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Soil: Its Geology and Use

by
R. F. LEGGET

Address as President of
Geological Society of America
given at the 79th Annual Meeting of the Society
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Address as Retiring President of The Geological Society of America, Inc.

Geology in its many and varied facets is splendidly pictured in the long succession of addresses delivered to this Society by its Presidents at successive annual meetings. The seventy-three resulting papers present a fascinating kaleidoscope of the science of the earth. From the "Geologic History of Sea Water" (Rubey, 1951) to "Dry Land in Geology" (Coleman, 1916); from "The Depths of the Earth" (Daly, 1933) to "Folded Mountains and Isostasy" (Lawson, 1927); from "The Hot Spring Problem" (Day, 1939) to the "Evolution of Oases and Civilizations" (Pumpelly, 1906)—so wide-ranging has been the choice of subjects for this annual occasion. One president chose as his topic "Eutopotropism" (Lane, 1932) for the explanation of which unusual title reference must really be made to the address itself.[1]

The applications of geology in the service of man have not been neglected, C. P. Berkey's notable paper on the place of the geologist in public works being still remembered by older Fellows (Berkey, 1942). The Society's benefactor, R. A. F. Penrose, Jr., addressed the Society when he was its President on "Geology as an Agent in Human Welfare" (Penrose, 1931). Even broader in its implications was the choice of subject by another Canadian predecessor, W. H. Collins, speaking on "Geology and Literature" (Collins, 1935).

What, then, can be the subject for this talk, if repetition is to be avoided? The choice is the more difficult for one who has been concerned mainly with the applications of geology, a "worker in the kitchen of science rather than in the study" (if an old but singularly appropriate phrase may be borrowed for this occasion). Fortunately, a careful study of all the previous addresses provides a ready answer, for, wide as is the coverage of the science of the earth in these published addresses, they suggest that almost all earth scientists are "hard rock geologists," pure or applied, some few having special interest in mining and one or two in geophysics.

It has recently been estimated that at least 72 percent of the surface of the globe (excluding the area covered by ice, permafrost, and fresh water) is covered with soil (Goldberg and others, 1965). This striking fact appears to have been touched upon only rarely in the presentations of preceding Presidents. "The Pleistocene Formations of New York" (Fairchild, 1913) and a review of the "Present Phase of the Pleistocene in Iowa" (Calvin, 1909) are the only Presidential addresses devoted entirely to Pleistocene geology, although this branch of earth science was touched upon by Coleman (1916) and Scott (1925), while in a well-remembered paper on "Geological Geomorphology," Russell (1958) very naturally noted the importance of Pleistocene studies. But that appears to be all, and even in these five papers there is nothing about soil as a material.[2]

To deal with the mundane subject of soil on an occasion such as this might appear to be taking too great a liberty, were it not that there is some precedent for this choice of subject. Some time ago, on a somewhat similar occasion to this, a speaker used these words:

> I am called upon by command from your lordship and the council who direct the progress of (this) Society, to entertain this illustrious assembly with something which, being either derived from, or leading to, philosophical experiment, may be of real use, and suitable to the design of its institution. I am highly sensible of the honour which is done me, so of the great disadvantages I lie under for want of abilities to carry me through an undertaking of this importance, and before such acute and learned judges; but I hope

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[1] Since copies of Volume 43 of the Bulletin may not be conveniently available, the following (direct) quotation may be cited: "Some of my profane listeners will be inclined to say 'What in hell is eutopotropism?' . . . I made it up to shock you so that you will remember the idea. . . . Eutopotropism is the tendency or sense to know where you are well off and go there."

[2] Appendix A provides a chronological list of all preceding Presidential addresses.

Geological Society of America Bulletin, v. 78, p. 1433–1460, 15 figs., 8 pls., December 1967

that my obedience to your commands will cover these defects for which I can make no other apology. There are few here, I presume, who know not upon how innocent and humble a subject I have long since directed my thought; and, therefore, I hope they will not be displeased, or think it unworthy of their patience, if from their more sublime and noble speculations (and which do often carry them to converse among the brighter orbs and heavenly bodies) they descend a while, and fix their eyes upon the earth. . . .

Thus did John Evelyn address the Royal Society on the 29th day of April, 1675 (Evelyn, 1675). May I use his words, suitably democratized, as my own as I invite you to forsake extraterrestrial geology at least briefly and look down with me at some aspects of the soil, just as that audience did in London, England, now almost three hundred years ago.

The strange neglect of soil, and of Pleistocene geology in particular, to which I have ventured to refer, is reflected in several ways, not the least of which is in the geological curricula of recent decades at universities. This is in strange contrast with the long history of field studies of surficial deposits, a history that is notably reflected in the work and publications of the geological surveys of the English–speaking world (brief notes upon which are included as Appendix B). Fortunately, there has always been a small core of devoted workers in this fascinating field. Today, Pleistocene studies are slowly gaining increasing recognition, the proliferation of those happy informal groups of "Friends of the Pleistocene" being but one indication of this growing interest. But geologists in general have been content to walk over soil, often denigrating it with such names as "mud"—in effect letting the grass grow under their feet, literally but naturally not metaphorically.

In agricultural studies, great advances have been made in the investigation of the soil in which crops grow, pedology being now a well–established branch of science. Engineers, correspondingly, have had to use soil and to move it in very large quantities in the course of their utilitarian operations. For a long time, and again apart from the pioneer effort of a few gifted individuals, engineers also treated soil with disdain. During the last thirty years, however, there has been a complete change in this attitude. The science of soil mechanics is now well established.

It may therefore be useful to review what this new look at soil has done and to inquire whether there are or can be any useful links between engineering and geological soil studies. This has naturally been done before—there was, for example, an admirable review by a geologist of this joint interest in soil published as early as 1950 (Kaye) and a corresponding review by an engineer delivered in the same year (Skempton, 1953), but appreciation of the importance of the joint discipline appears to be limited still to a very restricted circle. If, therefore, the occasion of a Presidential talk can properly be used for a broad-ranging but quite general review of soil in geology, possibly it will still be "suitable to the design of [the] institution" of our great Society.

A semantic problem must be faced at the outset—definition of the word "soil." In keeping with its Latin origin (*solum*, the ground), the word was used in all early geological studies in English–speaking countries to describe all the fragmented material in the crust of the earth below the size of small boulders. Even before the recognition of geology, John Evelyn used the word in this generally accepted sense, for in his "Discourse on Earth, Mould and Soil," he said that: "The most beneficial sort of mould or earth, appearing at the surface . . . is the natural under–turf earth; but for a description of the rest which succeed it in strata, or layers, till we arrive on the barren and impenetrable rock, I shall refer the critical reader to the old geoponic authors."

In his account of his famous "Map of the Strata of England," William Smith (1815) refers to "the general course and width of each stratum of the soil and minerals." J. W. Dawson, an early President of this Society, in his book *Acadian Geology* (1855) wrote that "the western part of Nova Scotia presents some fine examples of marine alluvial soils." The early volumes of the *American Journal of Science* contain repeated uses of the word used in this original sense (see, for example, Brewer, 1885). Innumerable other examples from geological literature could be given.

Engineers have continued to use the word in the same sense, soil being officially defined by the American Society of Civil Engineers jointly with the American Society for Testing and Materials as: "Sediments or other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter" (A.S.T.M. 1967). Soil Mechanics, a name that is an accurate translation of *Bodenmechanik*, includes the study of all the soils with which the engineer has to deal, and not just the topsoil. There has been an unfortunate tendency in recent geological writing, however, to follow the lead of agricultural soil scientists in confining the use of the general term "soil" to the topsoil, to the understanding of which pedological studies have made such great contributions. Semantic confusion of this kind is singularly unfortunate, especially when there is such fine and widespread co-operation between workers in the several disciplines involved. Since my own immediate colleagues include "soil scientists" of both persuasions, we have endeavored to trace the source of the confusion and I think that we have found the explanation.

At the First International Congress on Soil Science held in 1927 in Washington, D.C., C. F. Marbut presented a definition of *soil* limiting its use to what is commonly called topsoil "ranging in thickness from a mere film to a maximum of somewhat more than ten feet which differs from the material beneath it . . ." (Marbut, 1928). At the same meeting, C. F. Shaw presented a paper on a "Definition of Terms Used in Soil Literature" and in it he referred to a book by K. Glinka (Shaw, 1928). Glinka was an eminent Russian agricultural soil scientist who continued the pioneer work of Dokuchaev, generally regarded as the founder of pedology. But the German edition of Glinka's book, not the original, was referenced by Shaw (Glinka, 1914). It appears to be almost certain that in the process of double translation the fact that the Russians have two distinct words for "soil" and "topsoil" was obscured.

The definition of Dokuchaev of 1886, quoted by Glinka, and requoted (from the German) by Shaw was of "rock strata lying near the surface which are altered by weathering, air; living and dead organisms." By reference to original writings of Dokuchaev (1891), it has been found that he described such surface material as "*pochva*" which (he says) is "the product of the combined action of (a) ground ["*grunt*"], (b) climate, (c) vegetative and animal organisms . . ." (Dokuchaev, 1949). These two words—"*grunt*" and "*pochva*"—are still in use by Soviet workers, one of the leaders of whom has confirmed to me that "*pochva* is the term applied to the upper stratum of friable soil which is altered naturally by the effect of climate and various types of organisms . . . and which possesses the property of fertility. By *grunt* we mean . . . subsoil or all friable soil resulting from the erosion of the lithosphere . . . and not subject to soil forming processes" (Tsytovich, 1962). In Soviet soil mechanics work, the general term "*grunt*" is always used in this specific manner.

British engineers display semantic exactitude in using the word "soil" in accord with Professor Tsytovich's interpretation of "*grunt*," as shown in Figure 1 which is reproduced (by per-

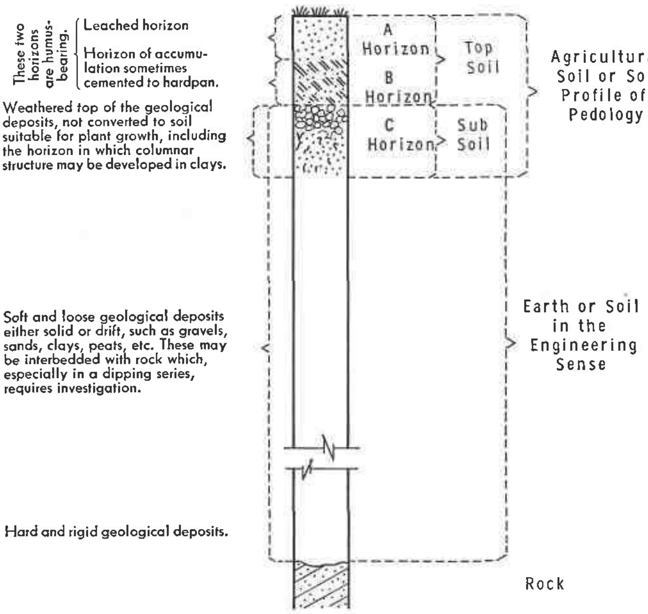


Figure 1. The relation between pedological soil and soil in the engineering sense (British Standard Code of Practice for Soil Exploration).

mission) from the British Standard Code of Practice for Soil Exploration (1957). Since the hands of the clock cannot be turned back, most unfortunately in this case, and the Russian practice of using two different words to describe the two different types of ground adopted in English, it may be suggested, with all due respect to agricultural soil scientists, that all concerned should continue to use the same familiar word *soil*, leaving to individual contexts any necessary restriction of its use to the "A" and "B" horizons of the pedologist. This is the invariable practice in soil mechanics; it should be reflected also in the literature of geology, continuing the invariable practice of earlier years.

The name of C. F. Marbut will be recognized by many as that of one of the great pioneer workers in the study of soil. Born in 1863, he was trained in physical geology at the University of Missouri where he taught from 1895 until 1910, when he commenced his illustrious career with the Bureau of Chemistry and Soils of the United States Department of Agriculture. One of his earliest publications dealt with the physical features of Missouri, and in a published lecture he once said that "Geologically, the soil layer and the rest of the unconsolidated material lying beneath the soil are constituents belonging to and constituting parts of one geological body . . ." (Krusekopf, undated). After attending an international conference of pedologists in Prague in 1922, he devoted all his efforts to the study of the surface soils of the United States, having the satisfaction of seeing published his famous soil map before he died in Harbin, China, in 1935. He was, clearly, an endearing character; his activity is reflected in the fact that he learned Russian when in his sixties in order to keep pace with Russian pedological work.

It was the husband of a Fellow of this Society who persuaded engineers to look at soil as they look at other materials: capable of analysis, laboratory testing, and so of predetermined use. Karl Terzaghi was a man of genius. When he died in his eighty-first year in 1963, he had seen the scientific study of soils for engineering purposes—soil mechanics, of which he was the acknowledged founder—in wide use throughout the world. Born in Prague in 1883, he was graduated in 1900 in mechanical engineering from the Technische Hochschule in Graz, Austria. His early interest in geology was indicated by his translating, while doing his army service, Geikie's *Outlines of Field Geology*, published in 1904. As he accumulated experience in construction, he

> had ample opportunity to witness the striking contrast between what we expected, digging into the earth or loading it, and what really happens. . . . I came to the United States and hoped to discover the philosopher's stone by accumulating and coordinating geological information in the construction camps of the U. S. Reclamation Service. It took me two years of strenuous work to discover that geological information must be supplemented by numerical data which can only be obtained by physical tests carried out in a laboratory (Terzaghi, 1936).

Engineers have all too often forgotten the warning implicit in these words—that soil mechanics must rest upon a sound geological foundation. One wonders if geologists, on the other hand, have taken full advantage of the information that laboratory tests on soil can provide.

