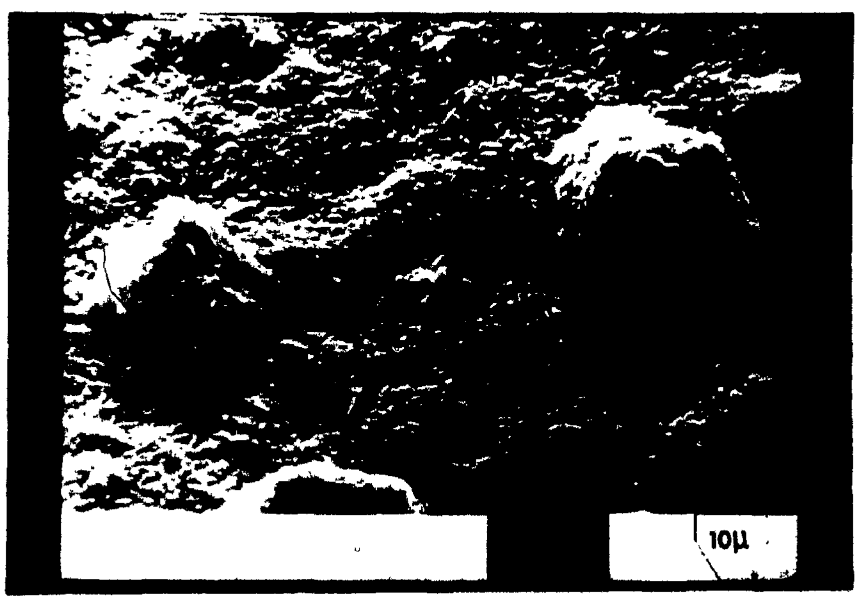


PLATE 36

PLATE 37



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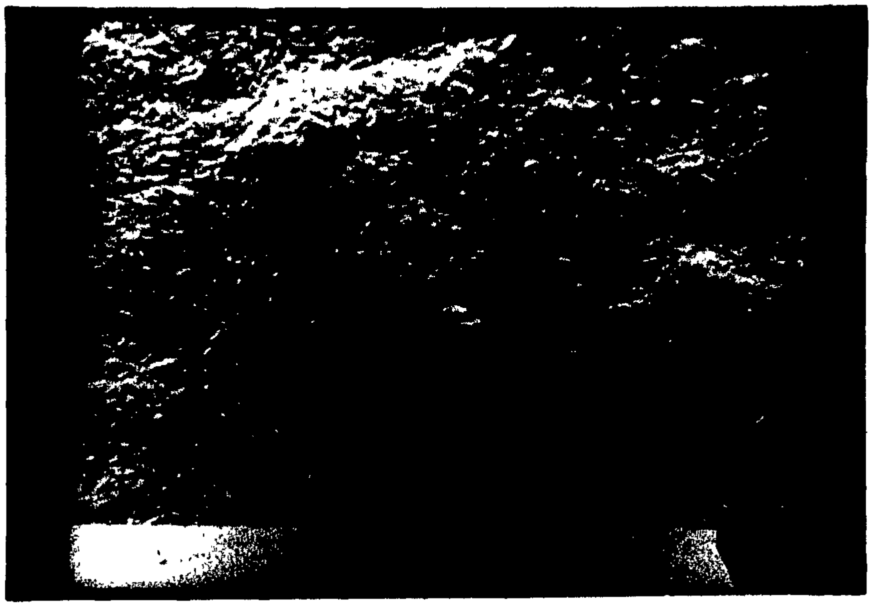

