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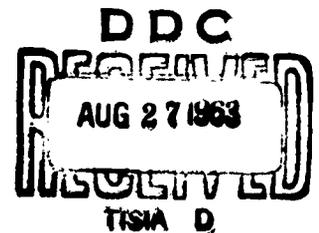
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GLACIAL AND POST GLACIAL QUICK CLAYS

Paul F. Kerr
Richard S. Liebling



Contract No. AF 19(604)8387
Project No. 8623
Task No. 862302
Scientific Report No. 1

Prepared for
Geophysics Research Directorate
Air Force Cambridge Research Laboratories
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

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Paul F. Kerr and Richard S. Liebling

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GLACIAL AND POST GLACIAL QUICK CLAYS

Paul F. Kerr and Richard S. Liebling

ABSTRACT

Essentially horizontal deposits of glacial and postglacial marine clays, long static in flat terrain, may suddenly display mass flowage with destructive consequences. The nature of the clays and the circumstances involved in their behavior have been the subject of study.

The mineralogy of these clays, known as quick clays, has been determined for samples from Scandinavia, Canada and the northeastern United States. Sheet layer silicates constitute the greater part of the clay size fraction. Illite and chlorite occur most frequently, but interlayered illite-montmorillonite is common. Interlayered chlorite-montmorillonite occurs infrequently; interlayered illite-vermiculite is present in one sample. Quartz, feldspar, hornblende, and calcite predominate in the coarser size fractions and often occur in the clay size fraction.

Particle size measurements of non-quick clays yield an average amount of material less than two microns of 31.6 per cent by weight, but in quick clays the amount is 57.3 per cent. Comparative samples of glacial fresh water clays contain smaller amounts of colloidal size particles than marine clays.

Chlorinity tests show that pore water salinity of marine quick clays, believed to have been about 35 grams per liter when the clay was deposited, now ranges from

0.3 to 15 grams per liter.

Measurements show that the amount of water held by quick clays generally exceeds 50 per cent in terms of weight of water to weight of sediment; in some cases it is as high as 80 per cent.

The major critical conditions which contribute to quick clay movement in flat terrain appear to be: a substantial quantity of flake-like particles of colloidal size (equivalent to approximately 40 per cent or more by weight of dry sample); a substantial quantity of water (roughly 50 per cent); a reduction in electrolyte concentration below about 5 grams of salt per liter; and a random orientation of particles induced by coagulation during deposition.

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INTRODUCTION

The term quick clay has been applied to a clay mass which may rapidly and spontaneously undergo remoulding being converted from a solid to a viscous liquid (Reusch, 1901). In the process of remoulding, a quick clay first loses shearing strength (Murayama and Hata, 1957; Newland and Allely, 1957), following which smaller increments of additional stress produce correspondingly greater strains than required to cause the initial remoulding. Thus continued application of stress causes the clay to be remoulded more rapidly, and eventually the force required to produce strain becomes essentially imperceptible. As found as earth features, large scale slides or flows may result.

Quick clay slides may be initiated by some minor disturbance such as heavy traffic, implacement of pilings, slides, explosions, or earthquakes. The initial disturbance produces enough remoulding to reduce the shearing strength below the pressure exerted by the overburden on the clay. The static column then acts to remould the clay, thereby reducing the shearing strength even further. The effect is cumulative and the mass is rapidly transformed into a thick flowing liquid.

Two common forms of quick clay slide behavior have been observed (Meyerhof, 1957): (1) blocks of clay and silt rotate forward in a clay-water slurry having the consistency of lubricating oil (Figure 2); (2) forward

displacement of liquid material occurs (Figure 3). In (1), the disturbance starts from the foot of the slide and proceeds toward the head. In (2), movement is propagated from the head to the foot. The slide at Surte (Figure 4) is an example of type 2.

Slides occur on slopes which range from less than 1° (Caldenius and Lundstrom, 1956) to 20° (Eden, 1956), with low slopes being common. The slide cavity may assume the shape of a pear in plan view, wide at the head and narrow at the neck (Figure 5), as illustrated by a slide near Ottawa, Ontario (Figure 1; see Crawford, 1961). The liquid mass at Ottawa flowed outward from a low terrace, forming a wide apron. Many such slides occur in groups, as shown by an area along the Batiscan River near Ste. Genevieve, Quebec (Figure 6).

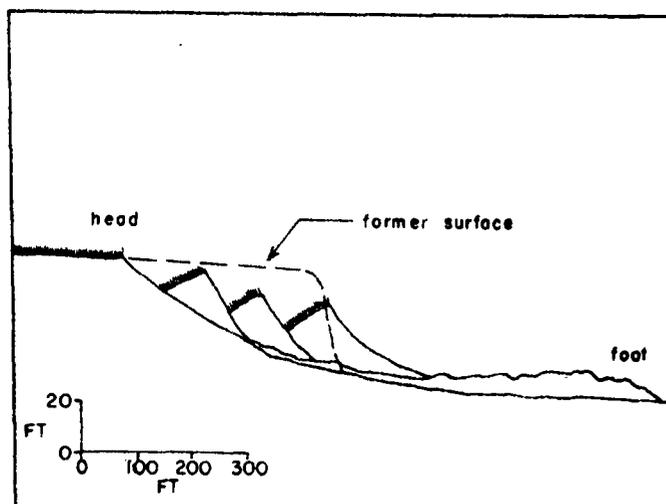
The mass of material disturbed during a quick clay slide may range from 250,000 cubic yards as at Rimouski, Quebec (Hurtubise and Rochette, 1956) to

25,000,000 cubic yards as at St. Alban, Quebec (LaFlamme, 1894). The

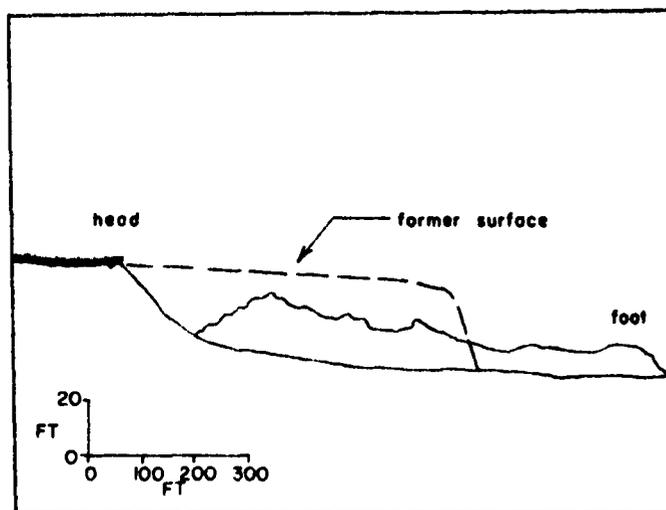


Figure 1. Quick Clay Slide Scar near Ottawa, Ontario. Courtesy of the Royal Canadian Air Force. Air Photo A17264-3.

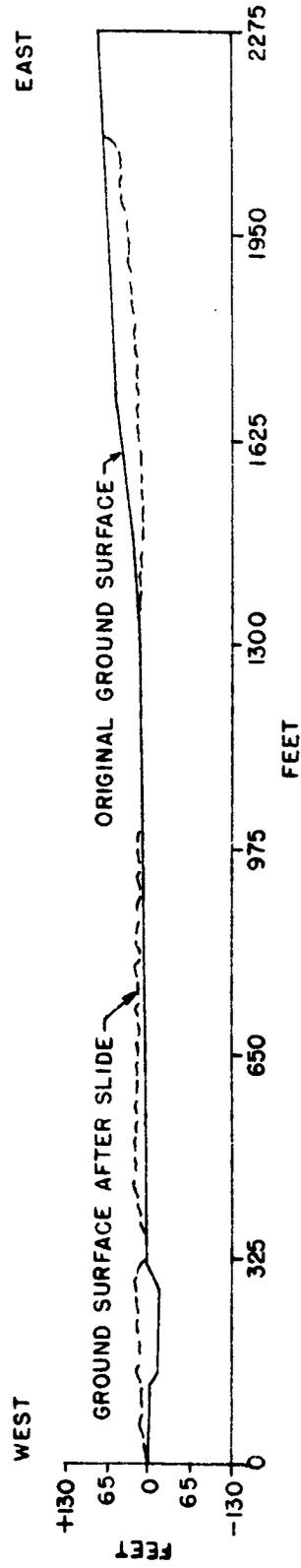
duration of movement may range from two to three minutes as at Surte, Sweden (Caldenius and Lundstrom, 1956) to a half hour, as at Rimouski, Quebec (Meyerhof, 1953).



**Figure 2. Quick Clay Slide, Type 1:
Blocks of Clay Rotating in a Clay-Water
Slurry. Vertical Exaggeration: 5x.**



**Figure 3. Quick Clay Slide, Type 2:
Total Liquefaction of Material. Vertical
Exaggeration: 5x.**



GROSS SECTION OF SURTE QUICK CLAY SLIDE
 (Adapted from Jakobson, 1952)

Figure 4

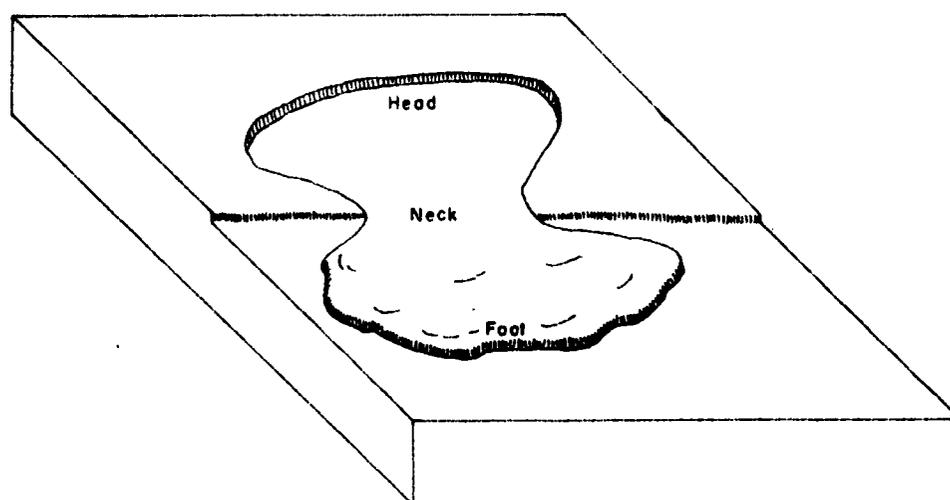


Figure 5. A Typical Appearance of a Quick Clay Slide.