Terzaghi's words were spoken in the course of the Presidential Address he delivered to the First International Conference on Soil Mechanics and Foundation Engineering, held at Harvard University in 1936 as a part of the University's tercentenary. In the three decades since that memorable meeting, the engineering use of soil has been revolutionized, typified perhaps by the fact that there is now under construction a dam consisting of nothing but soil, 924 feet high, with completion and safe performance assured. Behind all such achievements lies a great body of theory of soil action, not generally relevant to geology; a well-developed expertise in the taking of so-called "undisturbed samples" from great depths, providing specimens of soil in their natural condition (with the single exception of stress release) for the laboratory; and a continually developing suite of laboratory tests, without the results of which no civil engineering project of today would be complete.

This broad coverage includes the study of all fragmented materials from sand and gravel, through compact glacial tills, to the most sensitive of clays. The types of test will vary depending on the character of the soil, but the element of accurate measurement is always dominant. Correspondingly, not only Pleistocene soils are so studied in the field and in the laboratory, but soils of any geological age that may have to be used for engineering purposes. In England, for example, quite extensive studies have been carried out, using regular techniques of soil mechanics, into the properties of the Keuper Marl of Triassic age (Kolbuszewski and others, 1965). It would appear that the wider use in geological studies of the accurately measured properties of soils might have something to contribute to the advance of geological understanding. The oft–quoted dictum of Lord Kelvin, "when you can measure what you are speaking about, and express it in numbers, you know something about it," has assuredly been taken to heart by those who have to study soils for engineering purposes.

The first and most obvious test for all students of soil is the determination of the distribution of particle sizes. In soil mechanics practice this is carried out by a combination of sieving (down to the No. 200 sieve) and a simple application of Stokes's law for the fall of a solid from suspension; the results are usually recorded as a semilogarithmic plot. One would imagine that there would be general agreement as to the limits of the main divisions of soil particle sizes, but unfortunately this is not the case, despite a number of attempts at agreement. The Soil Science Society of America is now making one more attempt to introduce uniformity into the situation summarized in Figure 2, an effort which this Society is supporting through its Division of Engineering Geology, and one which, it is hoped, will succeed.

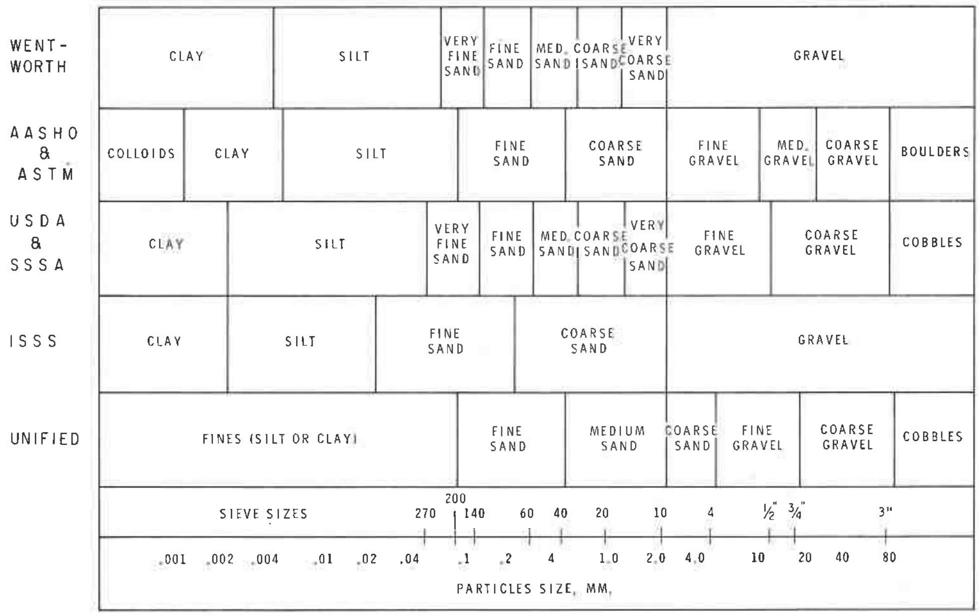


Figure 2. Subdivisions of soil by particle size in current use.

Despite the acknowledged limitations, for engineering purposes, of mechanical analyses of soils, they do provide some assistance in the recognition of frost–susceptible soils and in compaction and permeability studies. Naturally, they provide guidance as to the differentiation of the main groups of uniformly graded soils: gravels, sands, silts, and clays; and as to the grading of the mixtures of soil types such as are found in glacial tills. In the case of newly formed fine-grained soils of fresh minerals, generally the silts, there appears to be some evidence from northern Ontario that the degree of fineness of particles in silt and clay deposits may be related to their distance from centers of glaciation.

In a detailed laboratory study of varved clays from Steep Rock Lake, Ontario, Eden (1955) examined soil properties at intervals of about one fifth of an inch throughout a dark layer of a large varve just over three inches thick. The results are shown in Figure 4, grain size being indicated as the geometrical mean diameter (ϕ). The variation of particle size throughout the varve is clearly seen. This shows that the varves cannot be classed as diatactic, as suggested by Antevs (1951). This one diagram raises interesting questions about sedimentation which a detailed analysis of particle sizes might help to solve.

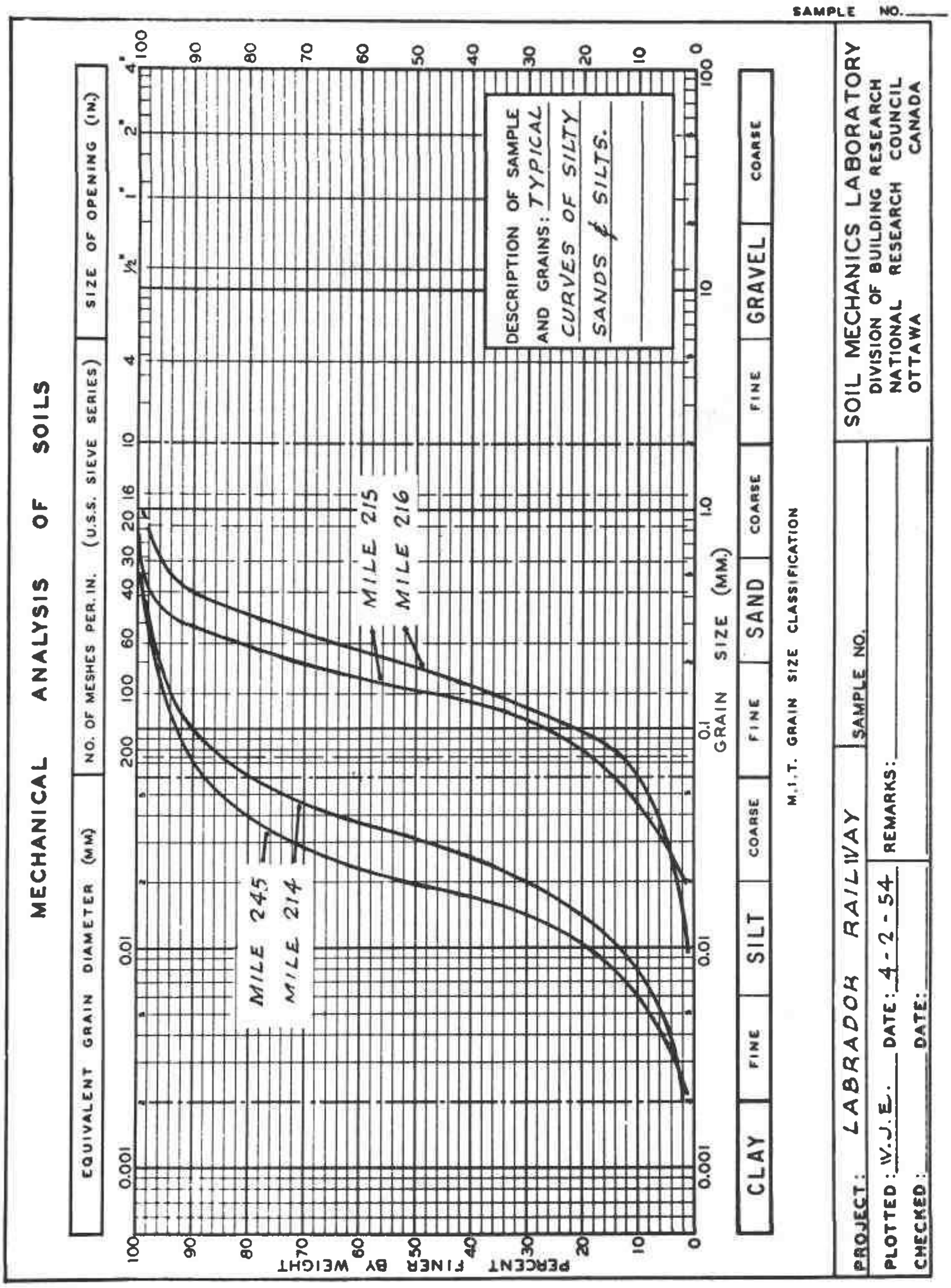


Figure 3. Grain size chart showing mechanical analysis of two soils.

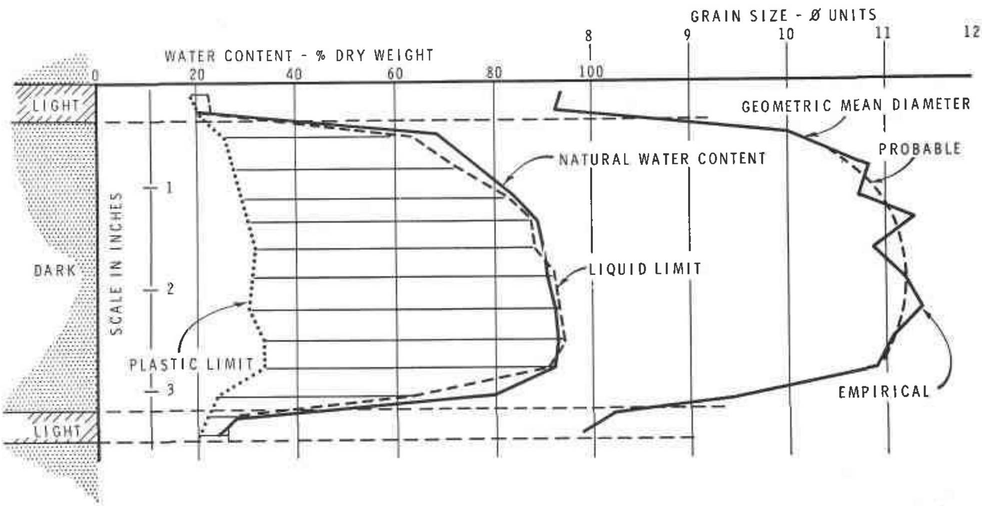


Figure 4. Variation of grain size, water content and plasticity within a varve (Eden, 1955).

It is, however, the mineralogical character of the particles in fine-grained soils that is rather more important than their size. The whole range of clay mineralogy is therefore of significant importance in civil engineering work. Only in special cases, however, it is economically possible to have detailed clay mineralogical analyses made. One such case occurred very early in this new phase of soil engineering, and in this city of San Francisco. Some may recall the Golden Gate International Exposition of 1938, and the creation of Treasure Island as the site in which a lagoon was a prominent feature. Clay lining had to be used about the sand-fill of the Island to form the pool. Although carefully placed, the clay proved to be permeable. The clay was known from tests to be a calcium-clay; the engineer responsible was familiar with cation-exchange and was assisted in his studies by soil scientists at the University of California. The lagoon was flooded with sea water for two months; fresh water was again introduced; the leakage had been reduced to a negligible amount. The lagoon was the focus of much attention from all visitors to that notable exhibition, few of whom probably realized how they were indebted to base-exchange for the beauty of the reflecting pool (Lee, 1941).

Fortunately, there is a "rough and ready" method available to provide quick guidance as to the mineralogy of fine-grained soils—the so-called Atterberg limit tests, adapted by engineers from early agricultural soil studies (Atterberg, 1911). They were brought to the attention of engineers by Terzaghi in 1926, refined and improved by A. Casagrande in 1932, and thereafter came into very general use. The tests involve the association of soil particles and water, a feature that invites attention to the three-phase character of soil: soil solids, air, and water.

If a fine-grained soil is allowed to dry naturally at normal temperature and is then ground up mechanically as finely as possible, the resulting powder will be a light air-solid system. If distilled water is then carefully mixed with the soil powder, the voids will gradually be filled with water, which will gradually replace the air. As an increase in moisture content takes place, a change in the consistency of the soil-air-water mixture will occur. Clay soils will gradually became plastic. As more water is added, the coherence of the mixture will decrease until eventually all the voids will be filled with water, and the addition of any more water will result in the liquefaction of the soil, the final stage being that of a free-flowing muddy fluid.

Atterberg developed two rather arbitrary tests in order to determine the solid-plastic and plastic-liquid transitions, the test results being expressed as the respective moisture contents, always given as the weight of contained water divided by the dry weight of soil solid. As refined by Casagrande, these tests have now been standardized. The test results, known as the plastic limit and liquid limit respectively, are widely used in engineering as "indicators" of soil properties.

The range of water content between the two limits is known as the plasticity index, being a measure of the plastic property of the soil. (See A.S.T.M., 1964, for details of the standard tests.)

