An engineering study of glacial deposits at Steep Rock Lake, Ontario, Canada

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Publisher's version / Version de l'éditeur:

Economic Geology, 48, 7, pp. 513-540, 1953-11

NATIONAL RESEARCH COUNCIL

CANADA

AN ENGINEERING STUDY OF GLACIAL DEPOSITS AT STEEP ROCK LAKE, ONTARIO, CANADA

BY

R. F. LEGGET AND M. W. BARTLEY

REPRINT FROM ECONOMIC GEOLOGY, VOL. 48

RESEARCH PAPER NO. 9

OF THE

DIVISION OF BUILDING RESEARCH

OTTAWA

N.R.C. NO. 3035
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Reprinted from ECONOMIC GEOLOGY, Vol. 48, No. 7, November, 1953
Printed in U. S. A.

AN ENGINEERING STUDY OF GLACIAL DEPOSITS AT STEEP ROCK LAKE, ONTARIO, CANADA.

ROBERT F. LEGGET AND M. W. BARTLEY.

CONTENTS.

ABSTRACT.

Steep Rock Lake, in Western Ontario, was drained in 1943–44 by means of a large pumping operation. As the water line dropped, serious movements of the exposed soil occurred. Study of these, in connection with the development of the open pit from which the valuable iron ore was to be mined, led to an extensive soil investigation. The varved "clays" revealed by the mining operations with a total thickness of over 100 feet were studied first with engineering objectives in view. These "soil mechanics" investigations led to a detailed study of the soil in individual varves. Results confirm several features of the well-known seasonal theory of deposition but raise some questions which suggest the desirability of carrying still further this laboratory soil research.

INTRODUCTION.

STEEP Rock Lake is located near the eastern end of the Rainy River District, about 140 miles west of Port Arthur, Ontario, Canada (Fig. 1). The area has long been noteworthy because of its interesting geology; many geologists have carried out intensive studies in the region around the Lake. Somewhat naturally, interest has been focussed upon the Precambrian bed-rocks. Geological literature contains a number of papers dealing with various aspects of the hardrock geology of the district (10).[1]

The existence of high grade iron ore beneath the waters of Steep Rock Lake was first suggested in 1897. It was not until 1942, however, that Steep Rock Iron Mines Limited was formed in order to develop this unusual source of iron ore. The operations of this Company had to start with the execution of some

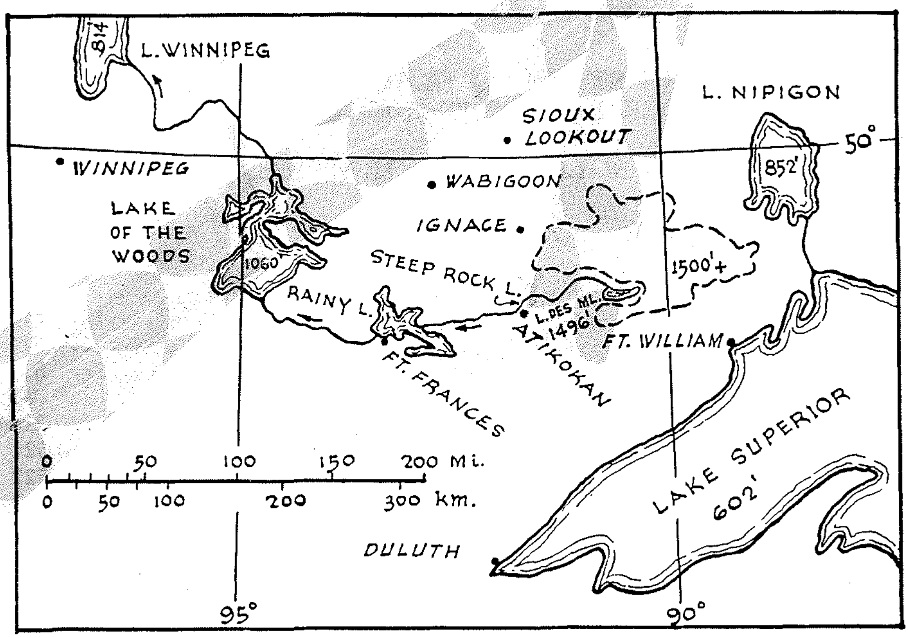

FIG. 1. Key map of location.

outstanding civil engineering works in order to divert the flow of the Seine River from the Lake, which was thereafter drained by means of a pumping operation of epic proportions (11).

The Lake had an area of about seven square miles; it was drained to a depth of over 140 feet below original water level. As the water level fell, the lake-bed deposits were exposed. At first they were unstable and many slides occurred. These drew attention to the need for a detailed study of the material constituting the lake bottom, many millions of cubic yards of which have had to be moved and controlled in connection with the open-pit mining operations (Fig. 2).

The slides revealed the varved structure of the extensive bed deposits. This has been studied concurrently with the necessary engineering investiga-

[1] Numbers in parentheses refer to Bibliography at end of paper.

tions of the soil. Even though the studies of this and other features of the local glacial geology have naturally had to be correlated with work directly related to mining operations, the authors are advised that their geological observations have revealed features of some interest. This general paper has therefore been prepared with a dual purpose in view. For geologists, it records briefly the development of the Mine after the draining of the Lake and

FIG. 2. General view of open pit workings.
FIG. 3. Section through end moraine at "esker cut."

summarizes the necessary engineering soil studies which have had to be made in achieving this result. The results of these studies appear to have some geological significance. For engineers, the paper presents a summary of the work in the field of soil mechanics necessary for the carrying out of an unusual excavation job and shows the scientific significance of this utilitarian task. Against the general background thus provided, it is planned to publish as soon as possible further detailed papers dealing respectively with specific aspects of the engineering and geological studies. In aiming at a dual objective, the authors have had admittedly to sacrifice some of the features that are desirable both in engineering and geological papers. If, however, the rapidly expanding field of engineering geology is to be well served by written records, it would appear necessary to produce some papers of this general character.

Although not now connected directly with the Steep Rock projects, the authors were privileged to be intimately associated with its development until 1947, respectively as a consultant on special soil problems from the start of the dewatering early in 1944, and as Chief Geologist from 1940 and later Production Engineer. Their interest has continued and they have been privileged to keep in touch with developments by repeated visits since 1947. The Mine authorities have always taken a lively interest in glacial geological features, as well as in the hardrock geology which is of such direct concern to their operations, and they have kindly authorized the publication of this paper. To M. S. Fotheringham, President, to Watkin Samuel, Consulting Engineer, and to Hugh Roberts, Consulting Geologist, the authors wish to express their thanks for stimulating encouragement.

STRATIGRAPHIC SUCCESSION.

The area in which Steep Rock Lake is situated is typical of the Precambrian Shield of Canada. It consists of rolling country, with many small lakes and rivers, the exposed bed-rock being glaciated to a uniform peneplain. The lowlands and depressions between outcrops of bed-rock cradle varying thicknesses of till, sand, silt and clay. These are conformable within themselves but unconformably overlie the Precambrian.

The superficial deposits consist of glacial till or boulder clay and drift boulders presumably deposited by the continental glaciers; stratified fluvio-glacial sands and gravels deposited from melt water streams; and glacio-lacustrine silt and clay deposits laid down in lakes formed during the retreat of the ice sheets. These are all overlain by recent deposits of alluvium and peat.

LITHOLOGY.

The boulder clay consists of unsorted material composed of angular, sub-angular and sub-rounded boulders of all sizes set haphazardly in a matrix of sand, rock flour and some clay. Many boulders show well developed facets, commonly striated. The till is generally colored red-brown and contains a considerable number of hematite and limonite pebbles.

Closely associated with the till is a series of rudely to well-bedded sands and gravels presumably of fluvio-glacial origin. The material consists of water-worn pebbles and grains representing all of the adjacent bed-rock rock types. The sand and gravel deposits overlie the till.

The thickest deposits encountered anywhere in the area are the well laminated varved silts and clays of glacio-lacustrine origin. These are characterized by their regular bedding. They vary in thickness from a few feet to at least 200 feet. It is this varved material in the old lake-bed that has been studied so carefully. A later section of this paper therefore deals with it in some detail.