Figure 6. Intersecting Quick Clay Slide Scars along the Batiscan River near Ste. Genevieve, Quebec. Courtesy of the Royal Canadian Air Force. Air Photo A 14596-23

QUICK CLAY FLOWAGE (THIXOTROPY ?)

The mass movement of quick clays has been referred to as thixotropic (Rosenqvist, 1960). As originally proposed (Peterfi, 1927), the term thixotropy refers to the transformation of a gel into a liquid, with subsequent regelation, the thixotropic change being rapid and produced by a shock. The phenomenon has been long recognized (Kühne, 1863; Howell, 1910). During the transformation, the material suffers a loss in shearing strength, which is regained after a lapse of time, without change in water content. This return of shearing strength is termed "thixotropic regain". Among those materials considered thixotropic, the regain is considerable. Early studies by Schalek and Szegvari (1923a, 1923b) show that ferric and tin oxide sols, and zirconium, scandium and aluminum hydroxide sols, which gel with the addition of electrolytes, are thixotropic.

Several chemists (van Olphen, 1956; Alexander and Johnson, 1949; Kruyt, 1952; Green and Weltman, 1946) believe that the development of a random mesh structure of elongate particles is responsible for gelation. Shaking or stirring destroys this structure, thereby converting the gel into a sol. In time, Brownian movement may enable the particles to reconstruct a random mesh configuration.

Clay minerals may be thixotropic in varying degrees. Some montmorillonite is thixotropic, at times exhibiting

a regain of as much as 130 per cent of its original strength (Skempton and Northey, 1952). Sols containing as little as 3 per cent bentonite are known to form gels which revert to sols when shaken (Iler, 1955). This transformation appears to require the presence of alkali ions (Searle and Grimshaw, 1959). Illite may be moderately to poorly thixotropic, its regain in strength probably not exceeding 50 per cent. Kaolinite shows practically no thixotropic regain.

According to some authorities, controlled laboratory tests show that most quick clays regain little of their former strength after remoulding (Grim, 1962; Skempton and Northey, 1952). In the field, water is lost during quick clay flowage and therefore any return to the original shearing strength cannot be strictly considered thixotropic regain. Thus the term "thixotropic" when used to describe quick clays is not precisely correct. The word "quick" itself is adequate, because it refers to a clay susceptible to spontaneous mass liquefaction and flow.

NATURE AND DISTRIBUTION

Many quick clays are of Wisconsin and post-Wisconsin age (Gadd, 1960) and seem to be restricted to higher latitudes and possibly elevated valleys containing clays derived from mountain glaciers. Quick clay slides have long been known to occur in the St. Lawrence River Valley in Canada (Figure 7), and the coastal areas of Norway and Sweden (Figure 8). These areas were glaciated during the Pleistocene with postglacial uplift of as much as 600 feet in Norway, 300 feet in Sweden (Meyerhof, 1957), and 600 feet in Canada. Quick clay slides appear to have occurred in the Portland, Maine, area during the mid-19th century (Morse, 1869). Occurrences of quick clays in Vermont have been suggested (Prof. Burmister, personal communication). Quick clays in southern Chile have been reported (Dr. G. Ericksen, personal communication). Some clay slides in the Peruvian Andes may also be of this type (Dr. V. Oppenheim, personal communication).

Quick clays represent fine-grained materials, apparently produced by ice sheet abrasion of bedrock, the fine debris often being carried into marine and brackish water embayments by glacial melt waters. Upon reaching saline waters, the fine particles become coagulated by sodium chloride and other salts in solution and rapidly settle. Toward the close of the Pleistocene, marine embayments were formed by the influx of sea water into recently glaciated areas still depressed from the weight

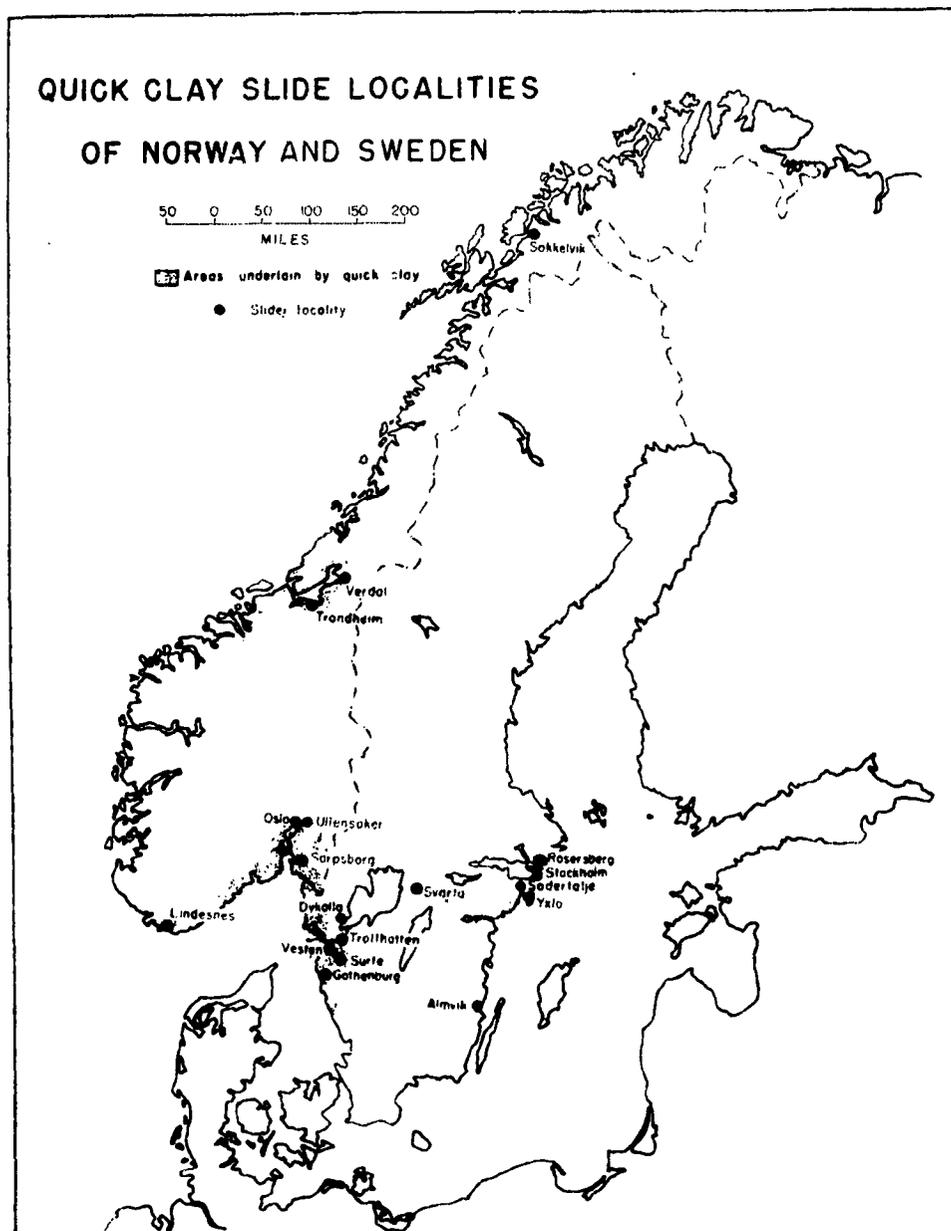


Figure 8. Quick Clay Slide Localities of Norway and Sweden. Gota River flows south through Trollhattan to Gothenburg.

of the ice. Isostatic uplift of these areas resulted in the retreat of the sea. One such invasion was the Champlain Sea which occupied the St. Lawrence trough in southeastern Canada about 11,000 years ago (Gadd, 1960). Another similar embayment exists in the area now occupied by the Gota River in Sweden (Caldenius and Lundstrom, 1956). The trend of the Gota River is parallel to the strike of the cleavage, jointing, and zones of weakness in the gneissic bedrock. Borings through the valley fill indicate that the valley is "U"-shaped in cross-section and that glacial scouring during the last ice advance is responsible for the cross-sectional profile. The ice retreated some 12,000 to 14,000 years ago, followed by invasion of the sea.

SOURCES OF THE SAMPLES INVESTIGATED

In this study field collections of clays have been made and specimens have been secured of clays from a considerable number of slide-producing areas, plus several similar clay samples from non-slide areas studied for comparison. Among the quick clays studied, 4 are from Sweden*, 1 from Norway**, 1 from Maine, and 9 from Canada. Among the non-quick clays, 4 are from Canada and 8 are from New York State (Figure 9). The Canadian quick clay localities are Rimouski, Ste. Genevieve, St. Alban, St. Thuribe, St. Stanislas, St. Vallier, Nicolet, Portneuf, all in Quebec, and Hawkesbury, Ontario.

The Canadian samples are all of glacial marine origin. Two Swedish quick clays from Vesten and Dykalla are of marine origin, whereas a sample from Rosersberg is of fresh water origin. The remaining two samples from Oslo, Norway and Portland, Maine, are of marine origin. The quick clays from all localities studied are dark blue-gray when wet and light gray when dehydrated.

The 4 Canadian clays somewhat similar in appearance but supposedly non-quick in type are from Ste. Anne de Beaupre, St. Joseph de la Rive, Trois Pistoles, and the east coast of Ellesmere Island on Darling Peninsula. The clays from Ste. Anne de Beaupre and St. Joseph de

*Swedish quick clays were received through the courtesy of Dr. Justus Osterman of the Swedish Geotechnical Institute