Simple and arbitrary as these tests may appear to be, they have been found to be highly significant, and readily repeatable with accuracy by different operators. After plotting the "Atterberg Limits" for a great variety of soils, Casagrande developed a further empirical relationship, called for convenience the "A-line," shown in Figure 5 (Casagrande, 1948). Admittedly the use

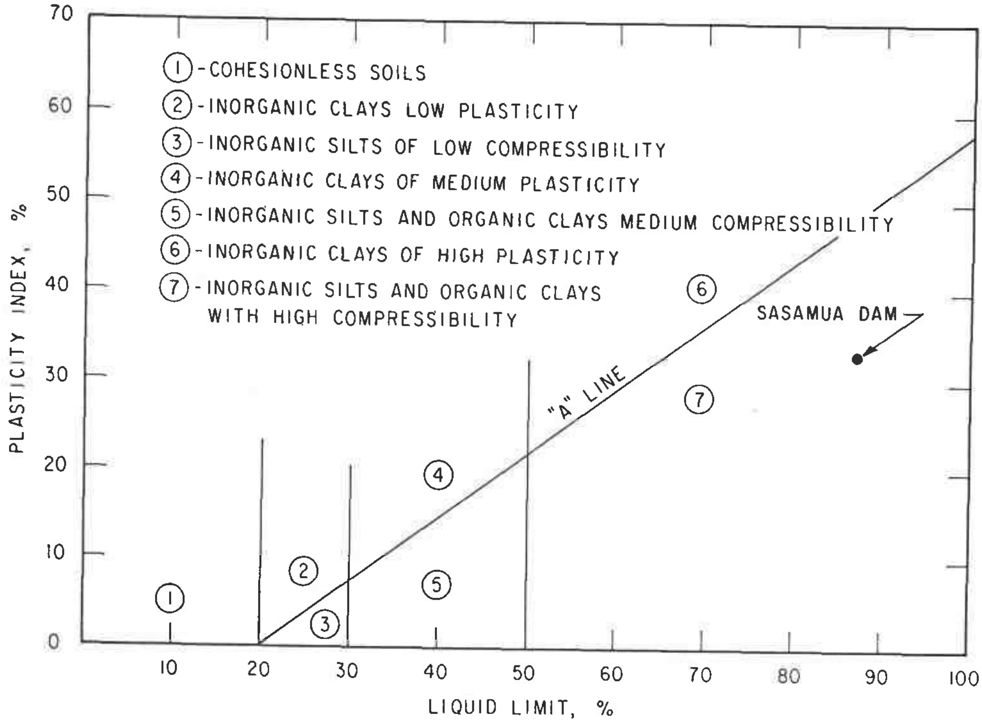


Figure 5. Plasticity chart (A. Casagrande, 1948).

of this chart is a rough guide only to the mineralogical character of soils, but it has been most useful in practical applications. Recent work at the University of California by H. B. Seed and others suggests that for artificially prepared fine-grained soils the ratio of plasticity index to the percentage of clay-sized particles (the "activity" of the soil as defined by Skempton) will be a good guide to the mineralogical composition, and that the same accuracy may be expected for natural soils, thus confirming the utility of Casagrande's earlier work (Seed and others, 1964).

An explanation of serious difficulties on a major engineering undertaking was suggested by the Atterberg limits for the unusual type of residual soil in question, which is noted in Figure 5 as being from the Sasamua Dam in Kenya. Difficult to handle with normal equipment, this soil was found to have a high plastic limit, but a much lower plasticity index than would normally have been expected, and a remarkable variation in the Atterberg limits depending upon the chemical used as a dispersing agent. A detailed mineralogical study disclosed that the soil consisted of almost 60 percent of halloysite, about 16 percent of goethite—unusual constituents that explained its unusual properties (Terzaghi, 1958).

That the Atterberg limits are good indicators of changes in the characteristics of more normal soils was clearly shown in studies by Rutledge and Romminger of soils deposited in glacial Lake Agassiz. By means of a statistical study of the results of engineering soil tests upon more than 300 disturbed and undisturbed samples, they were able to establish five stratigraphic units within

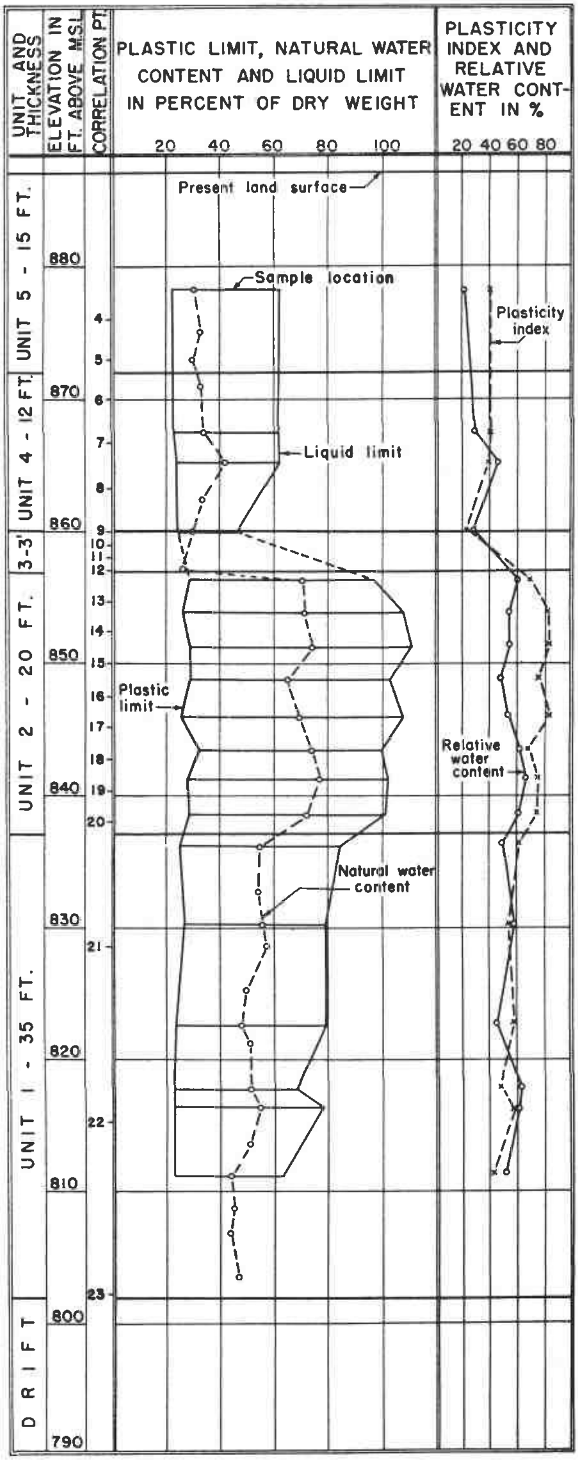
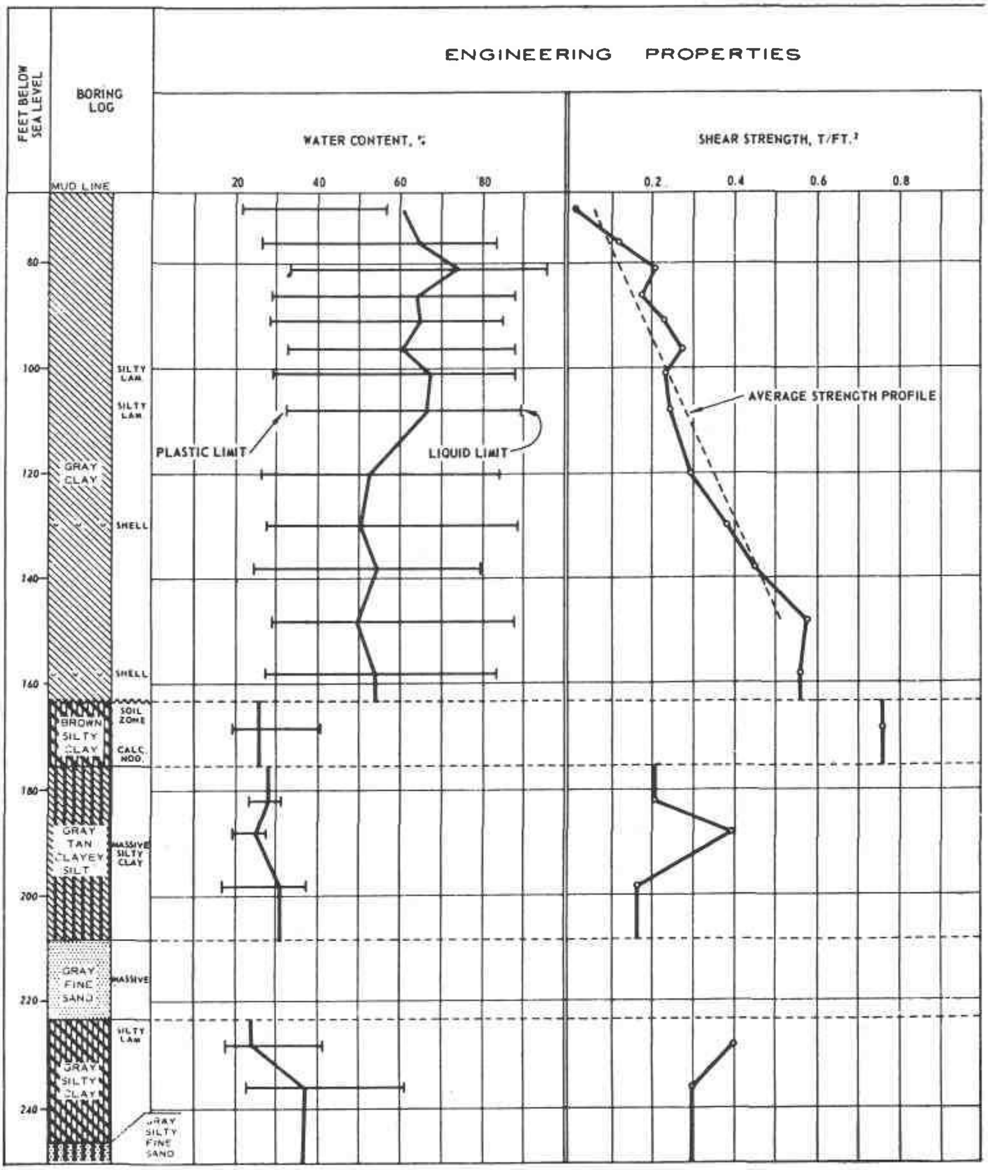


Figure 6. Typical boring log and soil test results from Lake Agassiz deposits (Romminger and Rutledge, 1952).

these sediments. This was pioneer work in the early 'fifties. It is somewhat surprising to find relatively few records of later geological work along similar lines (Romminger and Rutledge, 1952).

The potential that these simple tests present to geologists is shown even more clearly by the geological interpretation of the results of tests upon soil samples obtained while carrying out test drilling for the foundations for offshore oil drilling platforms in the vicinity of the Mississippi Delta. Fisk and McClelland summarized in a notable paper their co-operative work in studying the geological significance of the results of engineering tests (including the Atterberg tests) on soil samples obtained in the foundation investigations. Clear evidence of a sharp decrease in strength,



ENGINEERING AND GEOLOGIC DATA

Figure 7. Typical boring log and soil test results, Eugene Island, Louisiana (Fisk and McClelland, 1959).

among other things, was found at a depth of 164 feet below sea level, clearly marking the upper surface of the late Pleistocene sediments known to underlie the more recent deltaic deposits (Fisk and McClelland, 1959).

It is not only with recently formed soils that these simple tests can be geologically so significant. P. G. H. Boswell was one geologist who regularly used Atterberg limits in his studies of *Muddy Sediments*, the somewhat unusual title which he gave to a little book in which he summarized his investigations (1961). His many results for soils from a variety of geological horizons showed a mode of about 20 percent for the plastic limit which, he observed, "is close to the natural moisture content of Cenozoic, Cretaceous and Jurassic Clays." The coincidence is not without interest, as Boswell says, and even though it may be due to the selection of commonly occurring plastic clays for testing and industrial use, it yet points the way to another unexplored avenue of geological inquiry of potential scientific value.

It will now be clear that, in any study of fine-grained soils, the water associated with the soil solids will always be of significance. What of the water that is found in natural association with soil particles? Usually, it will be found to be relatively pure water with no more impurities than the fresh water of clear streams of today. When, however, fine-grained soils have been deposited in sea water, some of the original salt content may have been retained in the pore water of the soils. Although the same soluble ions as in sea water are found, for example, in the sensitive marine clays from southern Norway and in the Champlain Sea deposits of eastern Canada, the relative proportions of the various ions are not the same as in sea water of today. The ratio of the chloride to the sulphate ions, for example, is about 7:1 in sea water, whereas Rosenquist has reported a ratio of 1:4 for an Oslo clay (1955). He has also found clays with a total salinity of pore water of 3.8 percent which is about 0.6 percent greater than the normal salt content of sea water, a difficult phenomenon to explain. These characteristics of the pore water of marine clays are closely related to their sensitivity but the relationship is complex, involving also electrolytic factors. Penner, working on clays of the Ottawa area, has shown that the electro-kinetic potential of the Leda clay increases consistently with increase in the sensitivity of the clay (1965). He also has studied the leaching of the Leda clay, and its carbonate content, with results that raise interesting questions about recent geological explanations of variations in the Leda clay.

One would imagine that, irrespective of any salt content in natural pore water, the natural water content of normal soils in place would be below the liquid limit. If the soil is clearly in a solid state, how could it be otherwise? But fine-grained soils are regularly encountered in glaciated areas where the natural moisture contents are indeed above their liquid limits, and sometimes appreciably so. A typical record for a test hole through such a soil is shown in Figure 8. Since there is no doubt about the validity of such test results as shown for this case—even though when first encountered they are naturally viewed with skepticism—there must be something unusual about the way in which the pore water and the soil solids are associated.

Soil structure, in an engineering-mineralogical sense, must therefore be considered. It can readily be demonstrated that such soils have what was first described by soil mechanics workers as a honeycomb structure, resulting from interparticle attraction at the time of deposition. Early work of Goldschmidt was found to be relevant to this problem; he had described the structure as that of unstable card-houses (1926). Lambe and Rosenquist supported this view, but it was not until electron microscopy could be used that this type of internal structure was positively identified (Lambe, 1953; Rosenquist, 1959). Despite this internal structure, soils of this type in their natural position will be quite solid to the touch and often will possess considerable strength if not disturbed. Once disturbed, however, the internal structure will be destroyed, the excess water will be released and will very rapidly convert the previously solid material to a fluid.