Final deposition was a relatively thin mantel of unstratified alluvium, composed in part of rock flour and in part of gumbo clay. While this may be of lacustrine and fluvio-lacustrine origin, its location and character suggest that it is more likely to be a recent flood-plain deposit.

SUCCESSION OF EVENTS.

In the Steep Rock Lake area there is evidence of glacial advances from at least two directions. The earlier came from the northwest and north, probably from the direction of the Keewatin center of glaciation. The later advances were from the northeast, from the Labradorean center. The second advance was the stronger and all but obscured the original striae.

The strong Keewatin advance that deposited calcareous debris over much of the western section of Rainy River District, apparently died out before reaching the region under discussion. There are no calcareous tills in evidence. It is believed that a feeble lobe, bearing little if any material, overrode the Steep Rock Lake area and retreated without depositing appreciable debris.

The advances from the Labrador center were repetitious in nature, the original and greatest advance overriding the whole of the area, and depositing a general ground moraine. Subsequent readvances terminated farther north, forming end moraines immediately south of Steep Rock Lake and at the south ends of Finlayson and Marmion Lakes, north of Steep Rock Lake. The moraines are composed of unsorted till topped by a veneer of boulders. Associated with the retreats were glacial streams and ponds from which considerable fluvio-glacial deposits of sand and gravel were formed. These deposits are abundant south of Steep Rock Lake where kames and outwashes rest discordantly on the morainal till.

A glacial lake of considerable size and depth succeeded active glaciation. Suspended sediments carried into the Lake were deposited as varved sediments. Antevs, during his study of the deposits in 1946, recognized eight distinct series of subdivisions within the varve section (1). He accounts for the eight divisions by postulating four readvances and retreats, bringing in new volumes of silt and clay each time. The glacio-lacustrine deposits appear to be, in general, chemically and mineralogically constant for each series, indicating that the source of the materials was common. It is believed that this source was the region eroded by the Labradorean lobe. Further, it is evident from the extent of the sediments that they were deposited in a standing body of water of considerable size, Lake Johnston being the name for this suggested by Antevs. Beaches and varve material are noted at Elevations of 1275 and 1283 feet absolute, with beaches as high as Elevation 1363.

The execution of the civil engineering works associated with the development of the Mine exposed a number of sections through the superficial deposits, which have been described in general terms. The end moraine at the south end of Finlayson Lake (erroneously called an esker in local practice), for example, had to be cut through to form part of the new channel for the

Seine River. Apart from giving a remarkable cross-section through the moraine (Fig. 3), the excavation revealed no unusual features.

It is, indeed, somewhat surprising that despite all the excavation work which was carried out, only one unusual feature was observed. This is shown in Figure 4, a case of apparent faulting in the face of a gravel pit opened in a kame deposit in 1943, immediately to the south of the Lake. The usual explanation of such apparent signs of faulting in unconsolidated material is that they are the result of the melting of buried ice-blocks. Having carefully examined the exposed face shown in this photograph, the authors are unable to

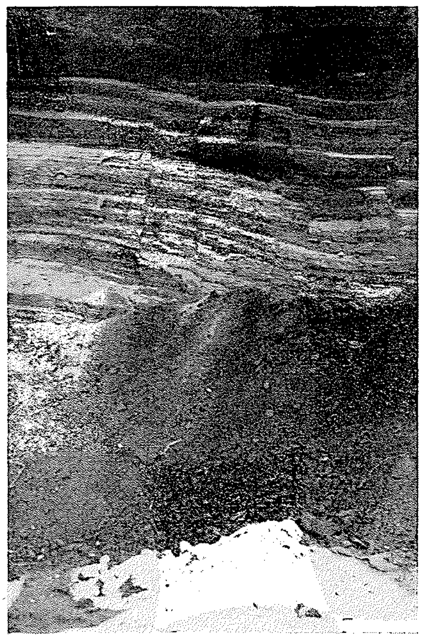

FIG. 4. Minor faulting in sand and gravel.

accept this explanation of the sharp shear failure planes. They are convinced that they constitute evidence of recent earth movement at this location, small in degree but similar in its effects to major earth deformation.

DRAINING OF THE LAKE.

The draining of Steep Rock Lake somewhat naturally revealed extensive glacial deposits. A discussion of their character consitutes the principal part of this paper. The draining of the Lake may therefore be described in some detail.

Figure 5 shows a general plan of the Lake. N-shaped, it had a total length of 15.5 miles and an original water area of seven square miles. The Seine River had its course through the Lake but by means of a large diversion project, completed late in 1943, the river flow was led into Finlayson Lake and so into the west arm of Steep Rock Lake. A cofferdam ('D' in Fig. 5) and an existing concrete dam and power house then isolated the other two arms of the Lake, permitting the start of drainage operations.

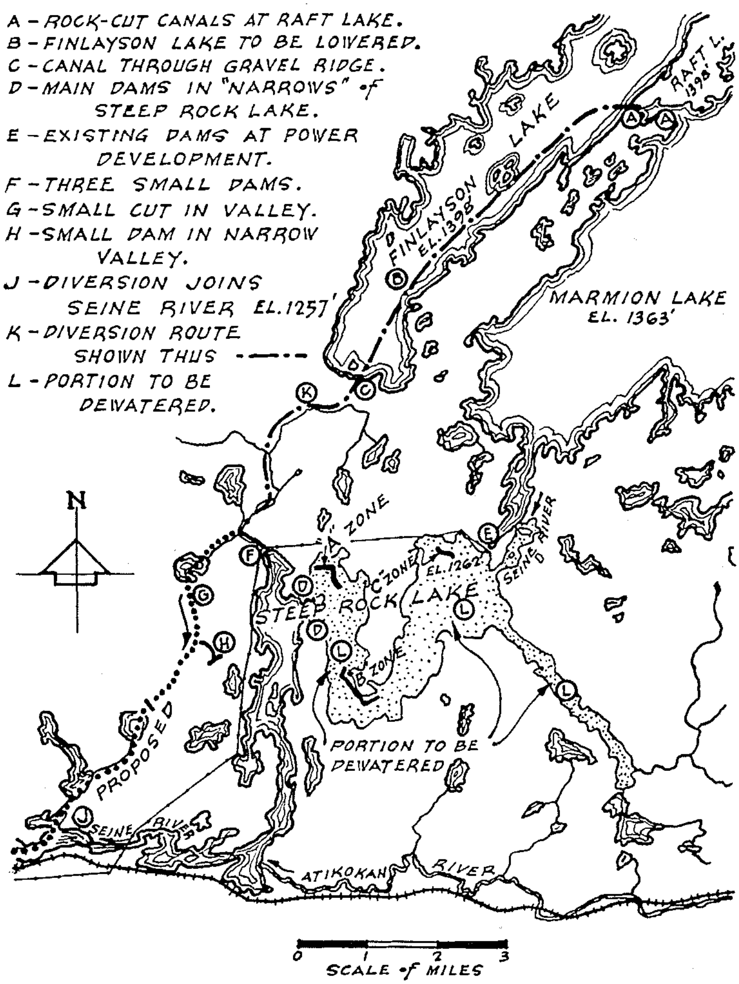

FIG. 5. General map of Steep Rock Lake.

Geophysical prospecting and intensive diamond drilling off the ice had located three iron-ore bodies beneath the bed of the Lake, designated 'A,' 'B' and 'C'. The 'B' orebody was the first to be mined but it lay beneath 100 feet of water so the pumping project was one of magnitude. Fourteen 24-inch electrically driven pumps started on the task in December 1943. By the beginning of April 1944, the water level had been lowered by about 75 feet.

Throughout the winter, the surface of the Lake had remained frozen, even though the ice cover was naturally broken. The lake-bed deposits along the more shallow parts of the Lake were similarly covered with ice and snow.

As the spring thaw progressed, however, not only was this protective frozen covering removed from the exposed bed deposits, but the melting snow from the area draining into the Lake started to run down towards the Lake. Instead of merging, as previously, into the waters of the Lake, this run-off had now to seek lower levels and in many cases seeped down beneath the shore deposits. As it emerged, it disturbed the stability of the slopes which had stood for so long under water. Many extensive "land-slides" took place and it was then that the character of the soils in the lake-bed was first revealed; it was then that this detailed study commenced.