**Supplied through the courtesy of Dr. I. Th. Rosenqvist, of the University of Oslo.

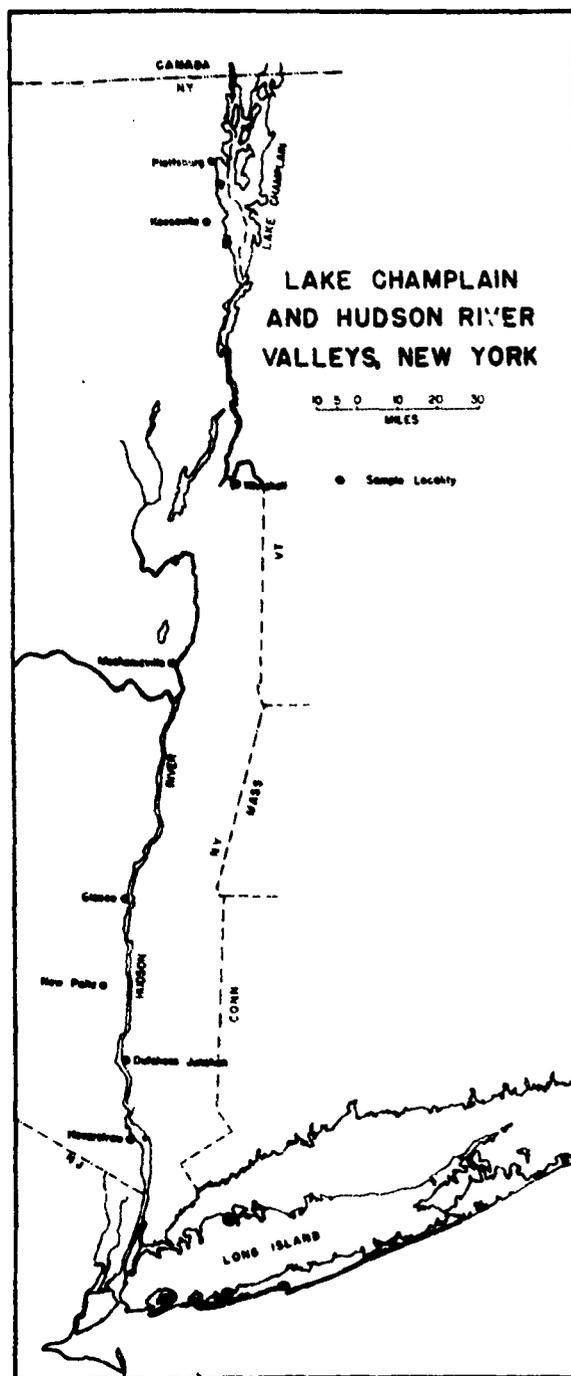


Figure 9. Lake Champlain and Hudson River Valleys, New York.

la Rive were collected from embankments containing lenses of coarse material. Such deposits may have been formed close to a glacier margin and therefore accumulated under fresh or brackish water conditions rather than marine. They are dark gray when wet but light gray when dry. The sample from Trois Pistoles is marine, but, unlike the other St. Lawrence Valley clays, is medium brown when wet; after drying, the clay turns light tan. The sample collected from Darling Peninsula on Ellesmere Island represents clay deposited from melt waters along a stream bank; it is therefore fresh water clay*. The clay is brown when wet, and alters to light brown upon drying. The remaining non-quick clays were collected in New York State: Keeseville, New Paltz, Dutchess Junction, Glasco, Mechanicville, Plattsburg, Haverstraw, and Whitehall. The Plattsburg and Whitehall samples are brown, but dry to a light tan. The others are gray when moist, and light gray when dry. The clays from Plattsburg, Keeseville, and Whitehall are from the Lake Champlain area, and were deposited in a southern extension of the ancient Champlain Sea. The Plattsburg and Whitehall samples may be marine clays. The other clays, from the Hudson River Valley, are considered lacustrine.

*Collected by Dr. Richard Kerr of the Geological Survey of Canada in the summer of 1961.

GRAIN SIZE

Grain size distribution was determined for each clay using the Bouyoucos hydrometer method (ASTM, 1959). In this method, 50 grams (dry weight) of each sediment are immersed in 125 ml of a 4 per cent solution of sodium hexametaphosphate for 24 hours. After 24 hours, the sediment plus solution are agitated in a Waring Blendor for one minute. 875 ml of distilled water are then added and the mixture placed in a Kimax liter cylinder. After being shaken 120 times in one minute, the sediment is allowed to settle. Bouyoucos hydrometer readings in grams per liter are then taken after intervals of 2, 5, 15, 30, 60, 250, and 1440 minutes. With the proper density and temperature corrections, particle sizes in equivalent diameters are calculated and particle size distribution curves plotted (Figures 10-15).

Tables 1 and 2 summarize the minus two micron portions. The average amount of minus two micron material for the quick clay samples is 57.3 per cent by weight. The average amount of minus two micron material for the non-quick clays examined is 31.6 per cent by weight. The per cent of less than two micron material ranges from 27 to 82 in quick clays, whereas the range in non-quick clays is from 11 to 77 per cent. However, whereas 10 of the 15 quick clays contain 50 per cent or more of the two micron material, only two of the 12 non-quick clays contain 50 per cent or more of the same size particles. Using a level

of significance of .01, a "t" test shows that the two types of clay contain significantly different amounts of less than two micron material. Data (Crawford, 1961) on quick clays from Beauharnois, Quebec, Massena, Ontario, and Ottawa, Ontario, show the following amounts of the minus two micron fraction: 47-72, 30-55, 55-80 per cent respectively. The samples from Trois Pistoles, Plattsburg, and Whitehall, are probably potential quick clays although no slides were observed nearby. They contain amounts of minus two micron material comparable with amounts found in quick clays. The geological situation is also likely.

It is necessary to consider the factors affecting grain size distribution in sediments to explain the significantly different amounts of fine-grained material in quick and non-quick clays. These factors include physical and chemical properties of the source material, climate, erosional agents, and depositional environment. Mineralogic similarities among the clays suggest that the source materials for these sediments were probably similar. In the regions sampled, the Pleistocene climatic conditions were probably more or less alike and the type and degree of weathering, except for local differences caused by topographic and soil biota variations, were probably also essentially the same. Although it is not certain that all these clays are the product of glacial abrasion, no doubt most are (Ries, 1900; Caldenius and Lundstrom, 1956; Eden and Crawford, 1957;

TABLE 1

Quick Clays: Colloidal Fraction (Less than Two Microns)

Clay Type*	Locality	Colloidal Fraction (Wt. Per Cent)
M	Rimouski, Que.**	27
M	Ste. Genevieve, Que.	34
M	St. Alban, Que.	41
M	Oslo, Norway	45
M	Portland, Me.	47
M	St. Thuribe, Que.	51
M	Dykalla, Sweden	55
M	St. Stanislas, Que.	55
M	Vesten, Sweden (two samples)	63, 65
M	St. Vallier, Que.	68
M	Nicolet, Que.	72
F	Rosersberg, Sweden	75
M	Portneuf, Que.	80
M	Hawksbury, Ont.	82

* M-marine, F-fresh

** Considered a non-quick clay by Meyerhof (1953).

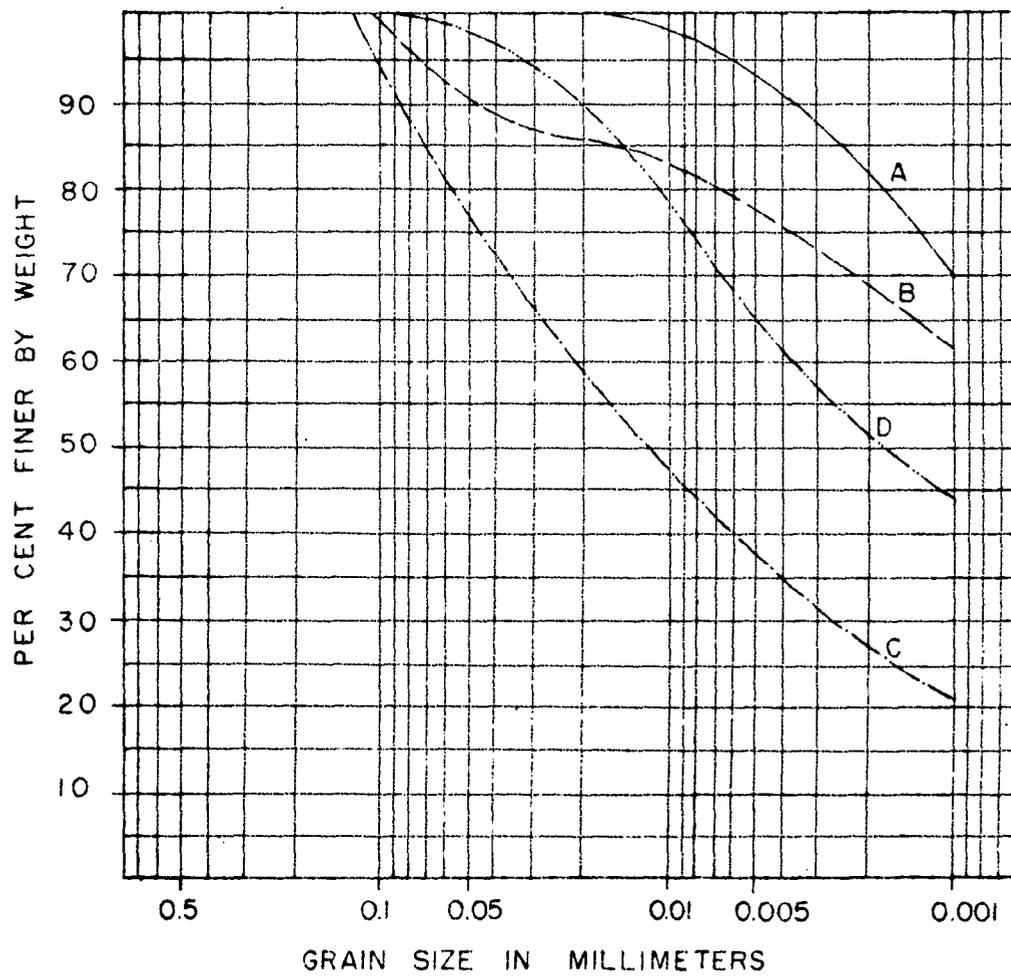
TABLE 2

Non-Quick Clays: Colloidal Fraction (Less than Two Microns)

Clay Type*	Locality	Colloidal Fraction (Wt. Per Cent)
F/B	Ste. Anne de Beaupre, Que.	11
F	Ellesmere Island	15
M	Keeseville, N. Y.	17
F/B	St. Joseph de la Rive, Que.	17
F	Haverstraw, N. Y.	18
F	New Paltz, N. Y.	19
F	Dutchess Junction, N. Y.	25
F	Glasco, N. Y.	40
F	Mechanicville, N. Y.	45
M	Plattsburg, N. Y. **	45
M	Trois Pistoles, Que. **	51
M	Whitehall, N. Y.**	77

* M-marine, F-fresh, F/B-fresh or brackish

** Probably potential quick clays



- A ————— Hawkesbury
- B - - - - - St. Vallier
- C - - - - - Rimouski
- D - - - - - Trois Pistoles

Figure 10. Particle Size Analyses for Clays from Hawkesbury, St. Vallier, Rimouski, and Trois Pistoles.