The vital importance of this soil property in engineering practice can readily be appreciated. Its geological significance arises from the fact that natural disturbance of such soils, as by an earthquake shock, or through progressive erosion at the toe of a slope, will result in mass movements that will be characterized as landslides. A variety of reasons for the occurrence of landslides in areas covered by sensitive clays will be found in even recent geological literature, such as their mineralogy, or the character of the salt content of the pore water, but a simple check on the natural moisture content in relation to the Atterberg Limits will quickly disclose the real cause. Even without laboratory facilities for carrying out the indicator tests, clays that do contain this "excess" of pore water can readily be detected by merely working a small sample between the

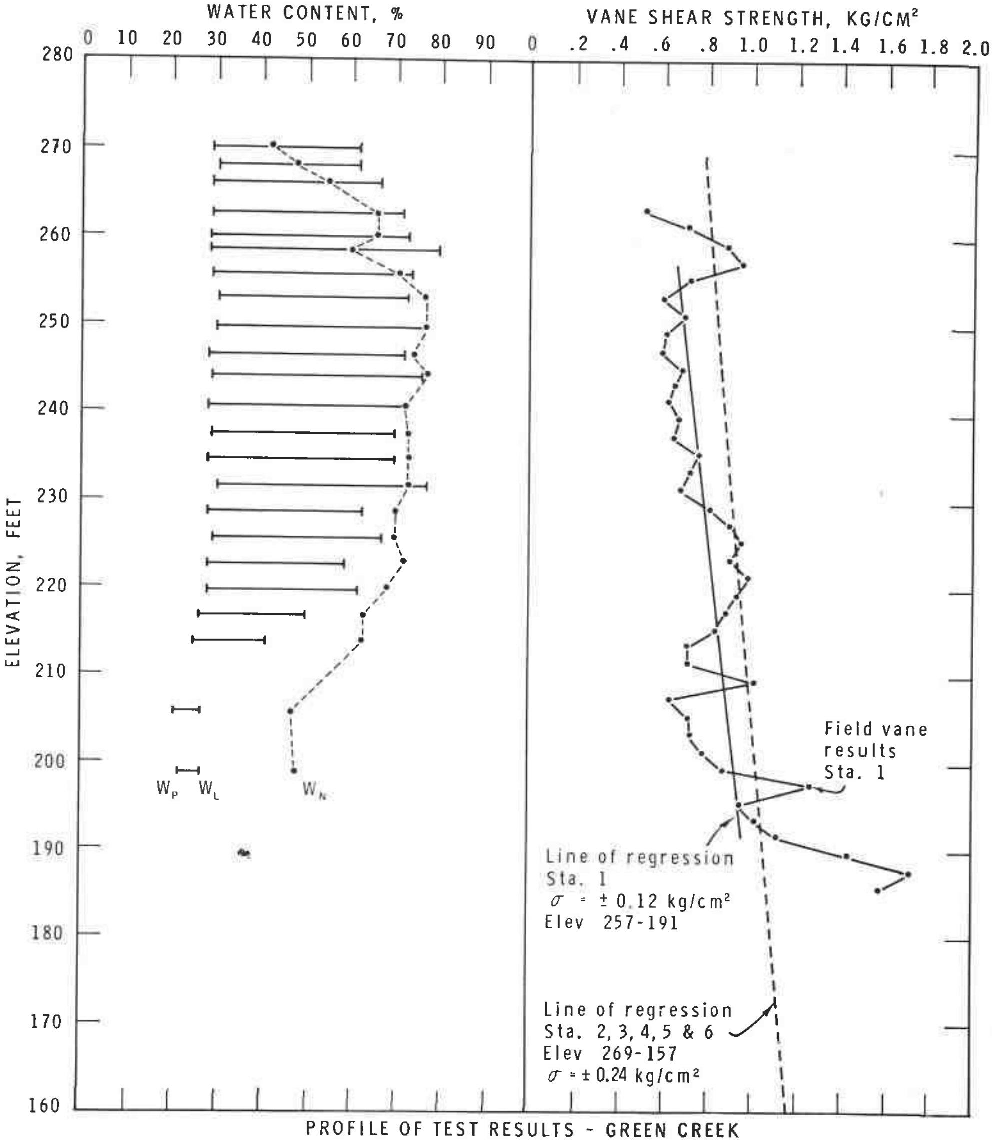


Figure 8. Variation of soil test results with depth in Leda clay, showing natural water content greater than liquid limit.

fingers. This will quickly display the sensitive character of the soil, as the excess pore water makes itself evident, with the obvious attendant implications if the soil is being disturbed by engineering works.

One of the most notable areas in which these sensitive clays occur is that which was once covered by the Champlain Sea, roughly the lower parts of the St. Lawrence and Ottawa River valleys. (Is there any other village in the world with a name equivalent to *Les Éboulements*, a small settlement one hundred miles below Quebec City, on the north shore of the St. Lawrence, founded on the detrital fan of a flow slide in the Leda Clay now centuries old?) Historical records provide graphic accounts of more than a dozen vast slides in this area. Examination of aerial photographs discloses innumerable old slides adjacent to almost all steep natural slopes in both the Ottawa and St. Lawrence valleys. These features are now so well obscured by the effects of vegetation and surface that they will usually be undetected in ordinary field studies of local physical geology.

When the actual mechanism by which such slides develop is studied, the initial cause having been recognized, consideration has to be given to one of the most important of all concepts in modern soil studies—the pressure in the water naturally contained within the pores of a soil. Now commonly referred to as merely the "pore pressure," it is allied with the concept of "effective stress" in a soil which has its seat exclusively in the solid phase of the soil.

The basic concept has been featured prominently in recent geological literature, notably in the dual papers of King Hubbert and William Rubey on the "Role of Fluid Pressure in Mechanics of Overthrust Faulting" (1959). Although these two authors make crystal clear their indebtedness to Terzaghi for his stimulus to their own thinking, through their gracious but properly qualified acknowledgment, one already encounters suggestions that the basic idea of pore pressure originated in the Rubey–Hubbert papers. These distinguished past Presidents would be the first to disclaim any such innovation, just as Terzaghi himself would have done, even though it was undoubtedly he who first focused accurate attention on the concept and first used it mathematically through his concept of effective stress.

If one "browses" through the pages of one of the later editions of Sir Charles Lyell's great work, the *Principles of Geology*, a salutary occasional experience for all geologists, one can see clearly in the working of his encyclopedic mind a general appreciation of at least the significance of pore pressure in soils. In his discussion of unusually interesting studies of soils in Egypt, in relation to the settlements of ancient monuments, Lyell almost enunciates some of the principles of soil mechanics, including that of pore pressure (1872). A. W. Skempton has noticed an even more definite indication of this in Lyell's *Student's Elements of Geology* from which he quotes the following words in a notable review of Terzaghi's "Concept of Effective Stress" (Skempton, 1960).

> When sand and mud sink to the bottom of a deep sea, the particles are not pressed down by the enormous weight of the incumbent ocean; for the water which becomes mingled with the sand and mud resists pressure with a force equal to that of the column of fluid above.

The use made of these basic concepts by Hubbert and Rubey was in relation to a phenomenon of solid rock formations. Their suggestion that "the phenomena of soil mechanics (represent) in many respects very good scale models of the larger diastrophic phenomena of geology," although perhaps implying unwittingly that the scientific study of soils is not geology, yet indicates another bridge between different disciplines in the earth sciences that suggests real potential for progress. Certainly when one reviews the progress made in the study of the shear strength of soils, and notes the more recent work on the shear and compressive strengths of rock, one finds a unity of approach that belies semantic boundaries.

Rubey and Hubbert illustrated the earlier soil mechanics approach to the shear testing of soils through the use of a rectangular shear box to which is applied a planar shearing force. Although still of value, and still in use in a variety of forms, this type of soil shear test has been overshadowed in recent years by the so–called, and much more versatile, triaxial test. Cylindrical soil samples are used, carefully mounted between loading plates and so arranged that they can be surrounded by a suitable fluid, through which they can be subjected to predetermined principal stresses additional to that imposed by the external axial load. By using flexible impermeable membranes to hold the samples, this type of test can be used for almost all types of soil, from coarse sand to clay, and in natural or disturbed (remolded) states. A simple version of the test omitting

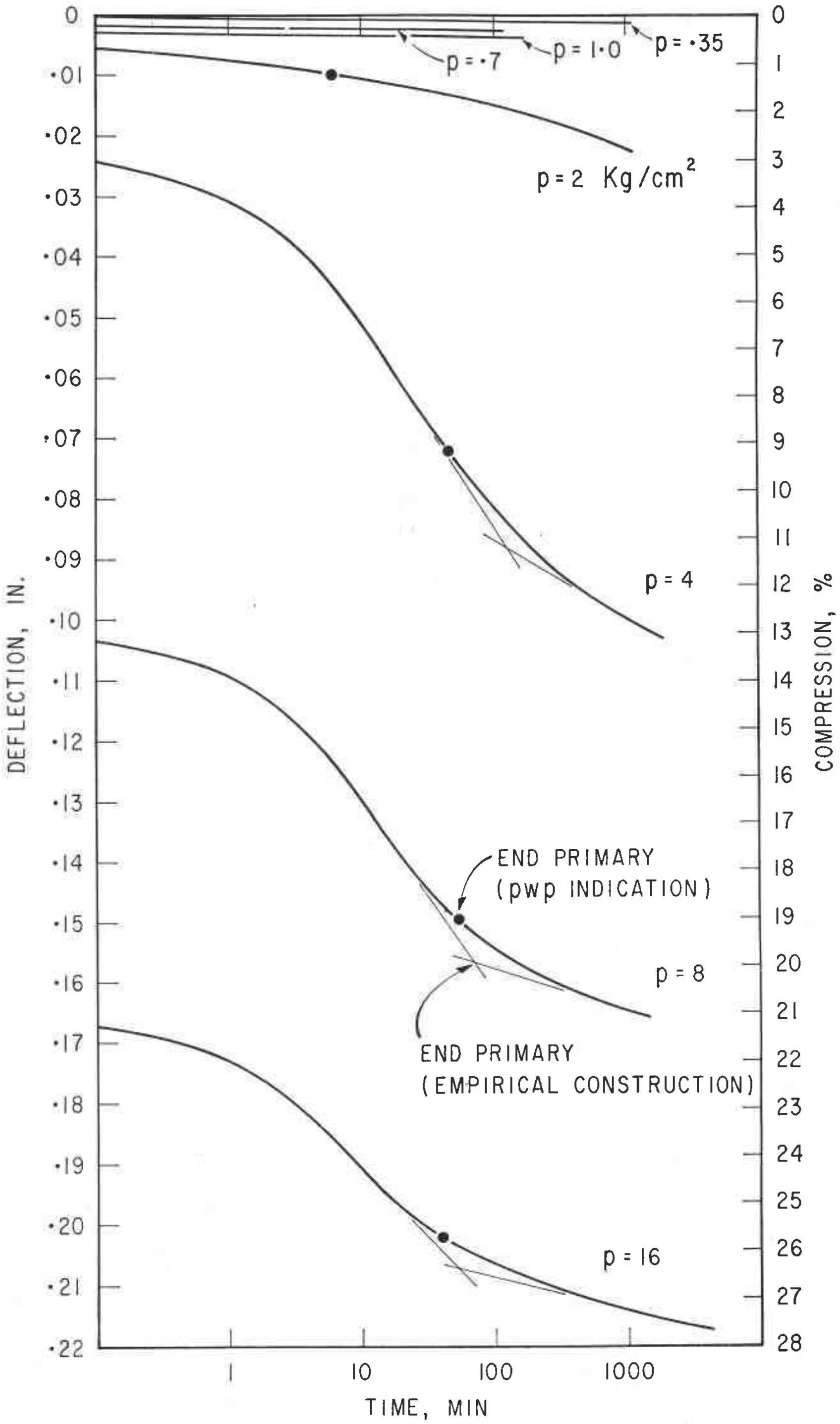
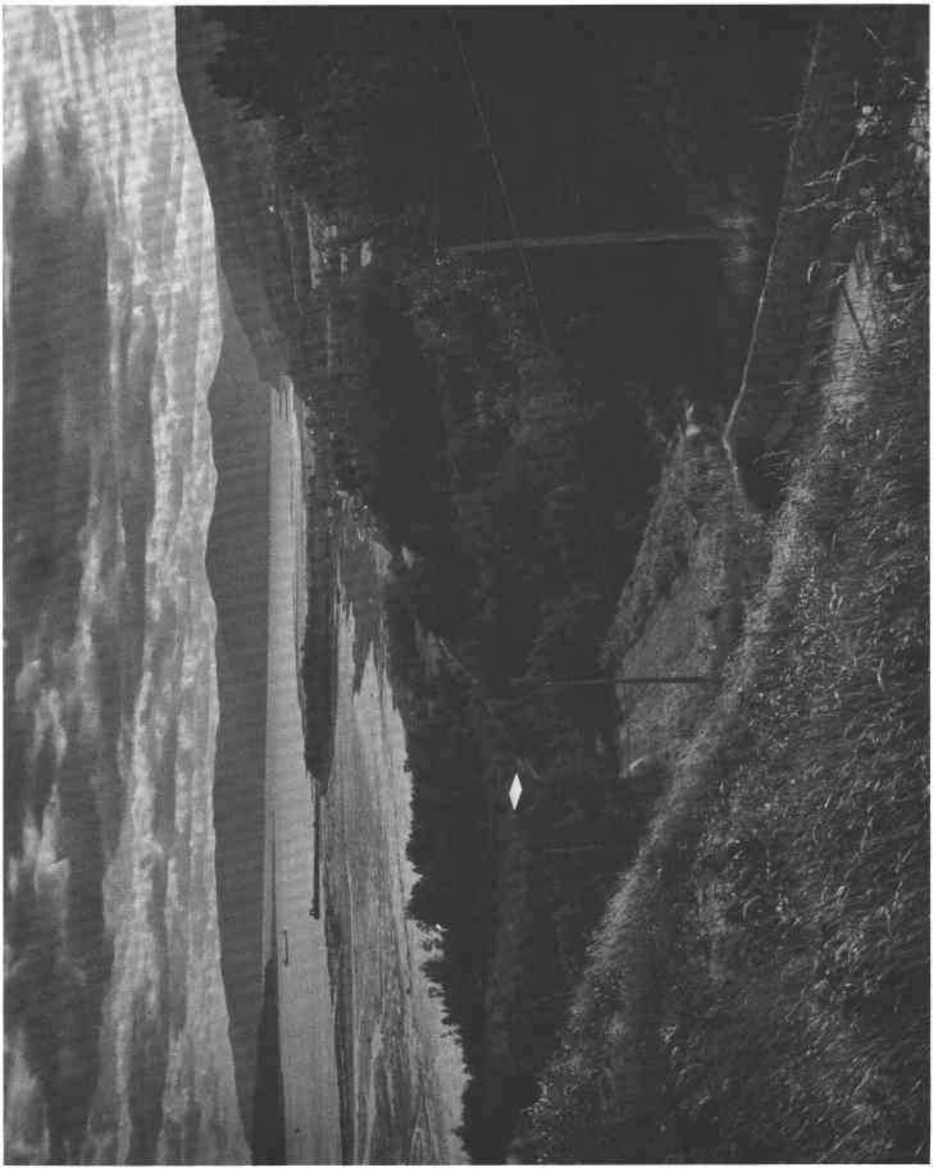
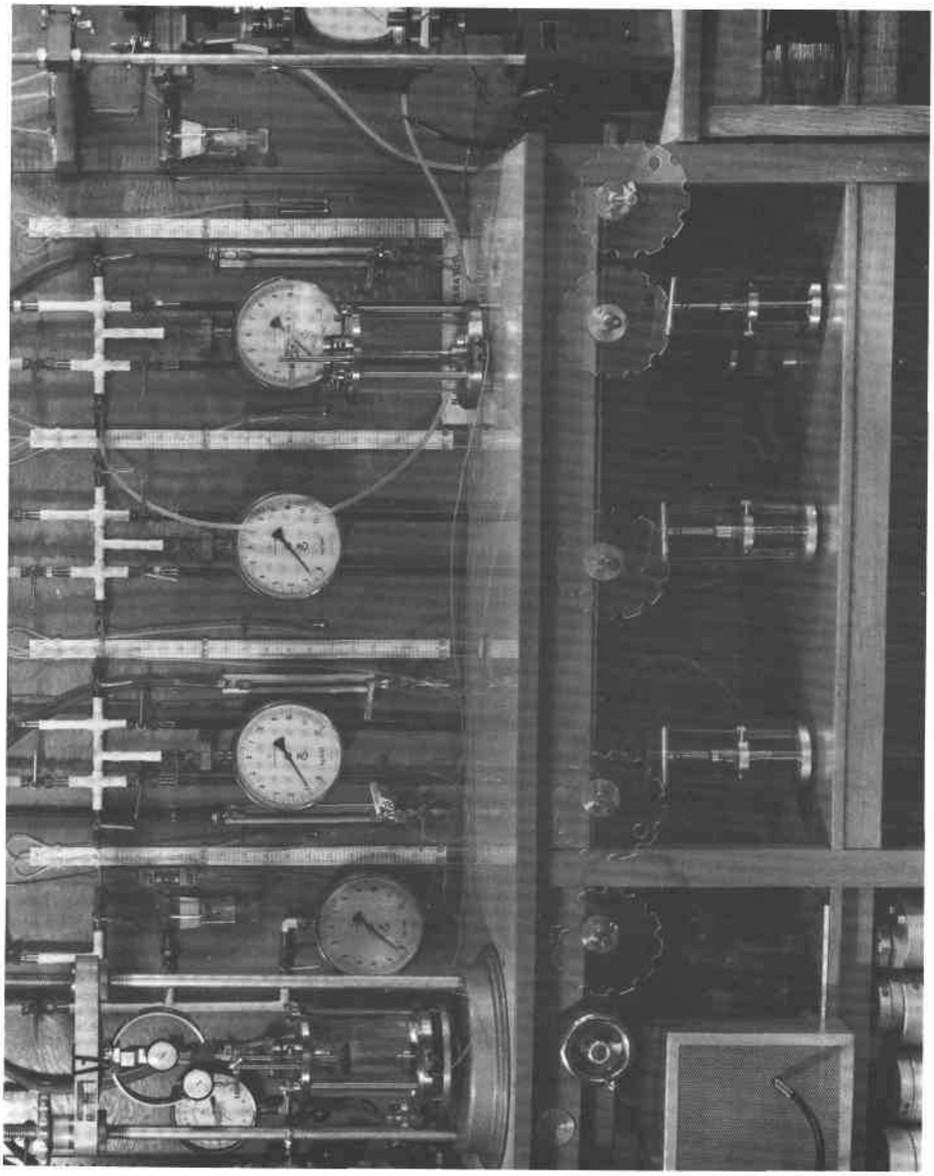