The modern engineering study of soils has made clear that landslides can be analyzed scientifically and generally classified. Application of such studies to the mass movements at Steep Rock Lake shows that when the water-level in the Lake was drawn down relatively suddenly, the factor of safety against failure of the slopes was greatly reduced and even made inadequate. Before draw down, the effective weight of soil in the slopes was the submerged or unit weight of the material. Failure in these slopes tends to take place along a circular arc and is due to the disturbing moment produced by the weight of the segment of material within the circular arc. After the draw down, this weight was approximately doubled and this increase in disturbing moment brought about complete slipping and failure of some slopes. This type of circular arc failure was seen at various locations around the Lake.

"Mud runs" were also prevalent, and were caused by percolation of ground water from the area adjacent to the Lake. The level of the groundwater table adjacent to the Lake rose in wet periods. This resulted in an increase in the pressure of the porewater in the coarser layers of the varves. The increased porewater pressure reduced the effective pressure, and thus the shear strength of the clay, so bringing about instantaneous failures in the slopes. Slides of this nature have been fully reported in the varved clays of the Hudson Valley (8) and described by Terzaghi (12).

By the end of 1944, the water-level had been lowered by about 140 feet and it has remained at about this elevation since that time. About 520 acres of the Lake bed in the vicinity of the 'B' orebody have been exposed. About 26.5 million cubic yards of the soil have now been removed, largely by dredging and pumping. Slopes and benches have been developed in this area to an extent that has permitted the working of the ore from an open pit now 3600 feet long, and 700 feet wide, and extending to a depth of 450 feet below the old lake level. Almost seven million tons of high grade iron-ore have been removed during seven working seasons. Concurrently, study of the exposed soils has continued at the Mine and in various laboratories. The senior author carried out the early soil investigations while on the staff of the University of Toronto. During the summers of 1948, '49 and '50 a member of the staff of the Division of Building Research of the National Research Council of Canada has spent some time at the Mine especially to study the soils exposed.

LAKE-BED DEPOSITS.

As the ice and snow gradually disappeared in the early summer of 1944, the shallower portions of the old lake-bed came into view, slowly increasing in extent as the water-level was lowered by the continuous pumping. Practically the whole of the exposed area was found to be covered by a black gelatinous-looking deposit, which was extremely unstable when wet and which appeared to be organic. The material was similar to the black "ooze" which is a feature of many northern lake bottoms. Its uniformity and generally shallow depth suggested a relatively recent origin.

Since this material was quickly removed from the areas that had to be disturbed, and elsewhere quickly dried up, forming the bed for the vegetation that has been developed wherever possible as a surface stabilizer, it was not studied in any detail. Extensive shrinkage cracks developed upon drying

TABLE 1.

Sample	Moisture	Loss on ignition+	Active organic matter	Easily soluble++			
				Ca	Mg	K	P
				ppm	ppm	ppm	ppm
"Black Muck"	9.26%	17.13%	10.75%	500	35	80	trace
Grey Silt	2.4%	2.32%	—+++	800	50	100	150

+ Loss of ignition at 550° C for 7 hours.

++ Calcium and magnesium values represent water-soluble determined by turbidimetric and colorimetric methods respectively. Potassium includes water-soluble and that easily exchangeable by sodium nitrite extraction and turbidimetric estimation by cobalt-nitrite method. Phosphorus—soluble in 0.05 N HCl determined colorimetrically.

+++ Not determined, as general character of sample and low loss on ignition value would indicate little or no active organic matter.

Note: These analyses were kindly carried out by Dr. G. H. Ruhnke of the Ontario Agricultural College, Guelph, Ontario.

(Fig. 6). A chemical analysis gave the results shown in Table 1. The low organic content is to be noted in view of the black appearance of the material.

The black muck generally overlay the varved clay except along the shallow south shore of the Lake. Here sand deposits, of a few feet in thickness, were common. The sand was uniform in grain size, being obviously water deposited; in places it exhibited pronounced false bedding (Fig. 7). This would not be remarkable were it not for the fact that the direction of flow indicated by the bedding was almost exactly at right angles to that of the flow through the Lake. These sand deposits in the lake-bed were small in extent, relative to the Lake as a whole, and so are probably not unduly significant. They show, however, how complex must have been the recent geological history of this and similar regions.

Practically all the unconsolidated material in the lake-bed consisted of varved clays. These are of such importance that they are dealt with in some detail in the next section. In the stripping work carried out adjacent to the open pit, the varved deposits have in places been removed down to the underlying bed-rock. In a number of locations, and in all cases where there was any protuberance above the general level of the glaciated rock surface, a few feet of compact glacial till was found between the rock and the first varved material. The results of preliminary diamond drilling suggest that the till is fairly widespread over the rock beneath the old lake-bed.

FIG. 6. Black muck after drying.
FIG. 7. False bedding in sand.

No unusual features were noted in the till, apart from its striking red color. Figure 8 presents a summary of the mechanical analyses which have been made of till samples, which have been quite uniform in character.

THE VARVED CLAYS.

Practically all the soil exposed in the drained lake-bed consists of banded sediments of the type commonly described as "varved clays." This descriptive term is therefore used generally throughout this paper although, as will be shown, it may not be terminologically exact. In the vicinity of the 'B' orebody, the scene of all the mining operations until 1951, varved clays were exposed from about Elevation 1155 to Elevation 1050. The exposures thus constitute one of the most extensive examples of varved clays on record.

Dr. Ernst Antevs was fortunately advised of the exposures and paid a brief visit to the Steep Rock Mine in the summer of 1946. The senior author had the privilege of accompanying Dr. Antevs during the first part of his field investigation and of describing to him some of the studies dealt with in this paper. With the assistance of a grant from the Geological Society of America, Dr. Antevs prepared an extensive report on the varves that he examined and in his paper was presented his interpretation of their deposition in accordance with the well known seasonal theory (1).

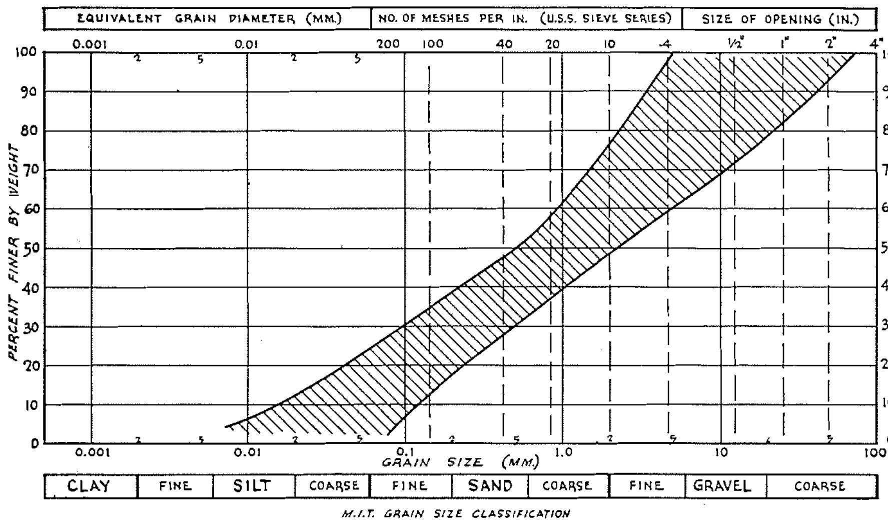

FIG. 8. Mechanical analysis chart for till.

In view of the detail with which Dr. Antevs has measured the varves throughout the complete profile that he examined, it is not necessary to give details in this paper. Attention may rather be directed to some of the features of the varving that seem to be significant in an engineering sense. Some laboratory tests that were made for engineering purposes will then be described.