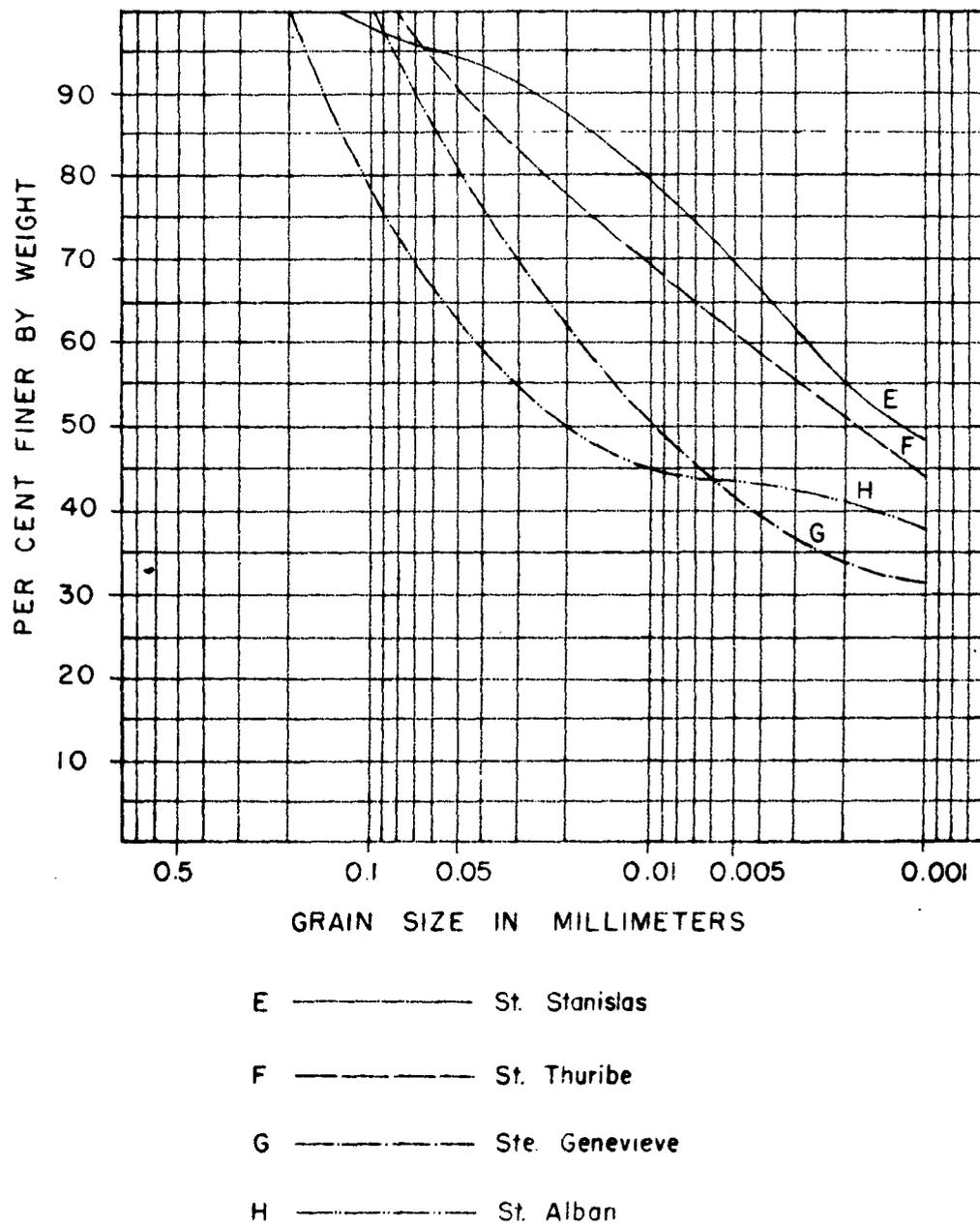
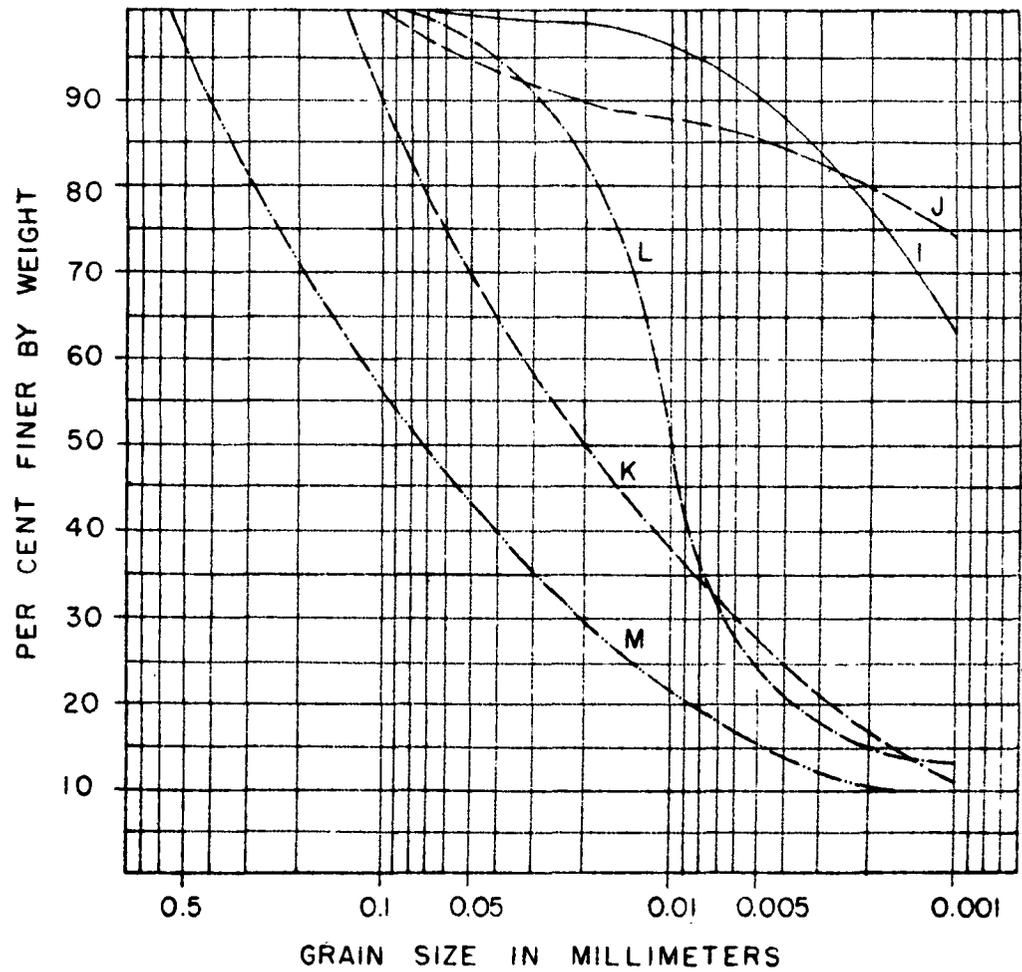
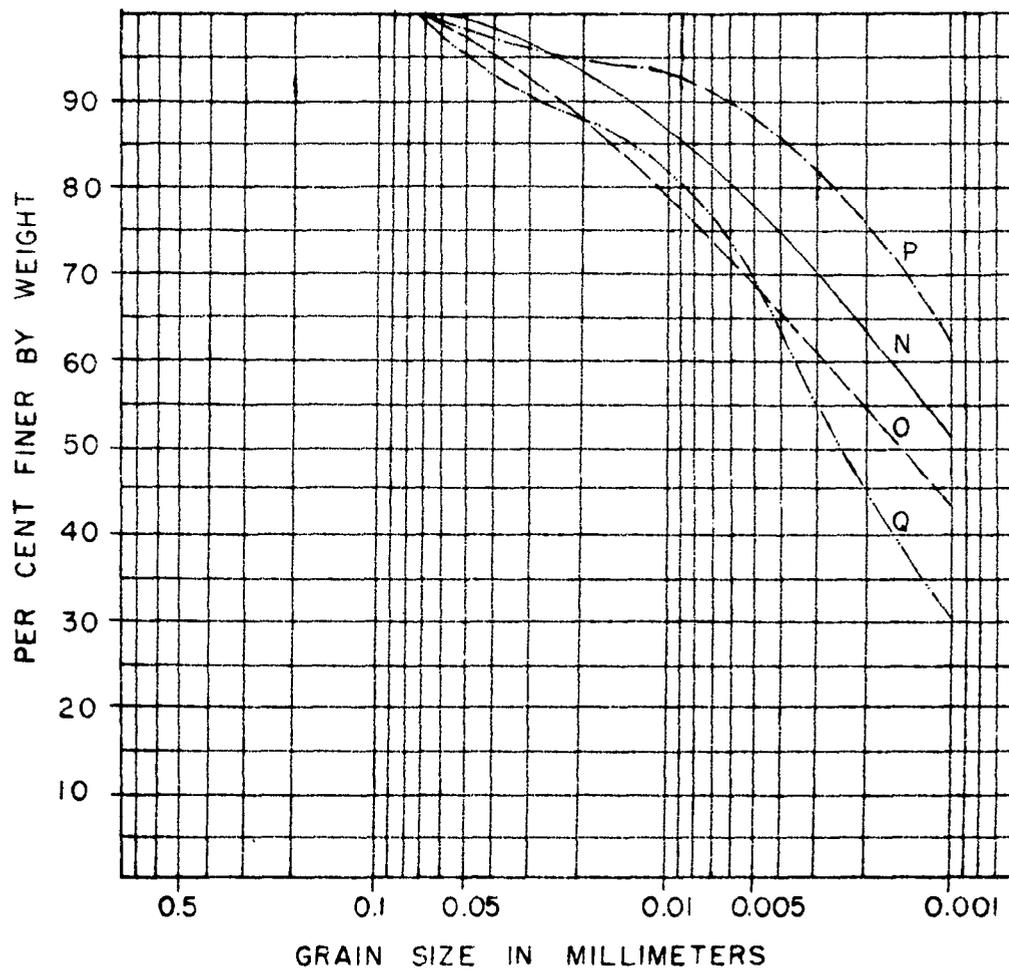


Figure 11. Particle Size Analyses for Clays from St. Stanislas, St. Thuribe, Ste. Genevieve, and St. Alban.



- I ————— Nicolet
 J - - - - - Portneuf
 K - · - · - St. Joseph de la Rive
 L - - - - - Ellesmere Island
 M - - - - - Ste. Anne de Beaupre

Figure 12. Particle Size Analyses for Clays from Nicolet, St. Joseph de la Rive, Portneuf, Ellesmere Is., and Ste. Anne de Beaupre.



N ————— Vesten
 O - - - - - Dykalla
 P - - - - - Rosersberg
 Q - - - - - Oslo

Figure 13. Particle Size Analyses for Clays from Vesten, Dykalla, Rosersberg, and Oslo.