Figure 9. Time–deformation curves obtained from a consolidation test on Leda Clay (Crawford, 1964).

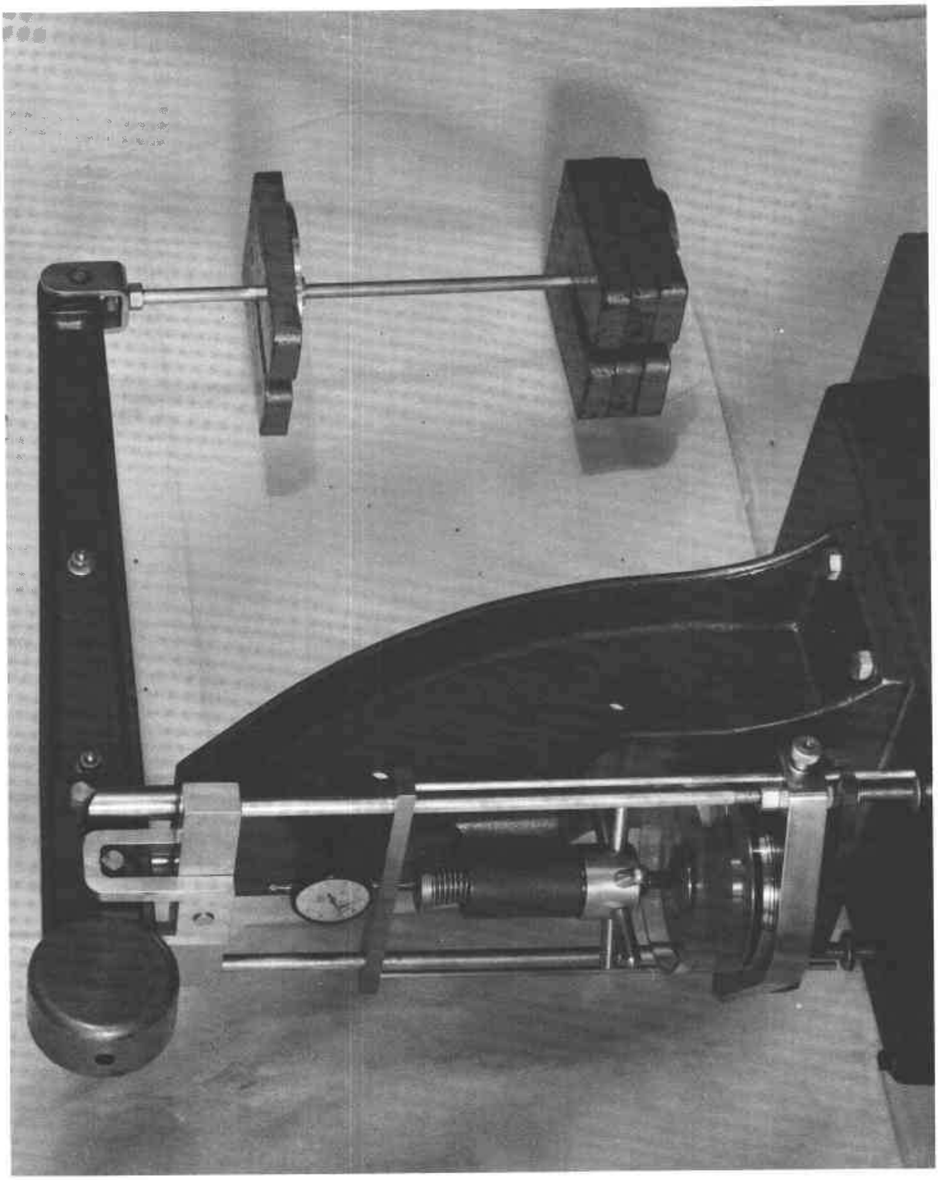


The village of Les Éboulements on the north shore of the St. Lawrence River, east of Quebec City.

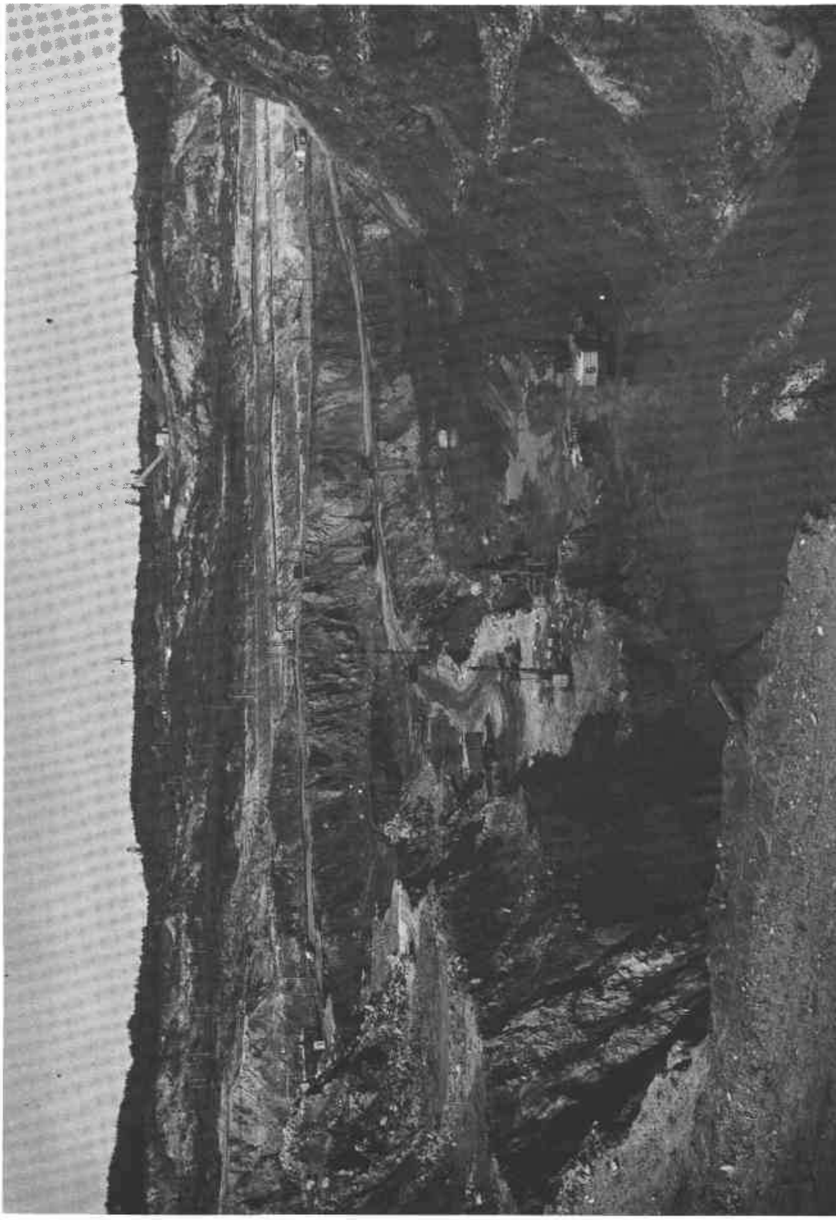
Typical old landslide in Leda Clay, one mile from Building Research Center, Ottawa.