The earth movements that started as soon as the lake level was lowered in 1944, and which have persisted irregularly ever since, naturally involved large volumes of the varved clays. All the major "mud-runs" that were studied were found to be due to a weakening or loosening of an underlying stratum or varve by the percolation of groundwater from the area draining into the Lake. This percolation could only be appreciable along a relatively porous band. Upon further study, it was noticed that a few thin sandy layers of widespread uniformity were to be found interspersed within the varved clays.

To the existence of these layers of sand can be attributed most of the initial soil movements that originally hampered the mining operations.

Another feature of some of the mass movements has been the exposure, after a mud-flow has occurred, of singularly smooth surfaces over which movement has taken place. To some extent these might be attributed to the effect of the moving soil upon that which stayed in place. Since, however, it is almost impossible to differentiate by eye between the soil that moves and that which does not (in the vicinity of a slide), and since the sliding surface often appears from a distance to be so clean as to be polished, it seems clear that these surfaces represent some disconformity in the deposits.

This supposition seems to be confirmed by one example, seen by the authors, in which a large mass of soil having originally a flat surface suddenly flowed through a relatively small gap, when its lower end was disturbed. When movement had ceased, a large area was exposed which appeared, even from a distance of about a hundred feet, to be a smooth glaciated rock surface, curved on its surface with a sharp edge sloped at about 45° to the horizontal. Figure 9 gives an impression of this surface.

Another significant feature (which has been found elsewhere in glacial lake deposits) is the occurrence, regularly in the lower varved deposits, of flat lens-like calcareous concretions. They are always found in the light-colored layers. These appear to have formed around nuclei and their presence suggests the existence, at the time of the deposition of the relevant varves, of water highly charged with calcium salts (see Appendix). It is of more than passing interest to note that similar concretions have recently been found in the extensive mud deposits at the mouth of the Fraser River, British Columbia. This important waterway is one of the largest rivers discharging into the Pacific Ocean. It does so through a large estuary wherein troubles with sediment deposition have long persisted. It is commonly thought that the deposition of such large volumes of sediment in the tidal part of the river is due, at least partially, to the flocculation produced by sea water. The occurrence of concretions in both locations suggests a similarity between processes of deposition.

Another feature of the varved deposits that calls for mention is the variation in color between the lower and upper deposits. All the sediments at first revealed beneath the top cover of black muck, had the dull grey color so typical of almost all clay deposits. When, however, bed-rock was approached, red coloring in the clay appeared. The lowest deposits of all were nearly as deep red in color as the orebody itself, the gradation from red to grey being gradual.

As the color of the soil changed, so did its general character, the red-colored varves being generally coarser grained than the overlying grey sediments. This variation in grain size was reflected in a number of ways, the most important from the engineering point of view being an increase in instability. When suddenly exposed to view, as by the cutting operation of the hydraulic jets used in the excavation, the red deposits frequently disintegrated rapidly for some distance back from the surface exposed. This is understandable with a silty or fine sandy soil in which the pore pressure of the entrained water is suddenly reduced.

In discussions of varved clay deposits and in detailed accounts of varved profiles much is made of the differences between different bands throughout the cross-section under study. It may, therefore, be useful to note that an equally dominant feature of the Steep Rock soils is the uniformity of many of the sections through varves that have been revealed by excavation and the extensive earth movements. Fig. 10 is typical of the appearance of many of

FIG. 9. Surface of clay exposed after a "mud-run."
FIG. 10. Cross-section through uniform varve deposits.

the exposures examined repeatedly by the authors. It will be seen that there are no "light and dark" bands, as usually reported in accounts of varved deposits. The regularity of the very thin laminations is notable. Only when dried did such material exhibit any variation between material in adjacent layers.

It must be emphasized that all the observations herein recorded are supplementary to those usually made of varved soils—the usual alternate banding, the variation in thickness of varves etc., all so ably recorded in the case of the

Steep Rock soils by Dr. Antevs. The most unusual feature of these soils, however, has yet to be mentioned, this being their behavior when disturbed. Reference has been made to the mud-flows or mud-runs that have caused many of the large mass earth movements, which originally led to such serious interference with the normal process of excavation at the Mine.

Many, if not all, of these appear to have been initiated by groundwater seepage disturbing the equilibrium of soil previously stable in the bed of the Lake. All have involved large quantities of the varved clays, some of the larger slides transporting up to half a million cubic yards of material through distances up to half a mile in the course of a very few minutes.

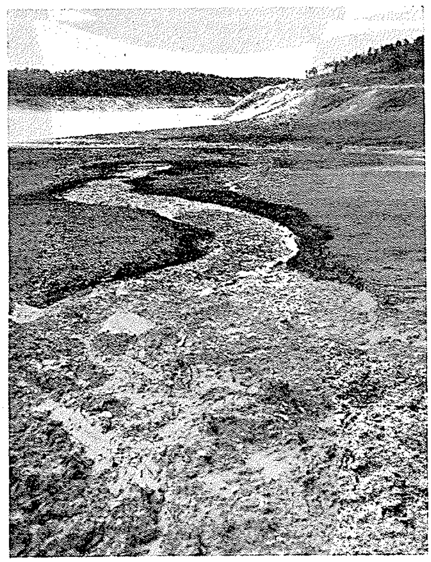

FIG. 11. Stream of disturbed clay.

Although evidence of movement is to be seen, incidentally, in some of the photographs that accompany this paper, Figure 11 has been included to illustrate this soil movement in a typical, although limited, example. The stream of "mud" here seen is actually flowing towards the remainder of the Lake (in the background) at a slow but quite perceptible rate. The material was that being dumped as individual bucketfuls by a mechanical "drag-line" excavator immediately behind the photographer (the senior author). This heavy machine had considerable difficulty in moving its bucket into the stiff grey varved clay that it was excavating for road construction, and similar difficulty in getting the sticky mass to shake loose of its bucket. But when once dumped, the apparently solid material "liquefied" as one looked at it and flowed smoothly away to join in the viscous stream on its way down the hill.

In an exactly similar way, when once one of the big slides or runs started, the entire mass of soil above the point of first movement appeared to become liquid and flowed rapidly, often through quite restricted openings, until the configuration of the ground dammed up the viscous fluid. In a relatively short interval of time, the soil that had moved would again be solid.

This flow phenomenon naturally attracted attention and invited study almost as soon as the soil problems at the Mine were recognized as an integral part of the task of development. Samples were secured and laboratory tests were initiated at the Mine and the University of Toronto. These tests were carried out, in the first instance, with engineering objectives only in view. As is often the case, however, with work in the new engineering field of "soil mechanics" (a poor and unfortunate translation of *Erdbaumechanik*) the test results have not only engineering significance but also some geological interest. A brief summary of some of the laboratory work done to date on samples of the Steep Rock varved clays will, therefore, be presented next.

Despite the character of the principal soil involved, it has beeen possible to develop orebody 'B' by means of the open-pit operation originally planned. With the aid of the theory and practice of soil mechanics—in which soil is not just regarded as "dirt" but as a material that can be studied scientifically, its mass stability being susceptible to reasonably accurate analysis—the Mine authorities have been able gradually to achieve a stable working area and to minimize serious earth movements in the vicinity of the open pit. Details of this achievement are not relevant to this paper but Figure 2 gives some idea of the system of benches and flat slopes which have been developed in the course of this work.

LABORATORY TESTS ON VARVED CLAYS.

Laboratory techniques, now well recognized, have been developed in the study of soil mechanics for the investigation of the physical properties of the unconsolidated materials that play so large a part in engineering operations, and which the engineer has come to call *soil* (following, incidentally, a long geological tradition).[2] Many hundreds of samples of the varved soils from Steep Rock Lake have now been subjected to these laboratory tests, by the writers and others, so that a summary only of the results obtained can be given here.

The earliest tests were carried out for the purpose of assisting with an understanding of the prevalent mud-runs and of determining the slopes that could safely be used in excavating through the varved material in order to form the area in which the open pit could be developed. The significance of the varves was not at first apparent and so all the early soil tests were carried out on composite samples, cut through several varves indiscriminately.

These tests included several series of tests upon samples obtained from bore-holes that were put down as soon as work could conveniently be carried out on the exposed lake bottom. Twenty-seven holes were drilled to elevations as low as El. 1,080 feet, samples being taken at approximately five-foot intervals. It was the results of the tests upon these samples that first showed the great extent of the varved deposits, and which led the authors to their considerations of the problems raised by these deposits, to which this paper is but an introduction.