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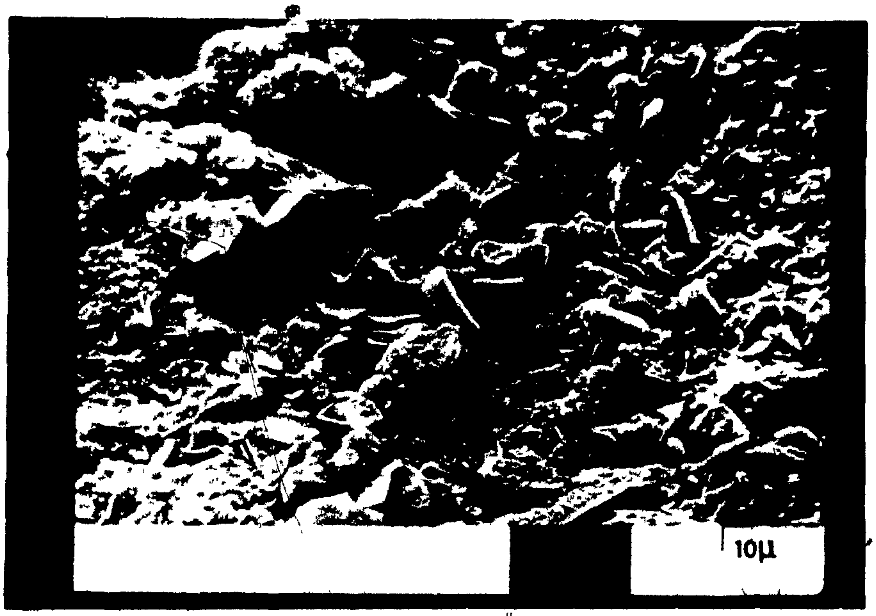

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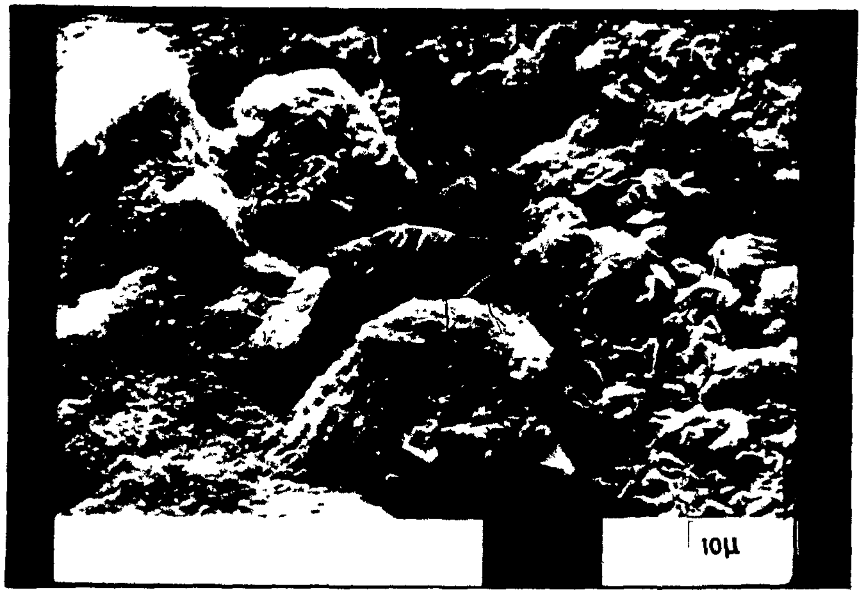

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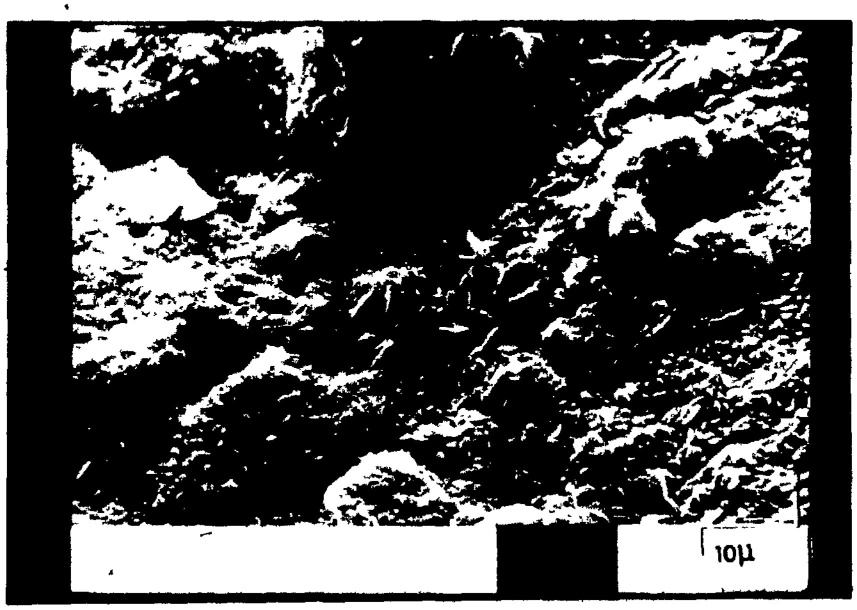