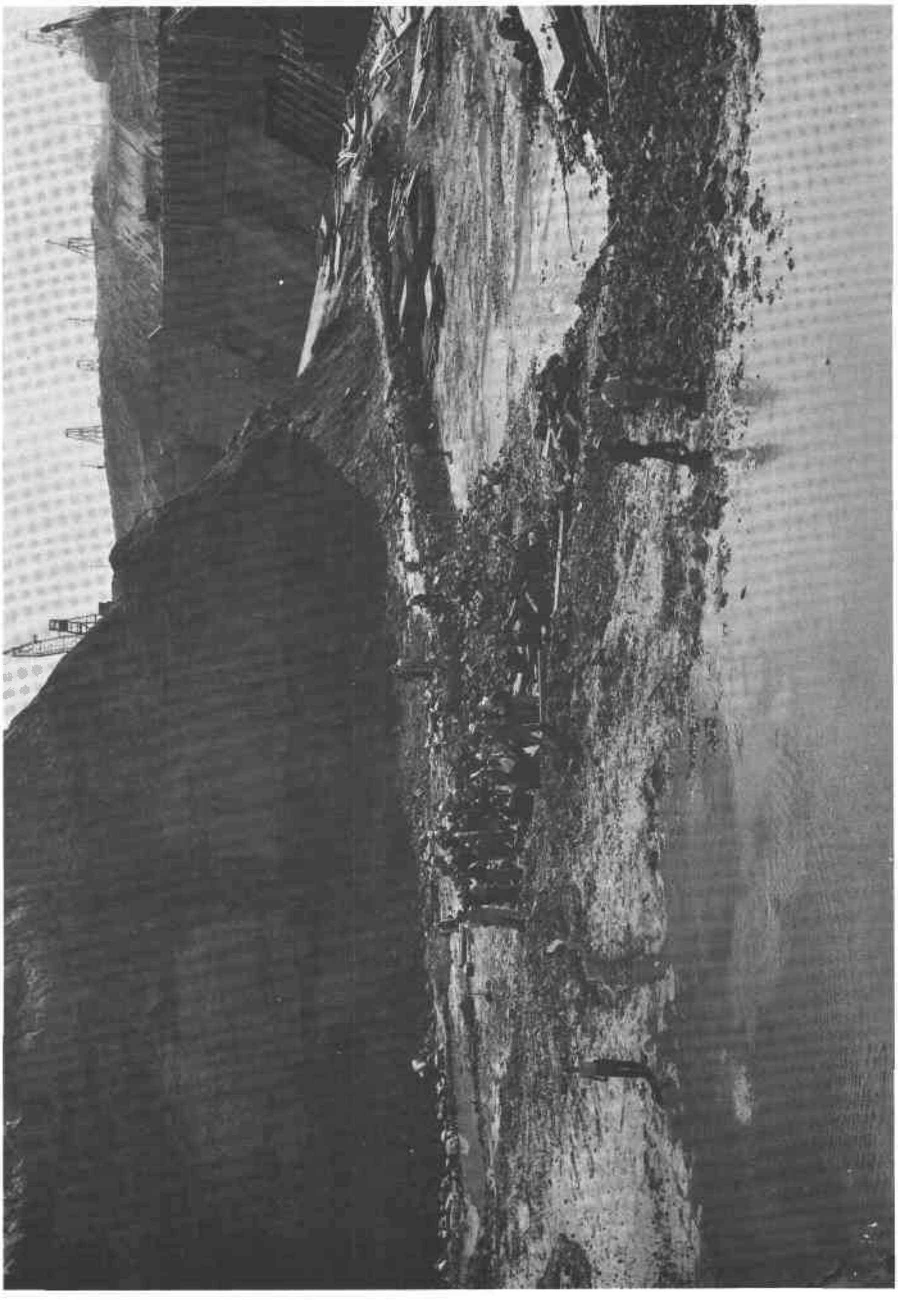
Triaxial shear test equipment; membrane-enclosed soil samples are placed in the transparent cylinders and subjected to fluid pressure and vertical loading.



Consolidation testing of a soil sample in progress, loading and deflection measuring devices being clearly seen.



Bed of Steep Rock Lake, Ontario, after drainage of lake and excavation of 150 feet from the old bed, iron ore being excavated in open pit; all the soil visible is varved clay generally with its natural moisture content above its liquid limit, stable slopes and benches having been designed using soil mechanics techniques.



Bed of the St. Lawrence River as exposed near the Long Sault Rapids (Malone, New York, and Cornwall, Ontario), showing the two tills thus exposed; the figures are of the Friends of the Pleistocene.

the enclosure of the sample, the unconfined compression test, can be used for the rapid evaluation of the strength of cohesive soils, even in the field through the use of a portable testing device.

One aspect of the compressive testing of soils has considerable geological significance: the consolidation test. Another unfortunate semantic difficulty has to be faced. In recent geological literature the word "compaction" is used to denote the *natural* compression of soils, such as clay, whereas the term "consolidation" has been used in soil mechanics work for the same purpose ever since the basic theory of this action was first enunciated by Terzaghi, in English, in 1925. Correspondingly, and for almost as long a period, workers in soil mechanics have used the term "compaction" to denote the *artificial* compression of soils that have been disturbed from their natural position, as by the operation of sheepsfoot rollers in the construction of earth dams and embankments. Here is yet another reason for desirable liaison between workers in different fields of earth science.

One of Terzaghi's many great contributions to the study of soils was his explanation and mathematical formulation of the consolidation, under load, of clays (1926). As an external (vertical) load is applied to a clay stratum, some of the pore water will be forced out of the voids in that part of the soil that is subjected to appreciable increased stress. It will then move slowly away from the highly stressed region under the hydrostatic gradient caused by the pressure that has been induced. The void ratio will decrease and the surface of the clay will settle, due to what is termed "primary consolidation." In many cases there will occur additional settlement, usually of minor degree, due to the rearrangement of the constituent solid particles under stress, but with no change in pore pressure, this being called "secondary consolidation."

By making certain reasonable but simplifying assumptions, Terzaghi was able to prove that

$$\frac{\delta u}{\delta t} = C_v \frac{\delta^2 u}{\delta z^2}$$

where u is the pore-water pressure
t is the elapsed time
C_v is the coefficient of consolidation
z is the depth below the surface

all expressed in appropriate units. C_v is dependent upon the void ratio of the soil, which is defined as the ratio of the volume of voids in the soil to the corresponding volume of soil solids, the permeability of the soil, the unit weight of water, and the coefficient of compressibility. This last factor is obtained from the results of the consolidation test; there appears to be some relation between this value and the liquid limit, but this is only one of several interrelations of soil characteristics that have yet to be fully explored.

This differential equation is the basis of the theory of consolidation. It is often called the "Terzaghi Equation." With its use, it is possible to determine the theoretical magnitude of the settlement to be expected under a building founded on clay, and the rate at which this will take place. Comparisons between such theoretical results and observations of actual settlements are not always as close as is desirable. This has led to extensive research, still in progress, into many aspects of the consolidation test. The test is conducted in a relatively simple apparatus, a cylindrical sample of soil (at its natural moisture content) being confined in a metal ring and held between porous plates of diameter such that they can move within the cylinder. Typical dimensions are an area of 20 sq cm and a height of 1 or 2 cm. The upper plate can be loaded through a suitable mechanism, and with appropriate instrumentation the consolidation of the specimen can be measured against time. A semilogarithmic plot of a typical test on Leda clay with incremental loading is shown in Figure 9 (Crawford, 1964). A more usual way of plotting consolidation test results is shown in Figure 10 and on this has been indicated the graphical construction by which the preconsolidation load can be estimated.

The shape of the experimental curve in Figure 10 suggests that the first part of the sample consolidation is not quite the same as the main part of the curve, which represents the effect of what is really the second loading upon the soil, that is, after it has been removed from the ground. If it has previously been loaded, while still in its natural position, this will be indicated by this first section of the experimental plot. It has been generally agreed to denote the "preconsolidation load" as that given by the intersection of the tangents to the first two parts of the plotted consolidation record. If only to indicate some of the questions in this field that are still unanswered, Figure 11 is included to show that, for some types of clay at least, the rate of loading in the test is of considerable significance. Crawford's work shows clearly that all the problems in soil mechanics are not yet solved—far from it. The phenomenon of consolidation is but one of the many areas of interest currently under active investigation throughout the world in this very lively branch of the earth sciences.

Despite some remaining uncertainties in special cases, attention is invited to the information about the superficial load to which the soil being tested has been subjected naturally, so readily obtainable from the standard consolidation test. Only very rarely will this have been due to recent

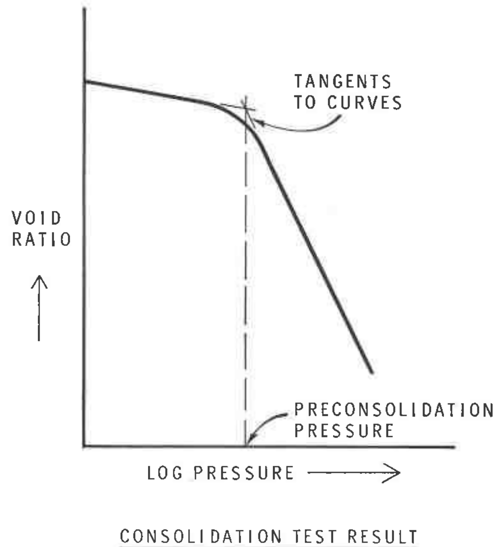


Figure 10. Schematic pressure–void ratio curve from consolidation test.

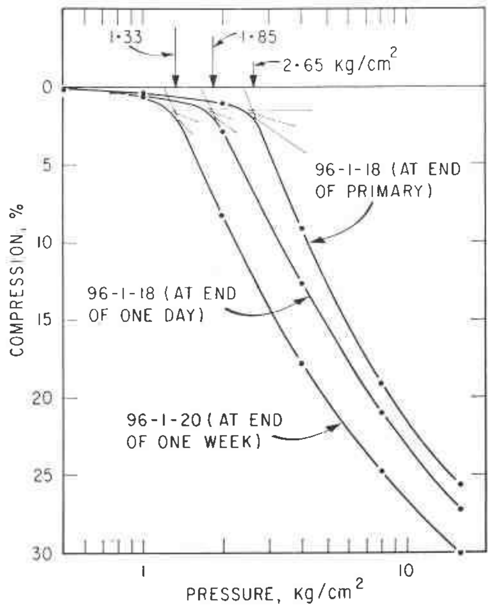


Figure 11. Influence of rate of loading on compression–pressure curves for Leda Clay (Crawford, 1964).

artificial loading of the clay, as by a building or an earth fill, or of the weight of a layer of soil that has only recently been removed. In almost all cases, the preconsolidation load as determined by this simple soil test will be a measure of the load to which the soil has been subjected in the course of its geological history. It may, therefore, be a measure of the depth of soil that has been eroded from the site, and in glaciated areas may even give some indication of the depth of ice that has rested upon the soil in question (see, for example, Harrison, 1958).

Figure 12 summarizes some of the consolidation test results obtained by Crawford and his colleagues for the Leda clay of the Ottawa area; the general correlation between elevation above present sea level and preconsolidation pressure will be clear. The three sets of records for clay from Green Creek illustrate yet another of the areas of continuing investigation. The two lower curves are based on results from samples obtained by ordinary "commercial" boring; the upper curve was obtained using samples procured by refined sampling methods (using very thin-walled samplers) and with improved testing methods. Although the variations are significant, they do not invalidate the general utility of the correlation. They point the way to even more accurate preconsolidation load determinations (Crawford, 1961).

Kenney (1964) has approached this broad problem from the other direction, by assembling geological records with which to develop the curve of eustatic sea-level movement for the late Pleistocene period shown in Figure 13. He then correlated this basic record with the results of consolidation tests upon soils from Boston, Nicolet, Ottawa, and Oslo; those for Oslo and Ottawa are shown in Figures 14 and 15. He suggests that both areas have been subjected to one period of submergence, followed by emergence, erosion, and weathering. For Oslo, the preconsolidation load as determined by test agrees with the geological evidence, but the test results for the Ottawa clay show some variation from the geological history as deduced by Kenney, features that are currently under investigation.

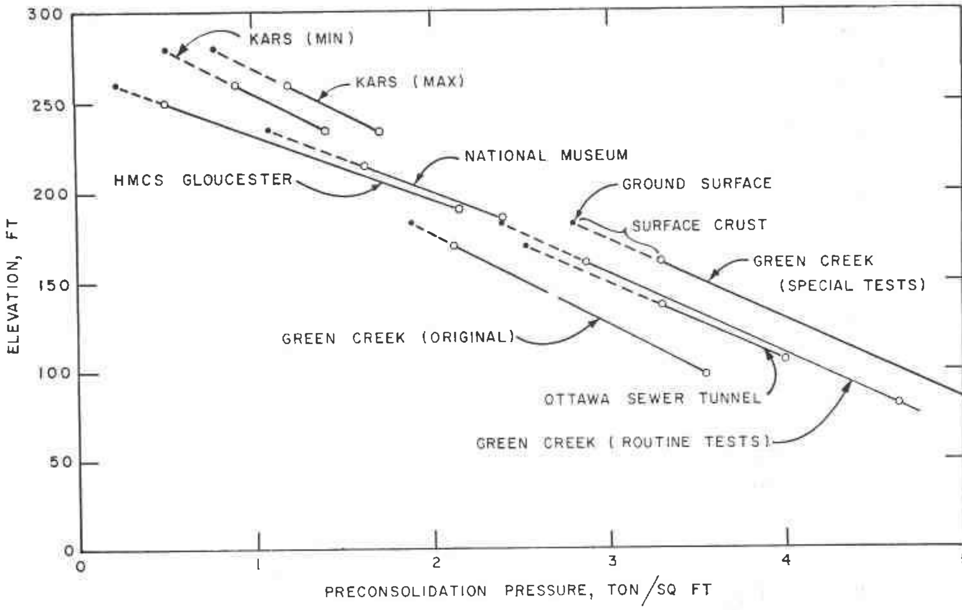


Figure 12. Relation between preconsolidation pressure and elevation for Leda Clay in Ottawa area (Crawford, 1961).

These diagrams show that glacial clays can reveal much about their geological history when samples are suitably tested in a soil mechanics laboratory. The same phenomenon can be demonstrated in similar and other ways for other types of soil—glacial tills, clay shales, and even sands, for which the relative density in place is a most useful indicator. In effect, soils have much of their history built in, in a manner comparable to that in which many solid rocks will indicate something of their history as, for example, by argon dating. With this demonstration of the interrelation of soil mechanics tests carried out in the laboratory and the Pleistocene geology of the field, with overtones provided by differential calculus, the case for the mutual interdependence of soil mechanics and geology may perhaps rest, and attention be directed, finally, to some rather more general considerations.