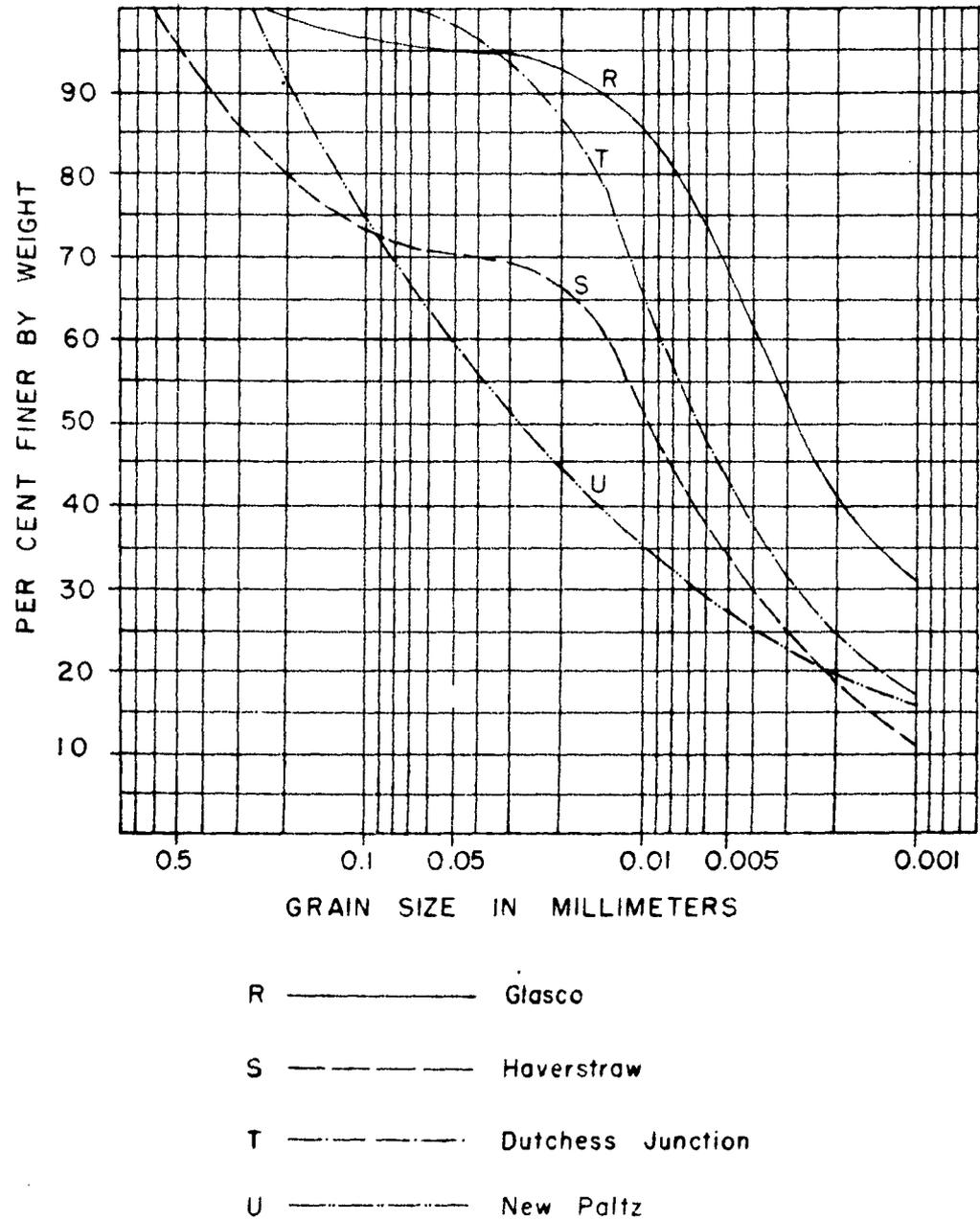
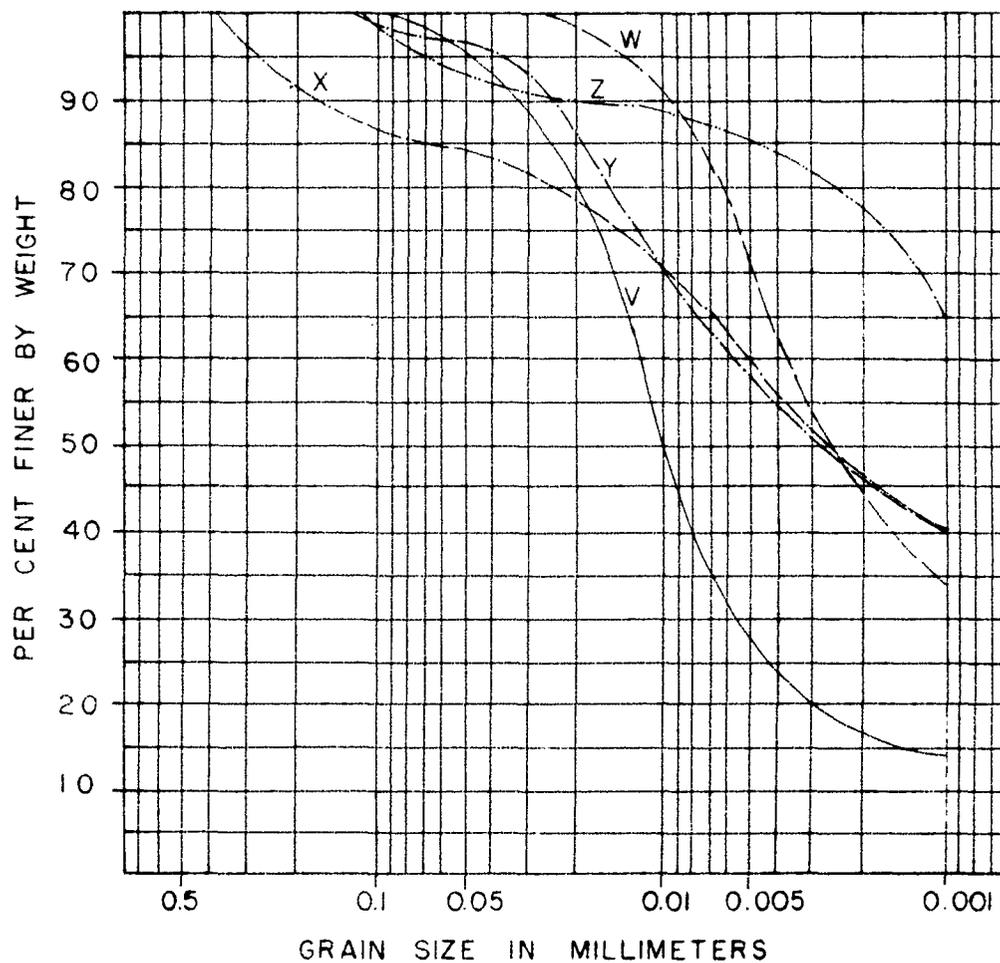


Figure 14. Particle Size Analyses for Clays from Glasco, Haverstraw, Dutchess Junction, and New Paltz.



V ————— Keeseville
 W ————— Mechanicville
 X ————— Portland
 Y ————— Plattsburgh
 Z ————— Whitehall

Figure 15. Particle Size Analyses for Clays from Keeseville, Mechanicville, Plattsburgh, Whitehall, and Portland.

Meyerhof, 1957; Gadd, 1960).

The significant difference among these clays is that some were deposited in marine waters and others in fresh waters. When the clays are classified as marine or fresh and the amount of colloidal size fraction present in each compared (Tables 1 and 2), it is found that, in general, the fresh water samples contain fewer colloidal size particles than marine clays. The average amount, in terms of weight per cent, of less than two micron material in the marine clays is 54.1, whereas the average amount in fresh water clays is 23.7 per cent. The difference between fresh water clays and marine clays may be explained as follows: fine particles (less than two microns) are not rapidly coagulated in a fresh water environment and therefore remain in suspension long after coarser particles have settled. Continued transport of the fine fraction by currents may be expected to prevent the fine fraction from accumulating with the coarser material. Marine clays are much finer, since in sea water, fine particles are rapidly coagulated into large masses by sodium chloride and other dissolved salts. Such large masses settle rapidly, thereby contributing significantly to the mass of sediment. Therefore, as a general rule, where most other factors are the same, fresh water clays are coarser than marine clays. Table 1 shows that most of the quick clays are quite fine-grained and that all, save one,

were deposited in a marine environment. Since fine-grained sediments may be particularly sensitive, a marine depositional environment is probably an important factor contributing to the formation of quick clays. Though quick clays seem to be closely associated with marine waters, Soderblom (1960) has reported the existence in Sweden of non-marine post-glacial quick clays.

ELECTROLYTE CONTENT OF PORE WATER

Pore water salinity analyses of the Swedish clays and some Canadian clays (Crawford, 1961) show that the clays from slide areas have a salinity considerably less than that of sea water (35 grams per liter). The fresh water clay from Rosersberg, Sweden, also contains little salt. This is to be expected since fresh water salinities generally range from .01 to 1.0 grams per liter.

TABLE 3

Salinity of Pore Water

Sample	Salinity (gr/l)
Vesten, Sweden	1.1-1.2
Dykalla, Sweden	0.4
Rosersberg, Sweden	1.0
Nicolet, Que.	5.0-9.0
Beauharnois, Que.	0.4
Massena, Ont.	0.6-2.0
Hawkesbury, Ont.	0.3
Ottawa, Ont.	0.5-15.0

WATER CONTENT OF QUICK CLAYS

The amount of water held by quick clays generally exceeds 50 per cent, in terms of weight of water to weight of sediment; in some cases (Crawford, 1961) it is as high as 80 per cent (Table 4). The high per cent of water is probably attributable to substantial amounts of colloidal material and a high void index (Skempton and Northey, 1952; Rochette, 1956). The high void index of quick clays probably accounts for their shrinkage and swelling during dry and wet seasons (Crawford, 1961; Barcos and Bozozuk, 1957).