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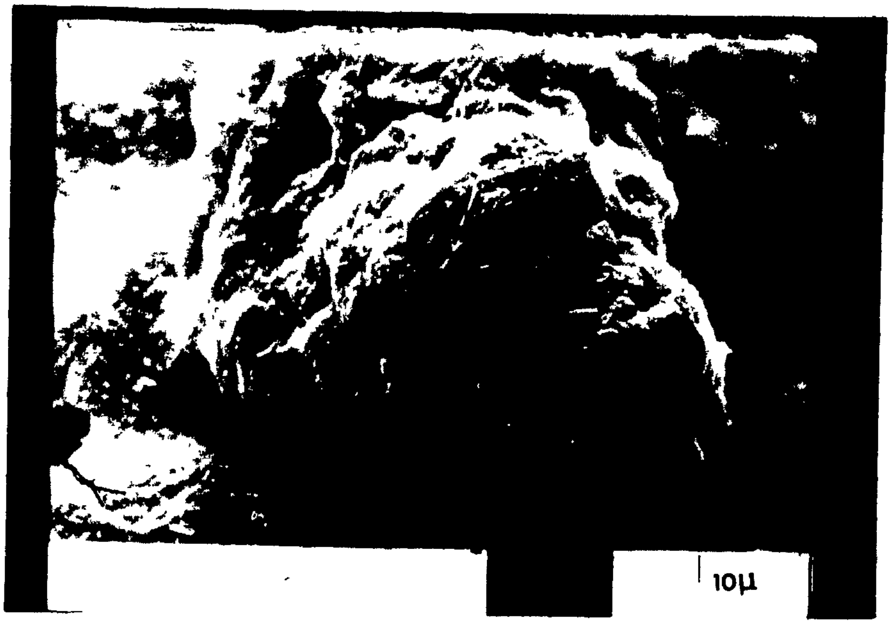

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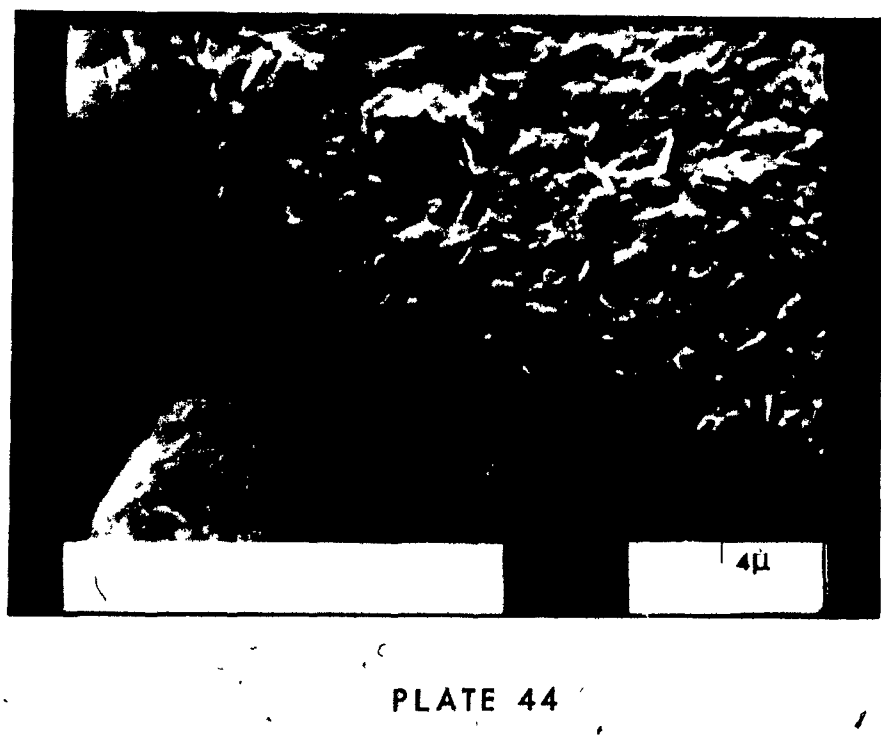

PLATE 44