[2] William Smith used the word in this way as early as 1815.

The samples from these holes (which had to be sunk by the technique of wash-boring) were obtained by forcing into the undisturbed soil at the bottom of the cased hole, at the appropriate depth, a "split-tube sampler," a sampling tool described by its name. This yielded small cylindrical samples of the soil in its natural state, except only for slight surface distortion, and at its natural moisture content. Such samples are called "undisturbed" in soil mechanics work.

In all soil studies, the natural moisture content is usually an important factor. All the Steep Rock soil samples, therefore, were placed in small glass jars as soon as they were taken out of the ground, the jars being sealed immediately with wax. The natural moisture contents to be recorded, therefore, may be regarded as reasonably accurate. As the soil investigation continued, block samples of the varved material were carefully carved out at suitable locations, packed in tight fitting boxes, sealed in with wax, and shipped in this way to the several laboratories in which the soil has been studied—in Canada at Toronto and Ottawa, in the United States and in Great Britain.

The natural moisture content of a soil considered just by itself may not be of unusual significance; its importance is relative and derives from its relation to the amounts of water necessary to change the character of the soil. As convenient indicators of these moisture contents, limiting quantities of water (as first suggested by Atterberg of Sweden for agricultural soil tests) have been adapted for use in soil mechanics. These "limits" and related factors are defined as follows:

Natural Moisture Content (W_n).—The weight of water in soil in its natural state, expressed as a percentage of the dry weight of solid material.

Plastic Limit (P_w).—The weight of water required to render a dry sample of soil plastic (as distinct from crumbly), expressed as a percentage of the dry weight of solid material.

Liquid Limit (L_w).—The weight of water required to render a dry sample of soil just fluid (as distinct from plastic), expressed as a percentage of the dry weight of solid material. (These two limits are clearly arbitrary values: they are determined for any soil by relatively simple but now standard laboratory tests) (2).

Plasticity Index (P.I.).—The difference between the liquid and the plastic limits, thus automatically expressed as a percentage of the dry weight of soil; it is a good indication of the range of plasticity of a soil.

A number of ways have been suggested for interrelating the limit values and the natural moisture content of a soil. Possibly the most convenient is the water plasticity ratio which, using the symbols shown above, is expressed as:

$$B = \frac{W_n - P_w}{L_w - P_w} \quad \text{or} \quad \frac{W_n - P_w}{\text{P.I.}}. \tag{5}$$

The relevance of these factors becomes clear when the records of tests upon soil samples from the bed of Steep Rock Lake are examined. Figure 12 is a graphical summary of test results for samples from a typical deep bore-hole through the varved material. It shows for each sample tested its natural moisture content, liquid and plastic limits, plasticity index and water plasticity ratio. The samples were cut without any attempt to separate the varves and are therefore composite in character.

Examination of the chart will show that, in the case of every sample tested, the natural moisture content was above the corresponding liquid limit. Not only so, but the difference is in every case so appreciable as to eliminate any possibility of this surprising feature being the result of experimental error. Several hundred soil samples from Steep Rock Lake have been tested; in practically every case, the same high natural moisture content was found.

This feature of the varved material raises some academic questions but it had an immediately practical application when first discovered. It explained the character of the extensive slides, or mud-runs, which have already been described. Once such material is disturbed, the bonds of the clay-water systems are broken, at least in part, thus leading to liquefaction of the disturbed mass, which will then flow until impeded by some obstacle, the excess water draining away, leaving the soil in a relatively much more stable condition than it was originally. In order to achieve proper stability for the purpose of developing the open-pit iron ore mine, it was, therefore, clearly desirable to keep all disturbance of the natural soil to an absolute minimum. This requirement has been closely followed by the Mine authorities since its necessity was fully recognized, even to the extent of controlling most of the groundwater seeping into the old lake basin from the small rocky drainage area around, seepage that was a potent cause of some of the early major slides.

The dimensions of the slopes and berms which have been developed as the open pit area has steadily been extended, have been calculated on the basis of what may simply be called "strength tests" upon undisturbed cylindrical samples cut from block samples of the varved soil. In this form, the soil has the consistency of soft cheese. It can be cut fairly easily, with suitable trimmers, but even when handled in this way, it does not usually indicate the excess water that it contains. Only when a sample is actually "re-moulded" in the fingers does one feel the sudden change in consistency. A peculiarity of the trimming of samples may usefully be noted. In many cases, cutting of a block sample would reveal a "blocky" structure to the mass, the sample breaking naturally into irregular prisms with major axes from one quarter to one inch in length. This structure would be shown while samples were being roughly trimmed, when natural fracture could take place along such random planes, before more careful and accurate final trimming was carried out. Beyond this feature, the strength tests revealed nothing of special significance to this discussion.

In all this early laboratory work, samples were obtained and tested without regard to the laminated divisions provided by the varves. For practical purposes, it was the action of the soil in the mass that had to be studied. As work progressed, however, and as the immediately urgent practical questions were gradually answered, attention was focussed to an increasing degree upon the relative properties of the light and dark varved material, and finally upon the variations of soil properties within individual varves.

The next group of tests were also performed initially, however, upon what may be called "mixed samples," i.e., with no attempt to separate individual laminae. These tests consisted of accurate determinations of the particle-size distribution curves for a large number of samples. In the technique of soil mechanics a convenient method is now almost universally used for this purpose, derived from a simple version of the same test developed for agri-

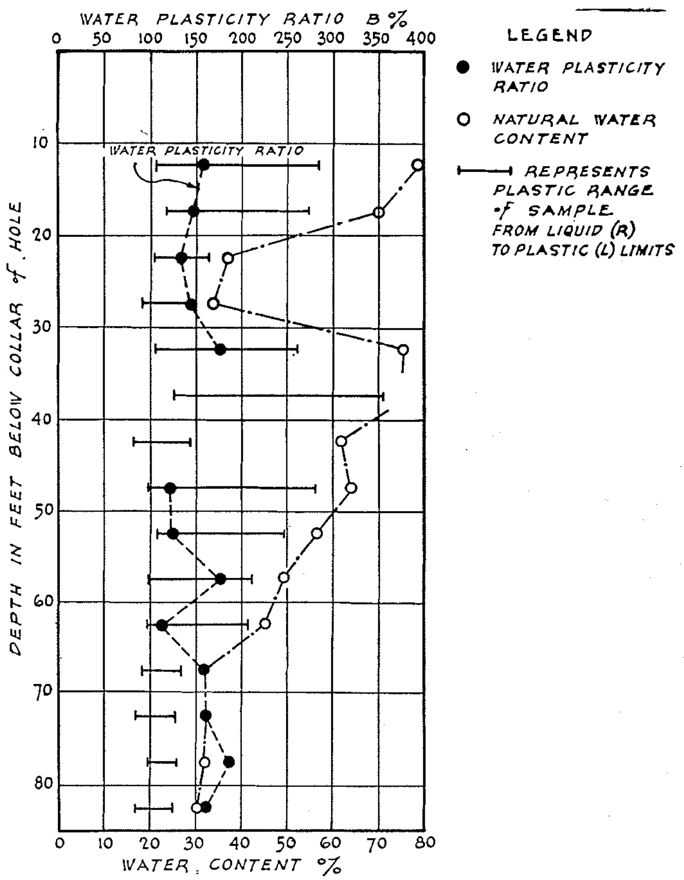

Fig. 12. Log of typical deep bore hole.

cultural soil studies by G. J. Bouyoucos (2). A soaked sample, carefully weighed, is thoroughly mixed with distilled water to make a suspension of 1,000 cc. A specially sensitive hydrometer is then inserted in the suspension at specific time intervals. From the values it gives for the specific gravity, the particle-size distribution is calculated. It is of some significance to note that a suitable deflocculating agent is added to the suspension before final mixings and that, at the end of the usual 24-hour duration of the test, a few drops of hydrochloric acid are usually added in order deliberately to flocculate the fine particles still in suspension after this interval.