TABLE 4

Natural Water Content of Some Canadian and Swedish Quick Clays. (Crawford, 1961, Canadian Localities; Osterman, personal communication, Swedish Localities)

Locality	Natural Water Content (Wt. of Water per Wt. of Sediment)
Vesten, Sweden	64
Nicolet, Que.	53
	65
St. Thuribe, Que.	44
Beauharnois, Que.	68
Massena, Ont.	60
Hawkesbury, Ont.	80
Ottawa, Ont.	80
	45
	65
Dykalla, Sweden	58
Rosersberg, Sweden	59

MINERAL CONSTITUENTS

Earlier mineralogic studies of clays of the Ottawa and St. Lawrence River Valleys seem to indicate that the clays vary somewhat in their mineralogic composition. According to Meyerhof (1957), the clays and silty clays of the region contain appreciable amounts of illite, whereas, the silts are dominantly quartz and feldspar. Eden and Crawford (1957) state that studies using X-ray diffraction and DTA techniques reveal that the Champlain Sea clays are composed mainly of "illite with a tendency toward mica, plagioclase feldspars, quartz and chlorite". They also report interstratification of illite and chlorite. Barcos and Bozozuk (1957) claim that the clays of the Ottawa and St. Lawrence Valleys (the so-called Leda clays) contain substantial quantities of montmorillonite. The Leda clays are described by Gadd (1956) as predominantly quartz and feldspar, containing only small amounts of clay minerals. In a study of 56 samples of clays and shales from eastern Canada and New England, Allen and Johns (1960) observed that hydrous micas and chlorite are the dominant clay minerals. Quartz and feldspars are also present, the quartz being far more abundant. Interlayered mica-chlorite is not common and montmorillonite occurs rarely. Mineralogic analyses of Champlain Sea sediments conducted by Brydon and Patry (1961) showed that quartz, feldspars, amphibole, micas, and chlorite

occur in the clay fraction as well as in the silt and sand fractions. The clays and micas are more abundant in the clay fraction. Beland (1956), in an analysis of Leda clay from Nicolet, Quebec, found the sediment to be predominantly quartz and feldspar, with mica, montmorillonite, and kaolinite occurring in small amounts only. Karrow (1957) noted the presence of chlorite, illite, amphibole, quartz, feldspar, and sometimes calcite in samples of Champlain Sea clay. Quartz and feldspar together account for probably no more than 20 per cent of the clay fraction. Grim (in Terzaghi and Peck, 1948) found that, in general, the silt fraction is predominantly quartz and calcite, and that the clay fraction is mostly mica-like illite and montmorillonite. The clay involved in the St. Thuribe slide contains mostly fine quartz with a little mica and possibly a trace of montmorillonite (Grim, in Peck, Ireland, and Fry, 1951). Rosenqvist (1960) believes that the Norwegian quick clays are generally illitic or chloritic and that quartz and feldspar are abundant in the finest size fraction.

In this study, an investigation of the mineral content of both quick clays and non-quick clays was made to determine whether or not these two types of clay differ significantly and also, to determine in what way, if any, the mineral assemblage in quick clays contributes to their behavior.

Microscopic study showed that quartz, albite, microcline, and muscovite were present in the sand and coarse silt fractions of all clays. Hornblende, biotite, and calcite are found in the sand and silt fractions of several clays. Clay size particles cannot be easily resolved under the ordinary microscope. Whereas valuable optical data may be obtained on clay-size material of a single mineral species, optical analysis of clay-size material consisting of several minerals is exceedingly difficult. Several attempts were made at determining refractive indices. Because individual grains were not discernible, determinations were obtained for the clay fraction as a whole. Observed values ranged from 1.55 to 1.57. Further analysis required the use of X-ray diffraction.

Mineral identifications were made with a Philips X-ray diffractometer utilizing the spacings between the basal atomic planes. Since clay mineral particles generally are flake-like, with flat surfaces parallel to (001), samples were sedimented so that the reflections observed were essentially those diffracted from the atomic layers parallel to (001).

The sedimented specimens were investigated in three ways: (1) untreated, (2) after heating at 550°C for two hours, and (3) after spraying with glycol.

The common sheet silicates involved have been found to be illite, chlorite, vermiculite, and montmorillonite.

A summary is given of the criteria used in distinguishing the combination of these minerals found in the clays.

Illite: Significant illite reflections occur at 10A, 5A, 3.33A, 2.5A, 2A, which are not affected by heating at 550°C or by glycolation. All quick clays examined contain illite.

Chlorite: Significant reflections at 14A, 7A, 4.7A, 3.5A, and 2.8A indicate the presence of chlorite. Generally, the 7A reflection is more intense than 14A. Heating at 550°C destroys all of the reflections except the 14A peak which becomes much more intense. Glycolation produces no effect on the reflections (except for some rare chlorites). Chlorite is a prominent constituent of a number of quick clays but is not always present.

Vermiculite: Significant reflections at 14A, 7A, 4.7A, 3.5A, 2.8A (corresponding to chlorite) may indicate vermiculite. However, in vermiculite, the 14A reflection

is ordinarily more intense than the 7A reflection. In addition, heating at 550°C generally causes the collapse of the 14A reflection to 10A, because of the removal of water from interlayered positions; at the same time the other reflections are destroyed. Glycolation may cause a displacement of the 14A to higher spacings. However, for ordinary vermiculite, the displacement is not great, often negligible. Vermiculite occurs in a number of quick clays.

Montmorillonite:

Reflections at 14A and 4.5A indicate the presence of montmorillonite. Heating at 550°C produces a displacement of the 14A reflection to about 10A and a strong reflection at 3.2A appears. Glycolation results in a pronounced increase in the basal layer separation causing a displacement of the 14A reflection to 15A-17A. Several quick clays contain montmorillonite.

The criteria (Molloy and Kerr, 1961; Brindley, ed, 1951) used serve as guides to identification. Occasionally only a few of the reflections characteristic of a particular mineral are recorded. In addition, unless heating is continued long enough, dehydration may not be complete and therefore the basal spacings may not collapse as much as expected. Furthermore, during glycolation, the organic liquid must be allowed to completely permeate the inter-layer positions. Otherwise only a partial expansion of the basal layers will occur. In the clay mineral descriptions given the term montmorillonite applies to a clay with an expanding structure.

Figures 16 to 24 furnish X-ray diffractometer patterns showing the clay mineral reflections. Since the (003) reflection of illite and (101) reflection of quartz overlap at about 3.34A ($26.6^{\circ}2\theta$), the (100) quartz reflection at 4.26A ($20.8^{\circ}2\theta$) has been indicated by a small apex at the peak intensity position. The (101) quartz reflection is 2.85 times more intense than quartz (100). Any excess is the illite contribution. Several feldspars, the remaining quartz, calcite and hornblende reflections have been eliminated to avoid confusion.

The following abbreviations have been used for the diffractometer patterns: I-illite; C-chlorite; M-montmorillonite; V-vermiculite; Mu-muscovite; C-M-chlorite interlayered with montmorillonite; C-V-chlorite inter-

layered with vermiculite; I-M-illite interlayered with montmorillonite; I-V-illite interlayered with vermiculite; and Q-quartz.

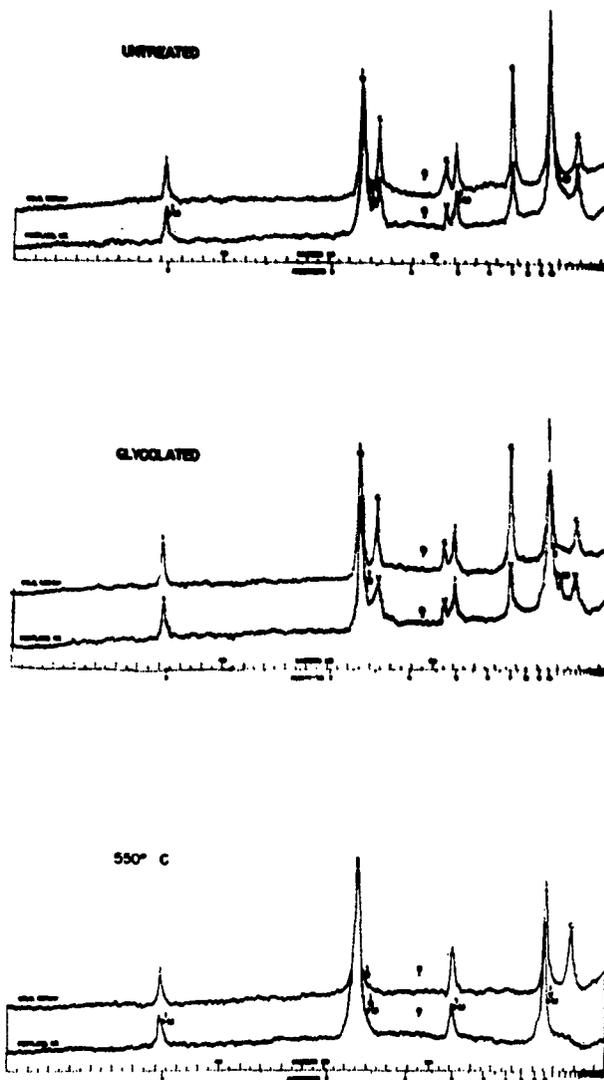


Figure 16. X-ray Diffractometer Patterns of Clay Mineral Constituents for Clays from Oslo, Norway, and Portland, Maine. See pg. 39, paragraph 3, for explanation of abbreviations.

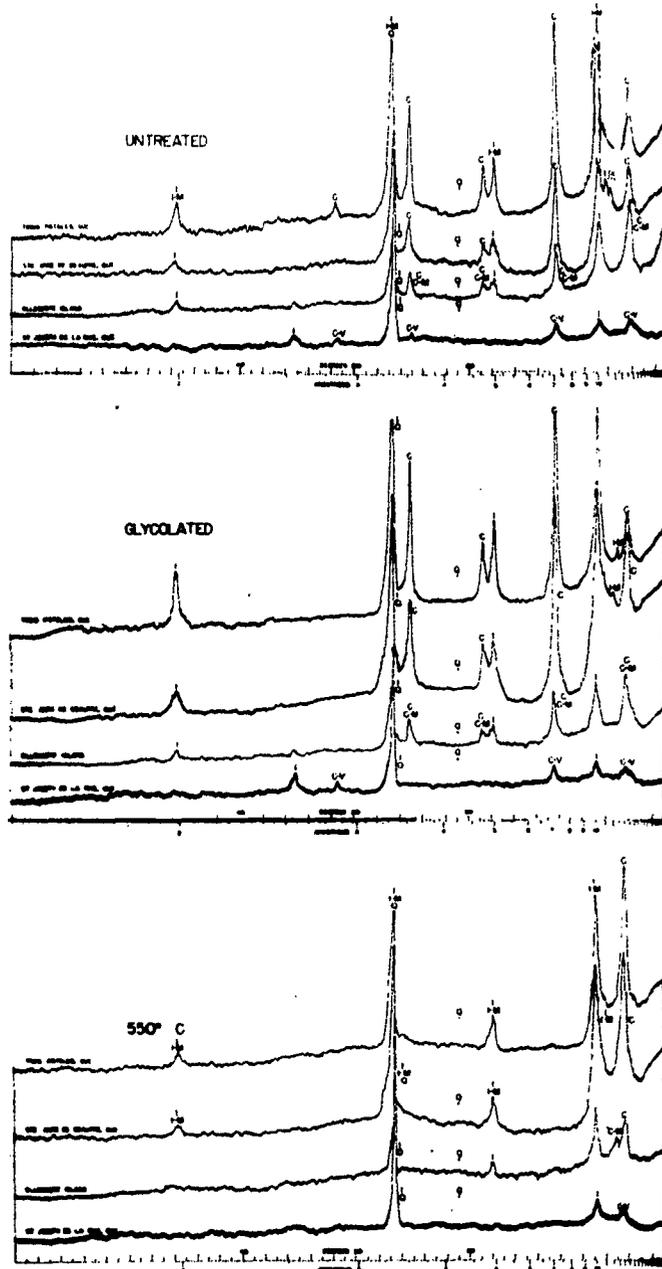


Figure 17. X-ray Diffractometer Patterns of Clay Mineral Constituents for Clays from Trois, Pistoles, Que., Ste. Anne de Beaupre, Que., Ellesmere Island, and St. Joseph de la Rive, Que. See pg. 39, paragraph 3, for explanation of abbreviations.