One sometimes hears it said by geologists who have some appreciation of the value of the tools that soil mechanics studies have made available to them, that it is "too bad that soil mechanics ever got away from geology." This lament is sometimes associated with similar regret, regret that is much more widely felt, at the actual separation of geophysics from geology, now more than thirty years ago, a separation that is most fortunately slowly disappearing. There is, however, no direct parallel between these two aspects of the development of the earth sciences, for the work done in soil mechanics has, from its start, been stimulated by the vital necessity for solving the constructional problems of the civil engineer. Without the imperative of these severely practical demands, nothing like the progress that has been made in these thirty years would be in evidence today. The more theoretical results of soil mechanics studies have been almost by-products of work that was started in response to demands from the practice of engineering. It is, therefore, useless to do other than to accept the situation that exists today with one vital and overriding

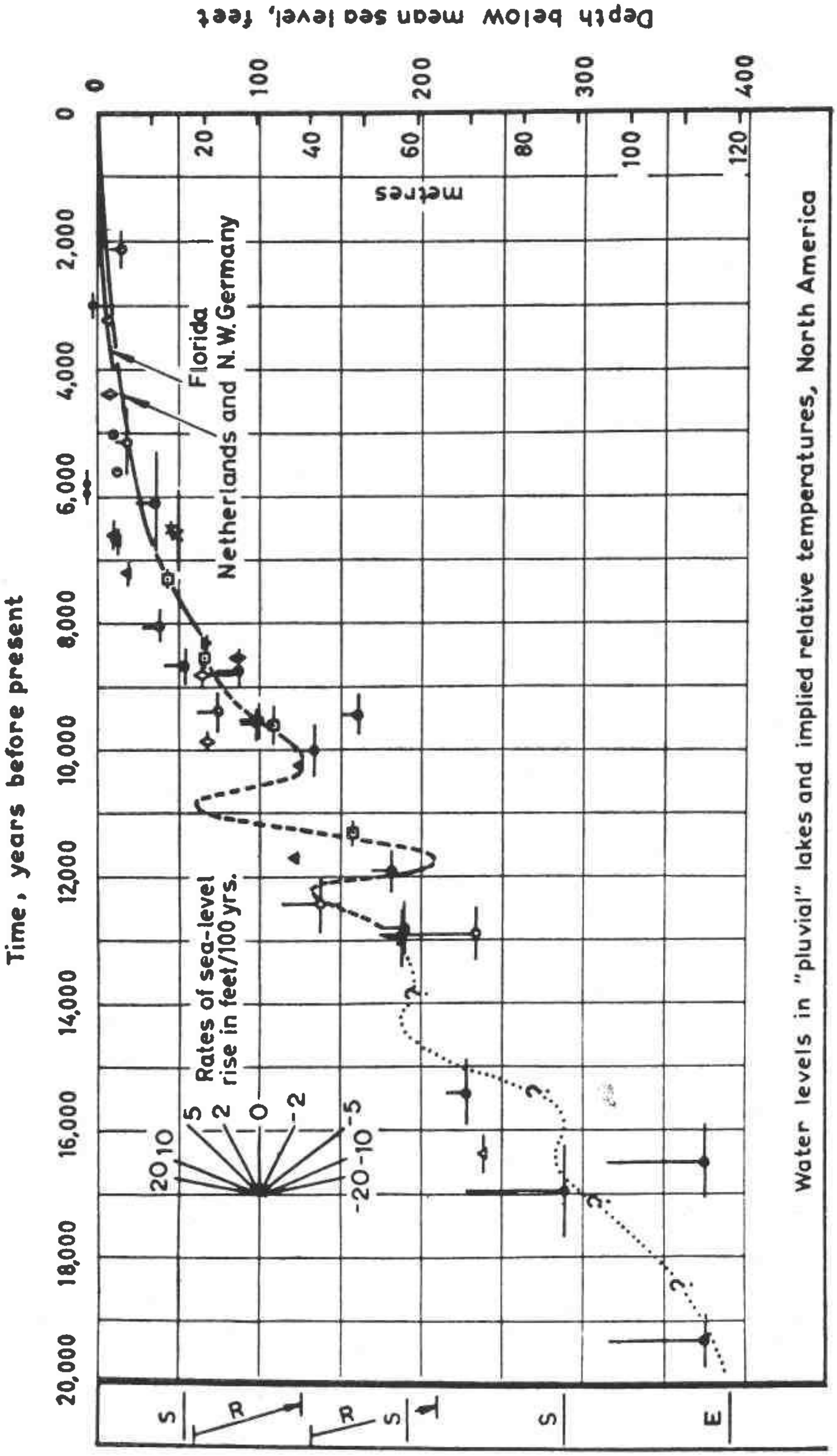


Figure 13. Eustatic sea-level movement curve for late Pleistocene period (Kenney, 1964).

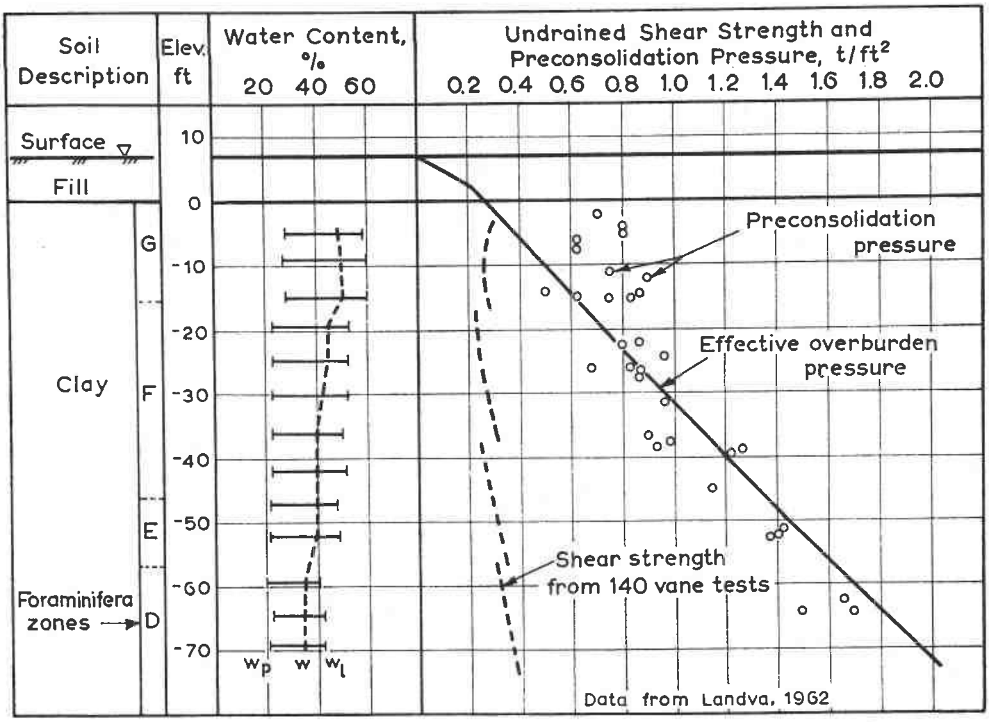


Figure 14. Oslo–Skabo. Soil profile and geotechnical test results (Kenney, 1964).

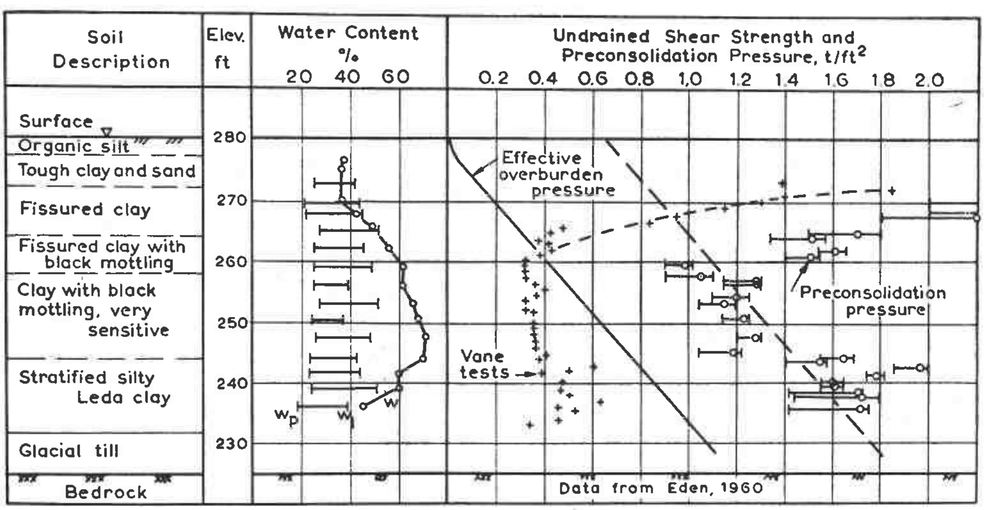


Figure 15. Ottawa–Kars. Soil profile and geotechnical test results (Kenney, 1964).

proviso—that there must be the closest possible collaboration, mutual respect, and joint activity between workers in soil mechanics and geologists, just as there should be between workers in every branch of earth science. Ecumenicity is a word much in vogue today. How appropriate it is when applied to the earth sciences, especially when one recalls the Greek origin of the modern word. It is a word that should issue a ringing and continuing challenge to all who are interested in the science of the earth—a challenge to work closely together, in harmony, sharing methods and findings, all working toward the same major goals, pursuing parallel paths but with no artificial barriers between, not merely for the sake of working together but with a view to cross-fertilization. If this talk is nothing else, it is at least a plea for geological ecumenicity.

Consider all the possibilities that co-operation of this kind presents even with regard to soils. Not only is there much to be gained by sharing laboratory techniques, but advances properly described as unique can result from co-operation in the field. Much soil mechanics work is necessitated by major excavation work in civil engineering. The exposures of soil thus revealed provide the geologist in almost all cases with opportunities for field study that he could obtain in no other way. All too often the exposures are covered up, as engineering work proceeds, without having been examined and recorded for posterity. It had been hoped to include, as an example, some results from laboratory tests on "blind" soil samples obtained in the Vancouver area (British Columbia) which might have lent some support to Armstrong's suggestion of marine-deposited tills (1954). Unfortunately, although the samples were obtained from carefully sunk boreholes, they were not suitable for accurate testing. New block samples will have to be obtained when deep excavations are opened up at suitable locations, desiccation to appreciable depths making deep samples essential. And these can be obtained only on engineering works.

It has been wittily remarked that a set of engineering test hole records is not geology! No engineer ever suggested that they were! But if the records and samples that test holes reveal are carefully studied by geologists, they can make unique contributions to geological understanding of an area. Much more so can the study aid during excavation, as it proceeds. It may be suggested, without any qualifications, that every university geology department should be alive to the possibilities presented in its own area for unique field studies; engineering co-operation is almost a certainty.

If only to show that in this matter, too, there is little that is new, a brief quotation from Sir Charles Lyell's diary of his first visit to North America in 1841 may be given (1845). Very shortly after he landed at Boston he found that "several excavations made for railways . . . through mounds of stratified and unstratified gravel and sand, and also through rock, enabled me to recognize the exact resemblance of this part of New England to the less elevated regions of Norway and Sweden. . . ." And when, on 14 June, 1842, he reached Toronto (population then, 18,000) he "found Mr. Roy, the civil engineer, expecting me . . . to examine (with him) those ridges of sand and gravel and those successive terraces, at various heights above the level of Lake Ontario, of which he has given an account in 1837 to the Geological Society of London." Co-operation in Toronto between geologists and engineers has continued. When Toronto started building its subway system, excavation penetrated the justly famous Toronto interglacial beds. Today a complete suite of soil samples from this excavation work in the heart of a great city is in the safekeeping of the Royal Ontario Museum, and in the literature of geology there are some useful interpretative papers (Legget and Schriever, 1960).

The draining of Steep Rock Lake in western Ontario, for the development of the important iron mine that operates there today, revealed what is probably one of the greatest exposures of varved glacial clays ever seen. Not only were these clays studied from the engineering standpoint, but the mine authorities gave every encouragement to a detailed study of the varves purely from the geological standpoint (Legget, 1958). Excavation for a new city hall for Hamilton, Ontario, provided samples and a soil profile that threw new light on the age of Lake Ontario (Karrow and others, 1961). The construction of the great international powerhouse on the St. Lawrence at Massena, New York, and Cornwall, Ontario, together with the associated navigation locks, necessitated excavation on a gargantuan scale, revealing much of the bottom of the great river for the first, and probably for the only, time in human history. MacClintock and his fellow workers made every use of this great opportunity and were given every possible assistance by the engineers responsible (MacClintock and Stewart, 1965). The exposures of till in the deep excavations assisted with the "unraveling" of the unusually complex Pleistocene geology of this interesting area.

So the record of studies already made can continue. What of the future? Here one may follow in the footsteps of past President King Hubbert who, four years ago, pointed ahead to some of the consequences of current population expansion (Hubbert, 1963). More recent figures, released by the United Nations, show that, provided the world—as all will pray—avoids a major calamity, and even allowing for some measure of birth control, the population of the world by the year 2000 will be at least 7.4 billion. Today it is about 3.2 billion. In little more than thirty years, therefore, the population of the world could double, and might even include an additional billion inhabitants beyond that incredible total. More recent studies still suggest that, before that point in human history is reached, a crisis will have developed with regard to the food necessary to keep such numbers from starvation. Agricultural soil scientists have their global challenge too, therefore, but our thinking may be confined merely to the challenge ahead of civil engineering, and so of geology.

Well before the end of this century, making even minimal allowance for some increase in the general standard of living—within the lifetime, therefore, of a majority of present members of the Geological Society of America—the engineers and architects of the world will have to build at least as many structures as exist in the world today—buildings, dams, roads, and all allied structures. And every single one of these structures must be built in contact with the ground, thus involving geology and usually excavation as well. In the years immediately ahead, therefore, there are going to be opportunities for joint study of the soil such as have never yet been imagined—joint opportunities and also joint challenges, since even today's phenomenal world rate of construction must soon be far more than doubled.