Results are generally plotted on special semilogarithmic forms similar to that used for Figure 13. On this diagram has been plotted the envelope of all the mechanical analyses of Steep Rock varved soils carried out by the senior author and by members of his staff. Equally of note is the relatively high percentage of soil particles in the Steep Rock varved soils which are below 0.002 mm. in equivalent diameter.

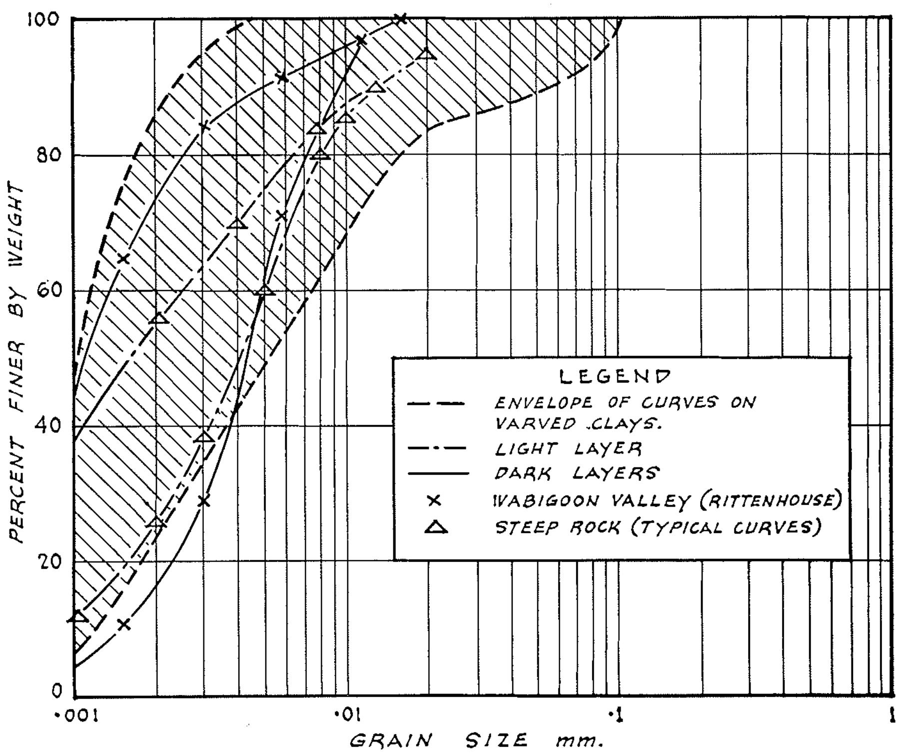

FIG. 13. Envelope of mechanical analysis curves for all clay samples.

The first mechanical analyses to be made (by R. F. L.) on material from individual varves were somewhat roughly carried out and suggested that there was little significant difference between the particle-size distribution in the dark and light bands. Subsequent tests, more carefully carried out, notably by H. B. Sutherland and W. J. Eden, have showed a definite and consistent difference, although still within the confines of the envelope shown in Figure 13. Typical curves have been plotted on the chart for dark and light bands and, for comparison, similar typical curves obtained by G. Rittenhouse in the only comparable investigation known to the authors.

Rittenhouse studied an unusual series of varved clays that he found in the Wabigoon Valley, in the district of Kenora, Western Ontario, not more than

80 miles from Steep Rock Lake. The reported abnormality included a dark red color for a series of thick dark varves, which appears to be very similar to the same feature that is so common in the lowest of the Steep Rock deposits. Rittenhouse reports mechanical analyses carried out by the pipette method; two of these have been plotted (9).

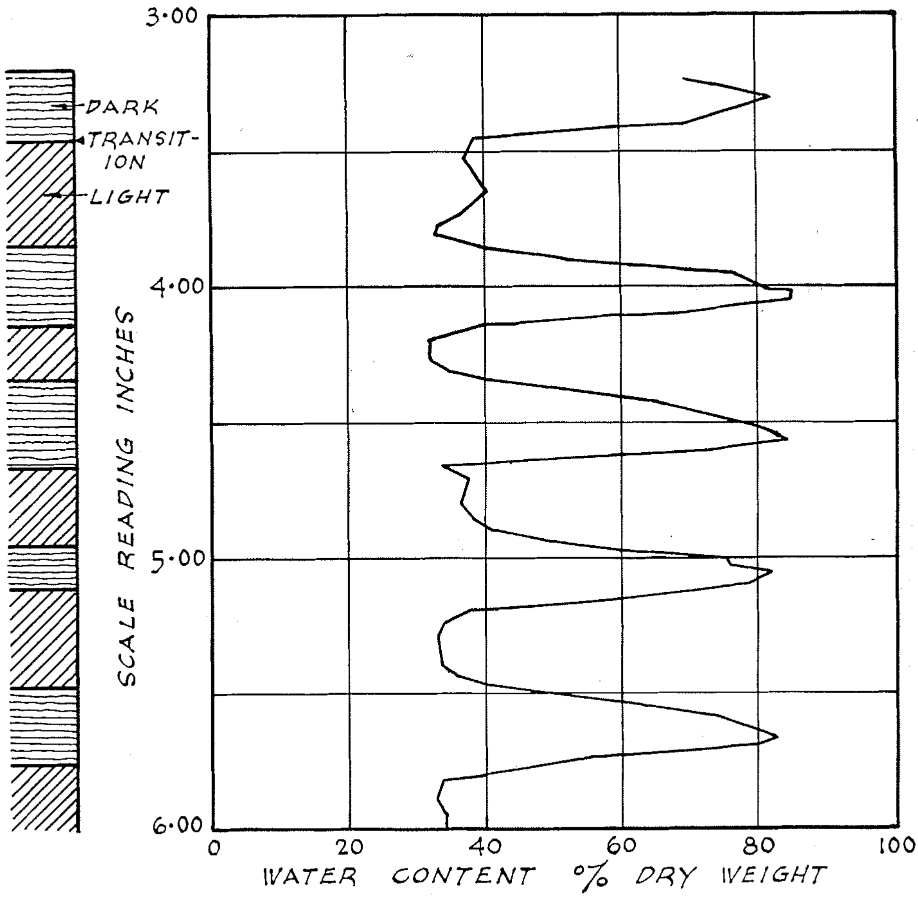

FIG. 14. Variation of moisture content within varves.

In a private report, H. B. Sutherland has summarized his findings regarding mechanical analysis of the varved materials by recording that, for the samples he analysed, 50 percent by weight of all the dark laminae tested was smaller than 0.002 mm. in equivalent diameter, whereas only 10 percent of the particles from the lighter varves were of the same order of magnitude. Variations in particle-size distribution within the varves have also now been studied. It is yet too early to report upon these variations in detail but it can be recorded that, in the samples so far studied, there does not appear to be any general gradation, uniform or otherwise, from top to bottom of the varve. Only in the case of the coarse red silty and sandy material found close to the rock, has any such gradation been detected, and even in this case, the gradation is not well defined and might even be explained by errors in sampling. The application of the refined methods of sampling and analysis may yet demonstrate that gradation does occur within laminae; variations in natural moisture content have already been detected.