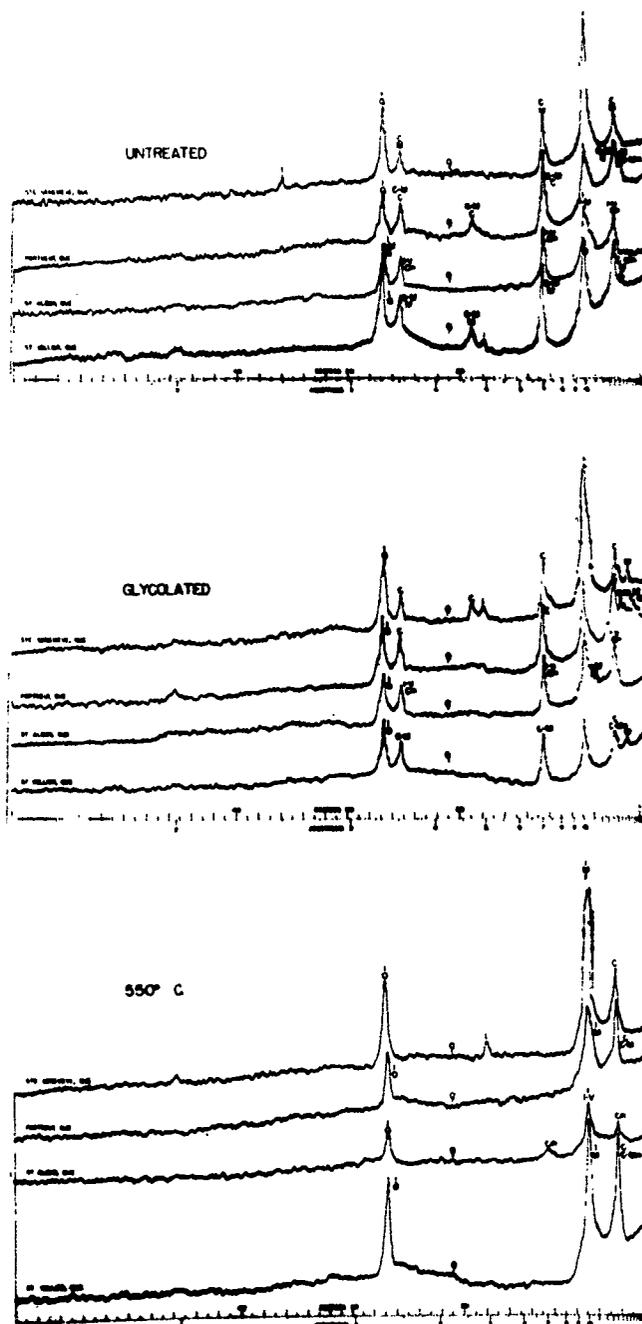


Figure 18. X-ray Diffractometer Patterns of Clay Mineral Constituents for Clays from Ste. Genevieve, Que., Portneuf, Que., St. Alban, Que., and St. Vallier, Que. See pg. 39, paragraph 3, for explanation of abbreviations.

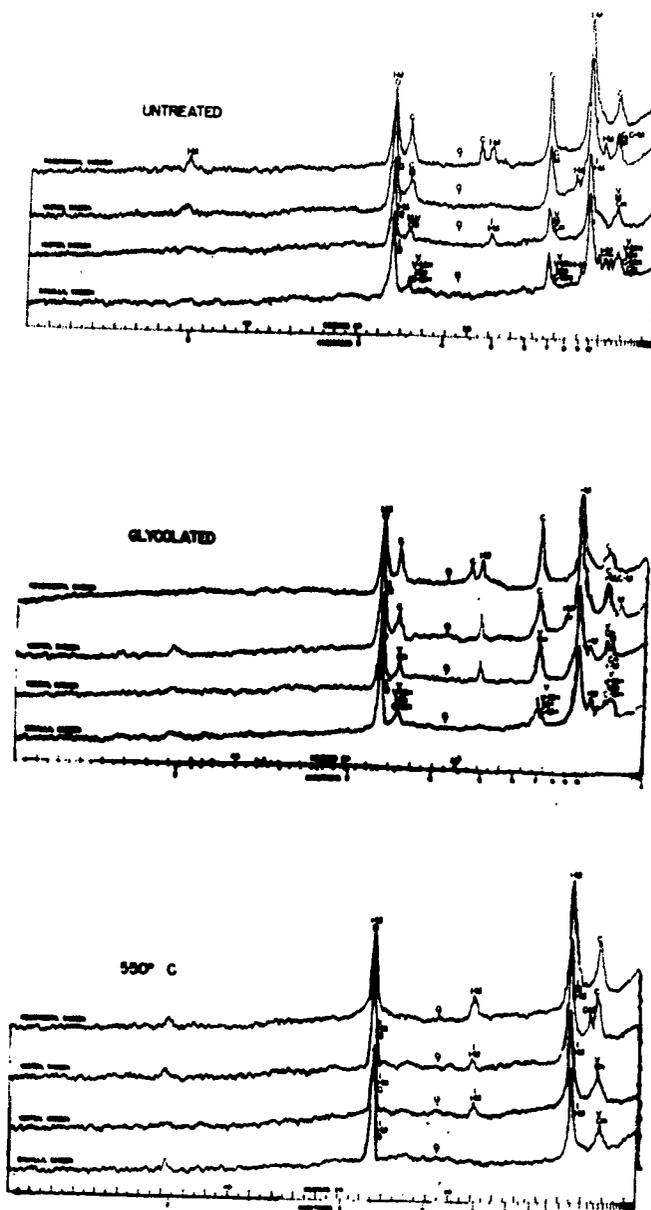


Figure 19. X-ray Diffractometer Patterns of Clay Mineral Constituents for Clays from Rosersberg, Sweden, Vesten, Sweden, and Dykalla, Sweden. See pg. 39, paragraph 3, for explanation of abbreviations.

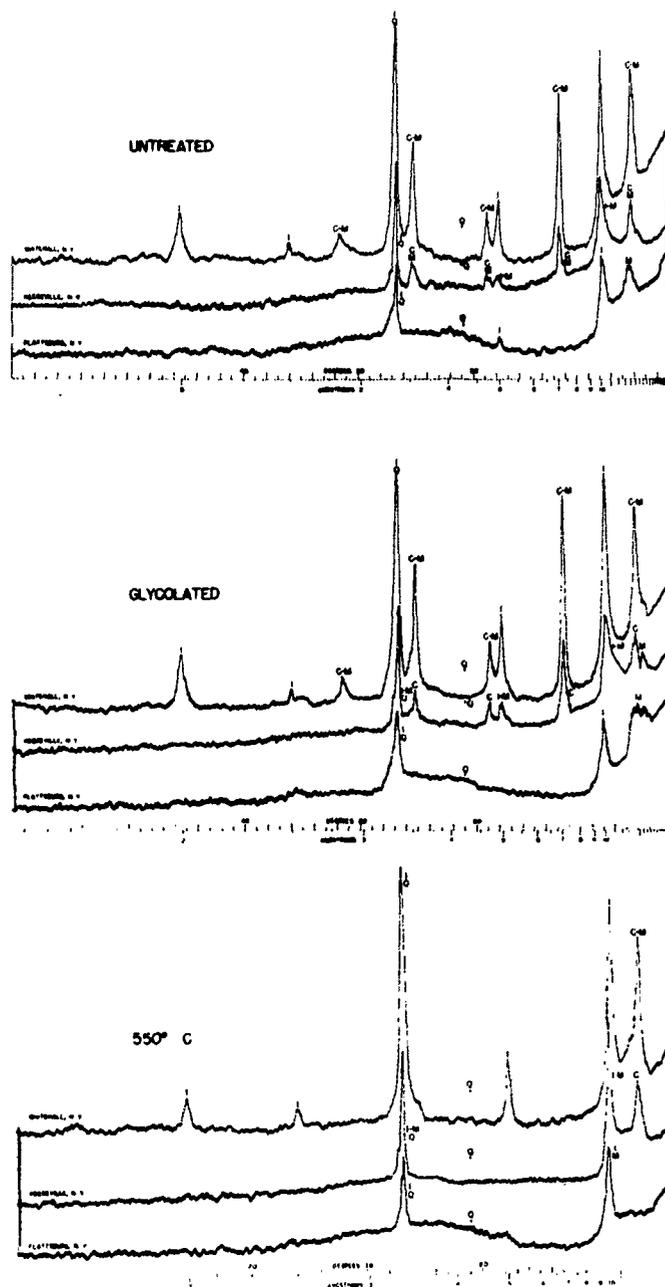


Figure 20. X-ray Diffractometer Patterns of Clay Mineral Constituents for Clays from Whitehall, N. Y., Keeseville, N. Y., and Plattsburg, N. Y. See pg. 39, paragraph 3, for explanation of abbreviations.