These are sober estimates and conservative statements. The great challenge will be in the field of applied geology, but the extent of these contributions will be matched by the vastly increased opportunities for field study of geology in new excavations. The advances in understanding of Pleistocene deposits that such study will make possible could well be remarkable, if the opportunities so presented are well used.

When it is appreciated that "the relatively short span of the Pleistocene brought greater changes to the face of the earth than any that have occurred during the previous seventy million years of the Cenozoic Era, the present boundaries between land and sea were [then] established, the earth obtained the relief it now has, much of the world's scenery was fashioned, and the physical and cultural evolution of man took place" (Ericson and Wallin, 1964), then perhaps the need for marshaling a concerted approach to the scientific study of the soil will be clearly apparent.

Gilbert's prophetic words of 1890 may fittingly be requoted, just as Russell used them in introducing his address nine years ago: "When the work of the geologist is finished and his final comprehensive report written, the longest and most comprehensive chapter will be on the latest and shortest of the geological periods" (Gilbert, 1890). These words re-echo as one stands fascinated in front of some new and quite remarkable contorted exposures found occasionally in Pleistocene deposits, or examines unusual soil structures under a powerful microscope. When it is remembered that much of what is studied in the Pleistocene has come to occupy its present position during the long course of the evolution of man, and that knowledge of prehistoric man is based very largely on what little has been found of his remains in Pleistocene deposits, then scientific interest deepens and the sense of wonder grows, with questions yet unanswered about all that is involved in the phenomenon of man and the ultimate purpose of scientific inquiry.

Fortunately, there has recently been among us—quite literally, for he attended scientific meetings in North America and wrote appreciatively of his residence at Berkeley—one who has faced these questions and essayed to answer them, a theologian, philosopher, and geologist extraordinary, friend and field companion of George B. Barbour, F.G.S.A. *The Phenomenon of Man* was the consuming interest of Pierre Teilhard de Chardin as he studied Pleistocene deposits in many parts of the world—China, South Africa, and even North America. His writings, most notable for the book with the title just quoted, are only now appearing in print; they have special appeal for many of his fellow geologists, even for this worker in the kitchen of science. Some do not agree with his geology; others differ from his biological views; and his great Order would not permit any of his writings to be published during his lifetime. But that he was a great and good man, all who have come to know him through his writings will agree.

That he was a geologist we should not forget, one who gained his inspiration by what he found in the soil and by his study of the soil itself. He has said, "I believe I can see a direction and a line of progress for life, a line and a direction which are in fact so well marked that I am convinced that reality will be universally admitted by the science of tomorrow" (de Chardin, 1961). And this from a student of soil.

The study of soil is surely not quite so mundane a matter as was suggested earlier. It is, rather, a truly vital part of the science of the earth.

ACKNOWLEDGMENTS

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APPENDIX A

GSA Presidential Addresses

(All references, with the two exceptions noted, are to the Bulletin of GSA)

1889 Hall, James, (Brief Historical Address) v. 1, p. 15–18, 1890.
1890 Dana, James D., (did not deliver an address due to illness).
1891 Winchell, Alexander, (A Last Word with the Huronian; delivered when acting President), v. 2, p. 85–124, 1891.
1892 Gilbert, G. K., Continental Problems, v. 4, p. 179–190, 1893.
1893 Dawson, Sir J. William, Some Recent Discussions in Geology, v. 5, p. 101–116, 1894.
1894 Chamberlin, T. C., Recent Glacial Studies in Greenland, v. 6, p. 199–220, 1895.
1895 Shaler, N. S., Relations of Science to Education, v. 7, p. 315–326, 1896.
1896 Le Conte, Joseph, Earth-Crust Movements and their Causes, v. 8, p. 113–126, 1897.
1897 Orton, Edward, Geological Probabilities as to Petroleum, v. 9, p. 85–100, 1898.
*1898 Stevenson, J. J., Our Society, v. 10, p. 83–98, 1899.
1899 Emerson, B. K., The Tetrahedral Earth and the Zone of the Intercontinental Seas, v. 11, p. 61–106, 1900.
1900 Dawson, G. M., Geological Record in the Rocky Mountain Region of Canada, v. 12, p. 57–92, 1901.
1901 Walcott, Charles D., Outlook of the Geologist in America, v. 13, p. 99–118, 1902.
1902 Winchell, N. H., Was Man in America in the Glacial Period?, v. 14, p. 133–152, 1903.
1903 Emmons, S. F., Theories of Ore Deposition Historically Considered, v. 15, p. 1–28, 1904.
1904 Branner, John C., Stone Reefs on the Northeast Coast of Brazil, v. 16, p. 1–12, 1905.
1905 Pumpelly, Raphael, Evolution of Oases and Civilizations, v. 17, p. 637–670, 1906.
1906 Russell, Israel C., Concentration as a Geological Principle, v. 18, p. 1–28, 1907.
1907 Van Hise, Charles Richard, The Problem of the Pre-Cambrian, v. 19, p. 1–28, 1908.
1908 Calvin, Samuel, Present Phase of the Pleistocene Problem in Iowa, v. 20, p. 133–152, 1909.
1909 Gilbert, G. K. (Did not deliver an address due to illness).
1910 Hague, Arnold, Origin of the Thermal Waters in the Yellowstone National Park, v. 22, p. 103–122, 1911.
1911 Davis, W. M., Relation of Geography to Geology, v. 23, p. 93–124, 1912.
1912 Fairchild, H. L., The Pleistocene Formations of New York State, v. 24, p. 133–162, 1913.
1913 Smith, Eugene Allen, Pioneers in Gulf Coastal Plain Geology, v. 25, p. 157–178, 1914.
1914 Becker, George F., Isostasy and Radioactivity, v. 26, p. 171–204, 1915.
1915 Coleman, Arthur P., Dry Land in Geology, v. 27, p. 175–192, 1916.
1916 Clarke, John M., The Philosophy of Geology and the Order of the State, v. 28, p. 235–248, 1917.
1917 Adams, Frank Dawson, Experiment in Geology, v. 29, p. 167–186, 1918.
1918 Cross, Whitman, Geology in the World War and After, v. 30, p. 165–188, 1919.
1919 Merriam, John C., Earth Sciences as the Background of History, v. 31, p. 233–246, 1920.
1920 White, I. C., Important Epochs in the History of Petroleum and Natural Gas, v. 32, p. 171–186, 1921.
1921 Kemp, James F., After-Effects of the Igneous Intrusion, v. 33, p. 231–254, 1922.
1922 Schuchert, Charles, Sites and Nature of the North American Geosynclines, v. 34, p. 151–230, 1923.
1923 White, David, Gravity Observations from the Standpoint of the Lorne Geology, v. 35, p. 207–278, 1924.
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1925 Scott, W. B., Geological Climates, v. 37, p. 261–278, 1926.
†1926 Lawson, Andrew C., Folded Mountains and Isostasy, v. 38, p. 253–274, 1927.
1927 Keith, Arthur, Structural Symmetry in North America, v. 39, p. 321–386, 1928.
1928 Willis, Bailey, Continental Genesis, v. 40, p. 281–336, 1929.
1929 Reis, Heinrick, Some Problems of the Nonmetallics, v. 41, p. 237–270, 1930.
1930 Penrose, R. A. F. Jr., Geology as an Agent in Human Welfare, v. 42, p. 373–406, 1931.
1931 Lane, Alfred C., Eutopotropism, v. 43, p. 313–330, 1932.
1932 Daly, Richard A., The Depths of the Earth, v. 44, p. 243–264, 1933.
‡1933 Leith, C. K., The Pre-Cambrian, Proceedings volume, p. 151–180, 1934.

* This address contains a full account of early organizations of geologists in North America, and describes the early development of the Society.

† This address starts with a philosophical discourse on the nature of presidential addresses in general.

‡ This is the only Presidential Address contained in a Proceedings volume and not in the Bulletin.

1934 Collins, W. H., Geology and Literature, v. 46, p. 355–374, 1935.
1935 Fenneman, Nevin M., Cyclic and Non-cyclic Aspects of Erosion, v. 47, p. 173–186, 1936.
1936 Mendenhall, W. C., Development and Present Status of Geology in North America, v. 48, p. 349–364, 1937.
1937 Palache, Charles, Present Trends in Mineralogy, v. 49, p. 447–460, 1938.
1938 Day, Arthur L., The Hot Spring Problem, v. 50, p. 317–336, 1939.
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1942 Johnson, Douglas, Problems of Terrace Correlation, v. 55, p. 793–818, 1944.
1943 Bruce, E. L., Precambrian Iron Formations, v. 56, p. 589–602, 1945.
1944 Knopf, Adolf, The Geo-synclinal Theory, v. 59, p. 649–670, 1948.
1945 Berry, Edward W. (No address as Dr. Berry died on 19 September, 1945).
1946 Bowen, Norman L., Magmas, v. 58, p. 263–280, 1947.
1947 Levorsen, A. I., Our Petroleum Resources, v. 59, p. 283–300, 1948.
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1951 Stock, Chester, (No address as Dr. Stock died on 7 December, 1950).
1952 Lovering, T. S., Safeguarding our Mineral-Dependent Economy, v. 64, p. 101–126, 1953.
1953 Woodring, W. P., Carribbean Land and Sea through the Ages, v. 65, p. 719–732, 1954.
1954 Cloos, Ernst, Experimental Analysis of Fracture Patterns, v. 66, p. 241–256, 1955.
1955 Bucher, Walter H., Role of Gravity in Orogenesis, v. 67, p. 1295–1318, 1956.
1956 Hume, C. S., Forest Structures in the Foothills and Eastern Rocky Mountains of Southern Alberta, v. 68, p. 395–412, 1957.
1957 Russell, Richard J., Geological Geomorphology, v. 69, p. 1–22, 1958.
1958 Moore, R. C., Stability of the Earth's Crust.
1959 Billings, Marland P., Diastrophism and Mountain Building, v. 71, p. 363–398, 1966.
1960 Hedberg, Hollis D., The Stratigraphic Panorama, v. 72, p. 499–518, 1961.
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APPENDIX B

Notes on Pleistocene Studies of Geological Surveys of the English-Speaking World

United States of America

The U.S. Geological Survey had a section concerned with Pleistocene geology beginning about 1886 and continuing through 1930. It was called at various times the Section of Glacial Geology, Division of Pleistocene Geology, and Section of Physiographic and Glacial Geology. It was concerned with fields of study that we now group informally under the general heading of Surficial Geology. Subsequently, this activity has been handled within various branches of both the Geologic and Water Resources Divisions, but it continues as a part of the program at about the same rate as before.

About 9 percent of the geological maps published by the U.S. Geological Survey throughout its history are surficial geologic maps. Of the total number 4640 are bedrock maps and 460 are surficial maps. A committee report prepared in 1958 stated that the Geologic Division was then spending 12 percent of its effort supported by directly appropriated funds on projects concerned with surficial geology. This figure was based on estimated project costs. The relative effort today is probably about the same.

(Personal communication from
W. T. Pecora, Director)

Canada

The Geological Survey of Canada has included Pleistocene studies in its work from its inception, Sir William Logan's "Geology of Canada, 1863" containing a lengthy section on Superficial Geology and a map of the unconsolidated deposits of eastern Canada. The Survey has published about 1500 maps showing bedrock geology and 150 showing Pleistocene geology; in addition to the latter, there were quite a number of similar maps published prior to 1900 which are not shown on current index maps, including a series covering the whole of New Brunswick.

More than 350 published papers on Pleistocene geology and related subjects have been written by members of the Survey staff, including about 50 dated before 1900 and 200 published prior to 1950. In connection with a postwar administrative rearrangement of the Survey, the importance of Pleistocene studies was recognized by the establishment of a "Pleistocene Section." It should be noted that prior to this there were no such subdivisions in the organization of the Survey for bedrock or any other subject, all work being then grouped under "Geology" and "Geophysics."

(Based on a personal communication from
Y. Fortier, Director)

Great Britain

(In Great Britain, a distinction has always been made between "Solid" and "Drift" maps. The distinction is retained in the following note, since the terms are still in use and will be encountered by those using British geological maps.)

"Very little could be achieved in the way of drift mapping so long as field work was carried out on the scale of one inch to the mile. Still, a start was actually made, covering a large part of Norfolk, by Joshua Trimmer, 1844–1846. His results are given in the Journal of the Agricultural Society for 1847, and of the Geological Society, 1851. Trimmer's interest in diluvial phenomena was of old standing, for in 1831 he had announced the discovery of marine shells in gravel well over 1000 ft. on Moel Tryfan, Snowdonia. In 1846 he joined the Survey, continuing till 1854, always keen on superficial deposits" (Bailey, 1952).

"The importance of mapping the superficial deposits or Drifts was strongly impressed on the surveyors about the year 1865 when they were actively engaged on the country around London. A geological map of Middlesex which does not show the gravels, sands, brickearths, and boulder–clay would lose half its value, and, so far as was practicable on the one–inch scale, these deposits were shown on the early maps published in 1868. A few years later better editions were issued (1871–1876) of the London Sheets and in 1873 a large special sheet of London and its Environs had been published. These later maps all showed the Drifts" (Flett, 1937).

Today, of the quarter–inch map series for England and Wales, four out of twenty–three are called Drift Maps. Of the Old Series of one–inch sheets, 89 out of 351 sheets for England and Wales are Drift Maps. Of the New Series, 225 out of 289 sheets are either Drift maps or "Solid and Drift" maps. For Scotland, 48 out of the 159 one–inch maps are Drift maps. All field surveying in the United Kingdom is carried out on the six–inch or larger scales, Drift being recorded as well as bedrock. The descriptive Memoirs include detailed accounts of the Drift deposits.

(Based on a personal communication from
Sir James Stubblefield, Director [now
retired] of the Institute of Geological
Sciences, which incorporates the
Geological Survey of Great Britain.)