Figure 14 shows some preliminary results from a detailed study of the natural moisture contents of light and dark laminae, carried out by W. J. Eden. As in the other tests reported, there is a marked difference in moisture content in adjacent laminae. Correlation of these differences with differences

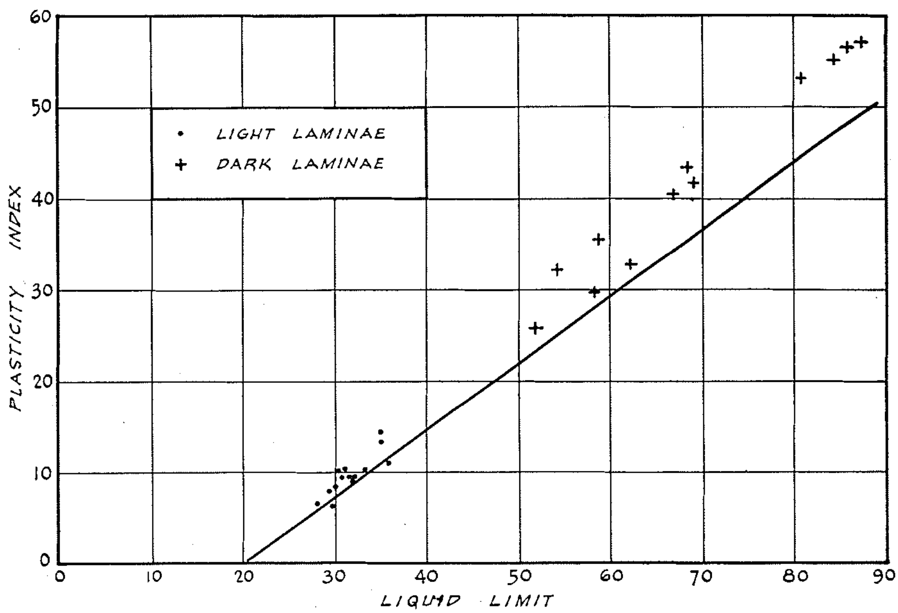

Fig. 15. Chart of liquid limit and plastic limit relationship.

in particle-size distribution appears to present a promising line of further inquiry. Difficulties in sampling and testing the necessarily small quantities of soil involved have impeded progress, but the work is continuing.

The plasticity of the samples tested calls for comment. It has been found that the plasticity of fine-grained soils is related to their clay content, i.e., not just to the clay-sized particles but to the actual properties of the clay minerals contained in the soil. The property of plasticity is thus a useful indicator of soil type and it is so used in the engineering study of soil. Graphical methods are again in common use as a useful means of presenting plasticity data. Figure 15 shows the relation between the plasticity index and liquid limit for some of the Steep Rock samples. A difference between the plasticity of the material in light and dark laminae will be at once apparent. That from the light laminae is almost all close to the classification of inorganic clays and silts of low plasticity, whereas that from the dark laminae is seen to be in the range of clays of high plasticity. Figure 16 presents a similar relationship between the Plasticity Index and the percentage of particles smaller than two microns (0.002 mm.) in corresponding samples. Again, there is a marked difference.

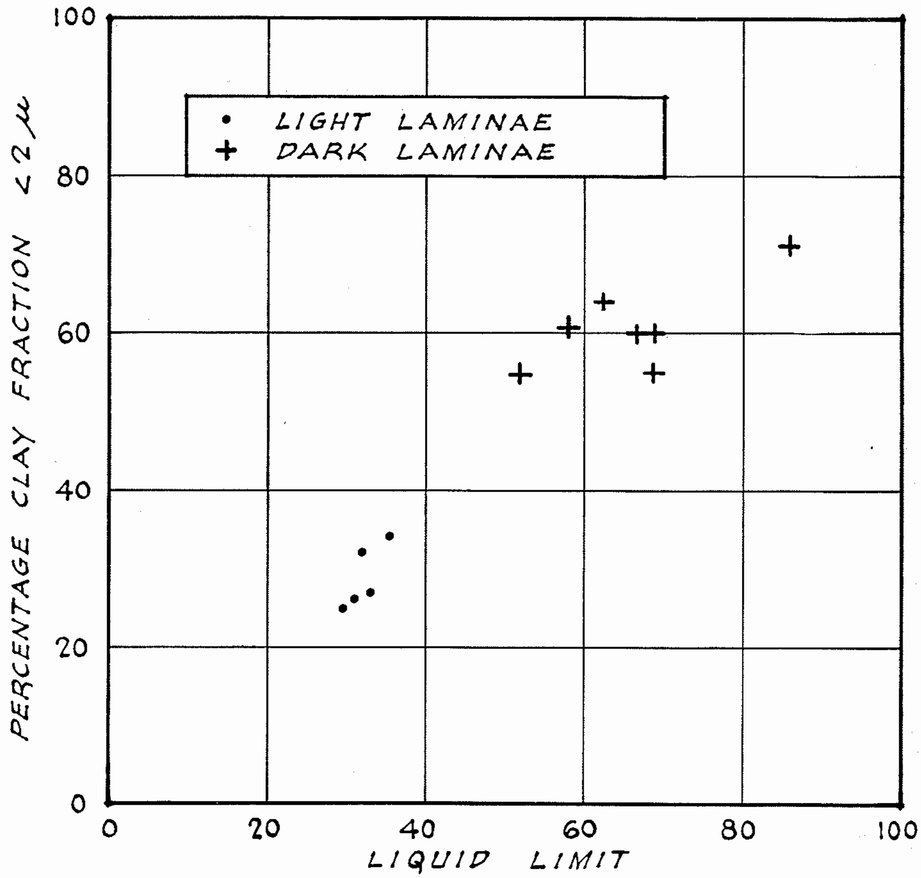

FIG. 16. Chart of liquid limit and particle-size relationship.

It will be clear that the study of these varved clays in the laboratory has already proved to be an extensive undertaking. A summary only has been here presented of work which has extended, intermittently, over a period of about five years. Amongst other tests that should at least be mentioned are the examination of soil particles by means of an electron microscope, and simple tests for thixotropy. The electron microscope photographs appeared to show rounded particles, suggesting a preponderance of fresh minerals, but this evidence is inconclusive at present. The thixotropy tests show also a difference between the characteristics of the light and dark varved material (3). Further investigations are in progress and it is hoped to study the mineralogical character of the soils in some detail.

SOME COMMENTS.

So much factual information has been presented in summary form in the foregoing pages that some general comments may usefully be presented in conclusion. Inevitably, these comments raise some questions since they relate to the complex phenomenon of the deposition of varved material.

The authors are familiar with the well publicized theory of annual deposition of De Geer and have studied the relevant literature. Since an extensive bibliography accompanies Antevs' recent paper (1), to which this paper is, in a sense, a companion, it does not appear to be necessary to repeat any such extended list of references.

Apart from the paper by Rittenhouse, and one by Fraser (7), however, the literature does not appear to contain any record of an approach to the problem of varve deposition by way of such laboratory soil tests as have been here described. It may therefore be useful to point out how the results of these tests lead to some conclusions similar to those derived from geological reasoning and to invite attention to some further questions that the test results suggest.

(1) The natural moisture content of the varved material calls first for comment, not only because of the lack of any tendency for it to decrease with depth (for mixed samples), and the almost constant value for the water-plasticity ratio with increasing depth, but also because of the variation between the water naturally retained in the light and dark laminae respectively.

(2) The variation of the natural moisture content of the varved material is partially explained by the variation between the plastic properties of the light and dark varved material. The essential differences between the two types of material are shown clearly in Figures 15 and 16. It is generally assumed that the more plastic is a clay-sized soil, the more the contained particles consist of the clay minerals. It can not be doubted but that this finely divided material is the product of glacial action, at least in part, originating as rock flour, which would be expected to display very low plasticity. What is not clear is how such a marked increase in plasticity, as is shown between light and dark varves, and therefore in mineral transformation, could take place in annual periods or, alternatively, could vary so regularly at semi-annual intervals. The difference so strikingly shown in Figure 15 can only be explained mineralogically, or by base exchange. It is not clear how such a significant change in the basic character of soil solids can be related merely to seasonal deposition.

(3) It may be pointed out that the light banded material is more coarsely grained and that this will explain the difference in plasticity, but the difference in particle-size, although definite, is still slight. In this same connection, it has already been noted that a relatively simple sedimentation test is used, in

soil mechanics, for particle-size determination. By means of the theory of this test it is possible to calculate the time required for soil particles such as those at Steep Rock to settle in still water. Particles, for example, having an equivalent diameter of 0.001 mm. in water at a temperature of 35° F will settle in 180 days only 28 feet. And not only does more than half the material in the dark varves consist of particles of this size or smaller, but the estimated depth of the glacial lake was over 300 feet.

In some discussions of varved depostion, circulation of lake waters due to thermal gradients is suggested. If there is circulation of any kind, there must be some other factor affecting deposition because the carrying power of moving water would effectively offset even the slow settling of the fine particles, since the velocity could not have been vertically downward at the lake bottom. There appears to be no gradation in particle-size throughout the section of a lamina. If, however, the soil material in a varve is dried, ground up, soaked in distilled water and subjected to the usual sedimentation test for particle size, it will gradually settle out with perfect gradation—from the coarser particles at the bottom to the very fine particles that remain in suspension.

(4) It is clear that some process in addition to ordinary sedimentation must have been operative when the varves were formed. Some indication of this is given by the consistently and "artificially" high natural moisture content of the varve material, a characteristic alien to sediments deposited by straight settling. From the description given of the soil, it can be seen that it must have a "honeycomb" type of particle structure, in order for so large an excess of water to be present without being evident. This would seem to be possible only if there existed some kind of interparticle attraction during deposition. This, in turn, suggests the phenomenon of flocculation. It is not without significance that, in conducting mechanical analyses of Steep Rock soil samples, it is almost always necessary to add hydrochloric acid to the 1,000 cc. suspension, even after it has stood for twenty hours, in order to precipitate, as a flocculant, the very finest particles still remaining in suspension. Correspondingly, more than the usual dispersing agent is required at the start of these mechanical analysis tests in order to break up the soil into its constituent particles.

(5) Recent experience at the Mine is related to this same feature in a practical way. Material from the lake-bed at the "A" orebody is now being pumped into the one section of the Lake that remains at its original level (the west arm). Through this large expanse of water, the Seine River now flows but at negligible velocity because of the large cross-section of the water area. Despite this, some material—pumped from its varved position—is picked up by this very limited flow of water, carried to the foot of the Lake and then down the old course of the Seine River for a distance of at least 50 miles without settling out, passing through many smaller lakes on the way. Tests have shown, however, that most of the soil that is pumped fails to break up into its constituent particles even in passing through the pumps, but is deposited after discharge in particle-assemblages that correspond in size to chemically formed flocs.

(6) Flocculation involves electro-chemical action. Similar action must have been involved in the formations of the concretions that are found in the light layers of the Steep Rock soils. Also of significance, in this connection, is the blocky structure of the soil despite its laminated nature. The senior author has seen exactly the same type of structure developed in a clay slurry that had been subjected to treatment by electro-osmosis. Sudden precipitation of river sediments when sea water is encountered is an associated phenomenon, even to the formation of concretions, as in the Fraser River estuary. It has been noted that the Steep Rock varved material has, when wet, a bleaching effect upon colored clothing material, thus further substantiating the idea of sediment flocculation.

(7) Study of these facts suggested that possibly something could be gained by reference to studies of other natural banded deposits. As is well known, discussion still continues regarding the exact origin of some of these. It is of interest, however, to note that in an extensive study of the radiolarian cherts of California (to which attention was kindly directed by Dr. H. H. Aldrich), E. F. Davis discards the idea of a rhythmical annual deposition (6). Opinion seems to favor either the idea of regular deposition from supersaturated suspension or the concept of rhythmic segregation of colloidal silica.

(8) The authors are aware that the concepts of flocculation, and of supersaturation, have been associated with the generally accepted theory of varve deposition. One of the clearest expositions which they have encountered in their studies is in a very short paper by E. M. Burwash (4). It is in a volume of a series not usually considered in relation to geological literature and so is reprinted, by permission, as an Appendix. The idea of climate is prominent, as usual, in this explanation, and it is this feature that the writers find difficult to correlate with their field observations. In addition to features already mentioned, they have seen an exposure of about 30 feet in depth in which the varves were all of identical thickness. Has climate changed, through the years, to the extent that such perfect regularity is just a thing of the past?

(9) Many details of the Steep Rock varved exposures raise other questions, although not usually of so general a character as those already noted. One of these should, however, be mentioned, this being the repeated exposure of very thin laminations all of a uniformly light grey color with no evidence at all of inter-bedding by darker material. Unfortunately, it has not yet been possible to make detailed studies of samples from these locations but their existence raises further doubts as to the climatic variations of the past being such as to eliminate entirely a long series of winters.

(10) Finally, possibly the most striking of all the observed features of the varving in the field are the remarkable distortions in the varving regularly to be observed. The first that the writers observed were near the surface of the lake-bed deposits and included almost complete "folds" of groups of varves. The action of surface ice seemed to be the only possible explanation of this phenomenal distortion. Later, far from the shore line, and well below the level of the recent lake bottom, similar distortions were again seen. A

vaguely possible explanation of these seemed to be the sliding in from the sides of material of the same age when the varves in question were at lake-bottom level. More recently, however, deep-seated distortions have been exposed, far removed from any shore line, far below the recent lake-bed level, and amid large areas of quite level varves. Figure 17 is a typical exposure.

FIG. 17. Deformation in varves.

CONCLUSION.

The foregoing comments indicate clearly the stimulus which the study of the Steep Rock soils has given to the thinking of the authors and all others who have worked with them in this investigation. In all these studies, not only have they had the benefit of discussion with the Mine officers, notably those previously mentioned, but also the active co-operation of Ben Eyton, Chief Chemist of Steep Rock Iron Mine Limited, and, through the Division of Building Research, National Research Council of Canada, of W. H. Ward of the British Building Research Station, H. B. Sutherland now of the University of Glasgow (who spent the summer of 1948 at the Mine), and F. L. Peckover and W. J. Eden of the Division's Foundations and Soil Mechanics Section, other members of which have contributed much in discussion and in test work. Laboratory studies of the varved soils continue at each of the institutions mentioned and it is hoped that more detailed accounts of some of the features mentioned generally in this paper may soon be available.

Division of Building Research, National Research Council,
Ottawa, Canada,
and Port Arthur, Ontario, Canada,
May 2, 1953.

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APPENDIX.

An explanation of varve formation by E. M. Burwash from his paper "The Deposition and Alteration of Varved Clays," Trans. Royal Can. Institute, vol. XXII, p. 3–6, Toronto, 1938.

As water cools, its capacity for the solution of gases increases. The water of a frozen lake therefore is more highly acidulated by absorption of carbon dioxide than the warmer water of the summer which at present ordinarily rises to a temperature of nearly 60° F. The solution of calcium carbonate in the water depends on that acidulation, and its deposition from the water probably on a decrease in the acidulation, which would be brought about by a warming of the water. On this basis we can perhaps correlate the deposition of the varves with the seasonal changes which must have been taking place at the time of the sedimentation.

(a) During the winter, the surface of the soil is frozen and precipitation remains upon it in the form of snow. Any slight liquefaction of the snow is frozen before it has time to run off in the form of drainage. It cannot penetrate the frozen upper layer of the soil. Underneath the frost layer, the unfrozen ground water continues to work its way slowly into the streams and lakes, carrying with it no solid sediment, but a considerable supply of dissolved salts, especially calcite. The cold acidulated water of the lake is well adapted to receive these, and retain them without precipitation, so that a condition of saturation is approached, perhaps nearly reached.

(b) With the arrival of spring the ice-cover of the lake melts more slowly than the snow on the adjacent land. The floods that follow the liquefaction of the snow and the thawing of the surface soil carry large amounts of solid sediment into the lake. The coarser parts are deposited near the shores, while the finer clay is carried further out and settles gradually over the bottom of the lake for great distances, covering the bottom of even large lakes. The floods once over, the streams become clear, much reduced in volume, and the amount of silt carried out is negligible.

(c) As the lake waters gradually warm by direct solar radiation and conduction from the air after the disappearance of the ice, and are further warmed by the inflow of warm surface waters, the capacity of the water to retain carbon-dioxide is decreased, and the deposition of part of the solids dependent on its presence would follow. This includes all carbonates but mainly calcite. The actual condition is that the water in the depths of the lake remains colder all summer than that on the surface. As is well known, the species of fish that prefer cold water are then found at a considerable distance below the surface. The calcite released from solution in the warmer water near the surface would sink until it came to the colder and more acidulated depths which would redissolve it, become saturated, and finally deposit calcite as a precipitate at the bottom. We may therefore refer the formation of the white partings in the clay to the summer season. The predominantly argillaceous layers must also be conceded to contain some calcite, apart from the presence of numerous calcareous concretions in them.

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