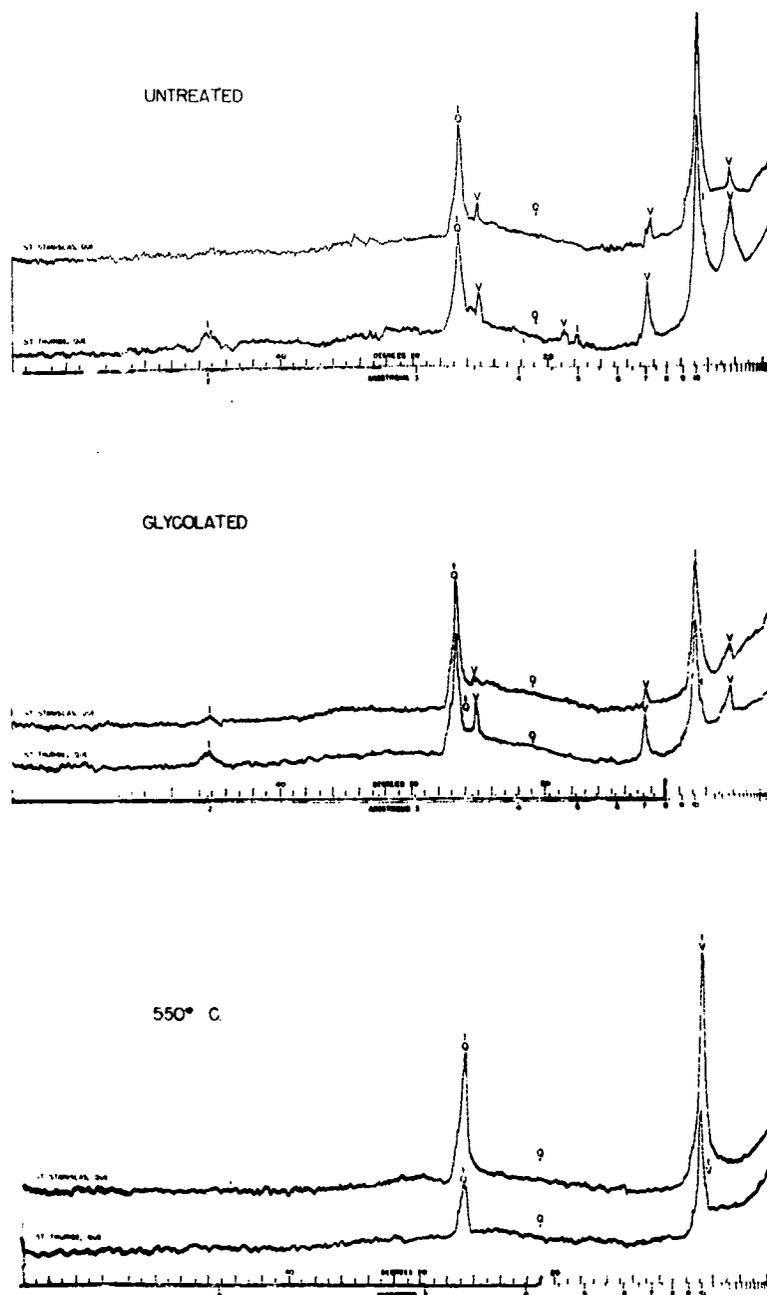


Figure 21. X-ray Diffractometer Patterns of Clay Mineral Constituents for Clays from St. Stanislas, Que., and St. Thuribe, Que. See pg. 39, paragraph 3, for explanation of abbreviations.

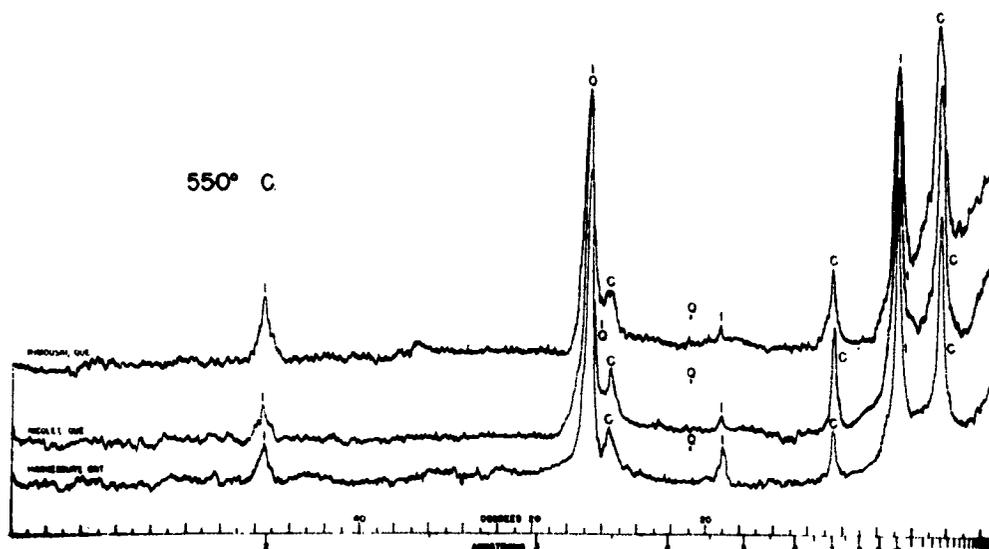
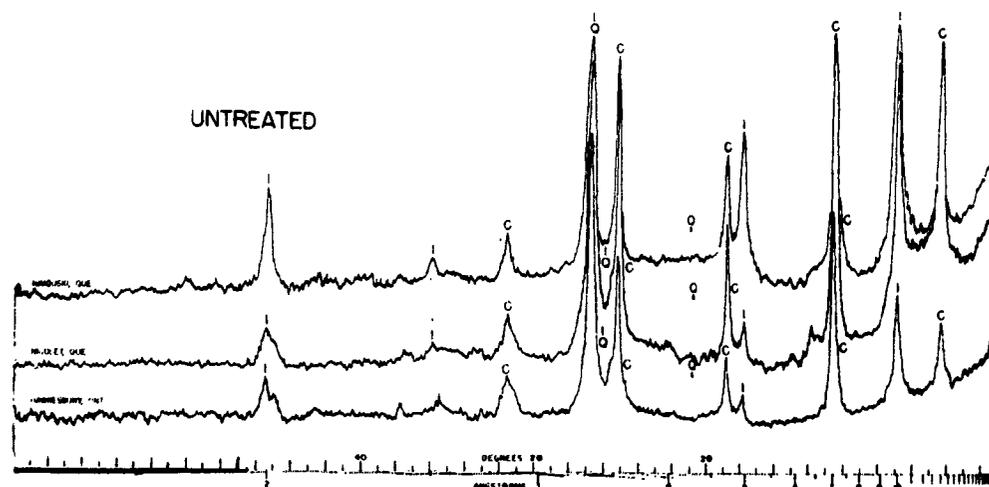


Figure 22. X-ray Diffractometer Patterns of Clay Mineral Constituents for Clays from Rimouski, Que., Nicolet, Que., and Hawkesbury, Ont. See pg. 39, paragraph 3, for explanation of abbreviations.

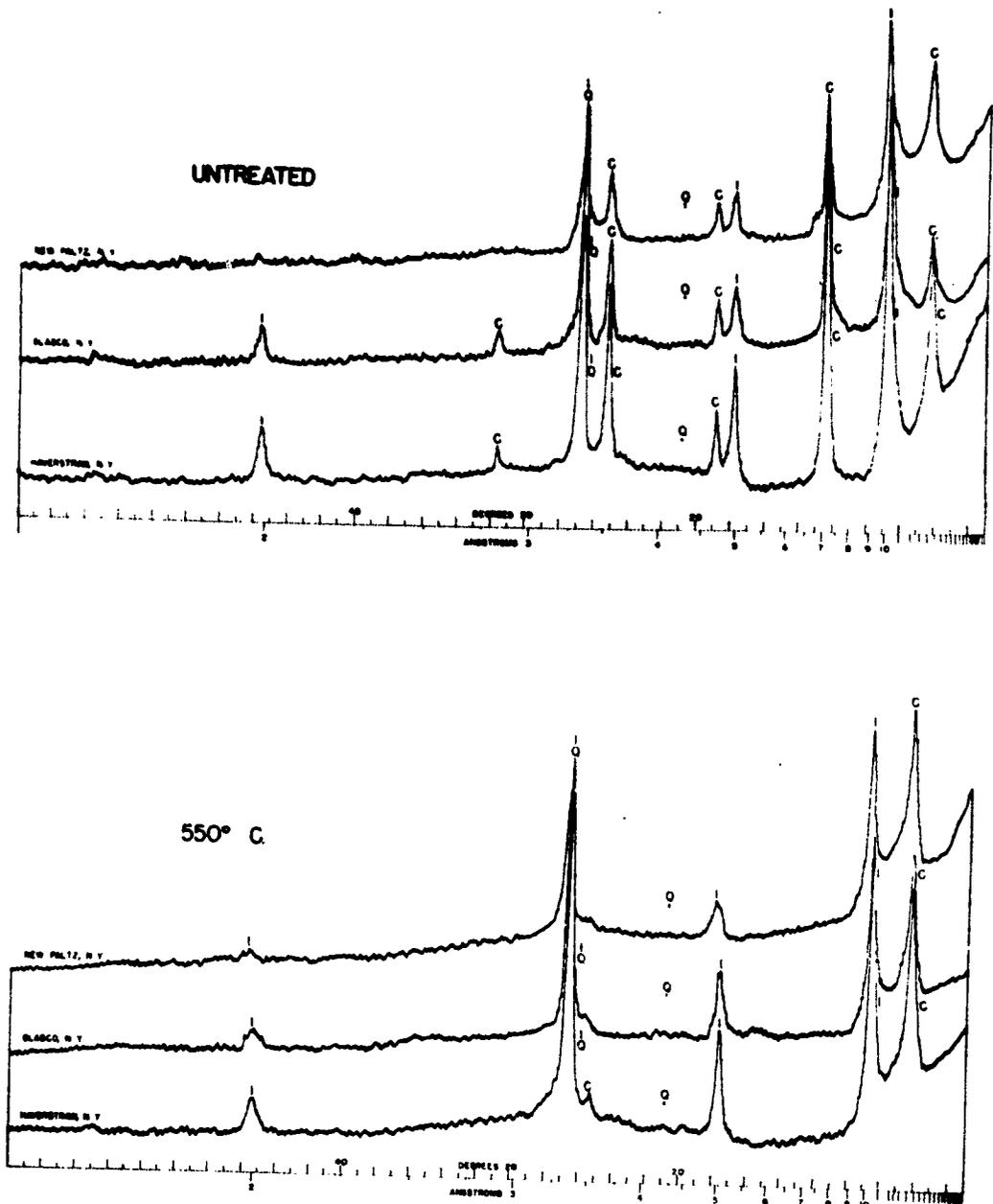


Figure 23. X-ray Diffractometer Patterns of Clay Mineral Constituents for Clay from New Paltz, N. Y., Glasco, N. Y., and Haverstraw, N. Y. See pg. 39, paragraph 3, for explanation of abbreviations.

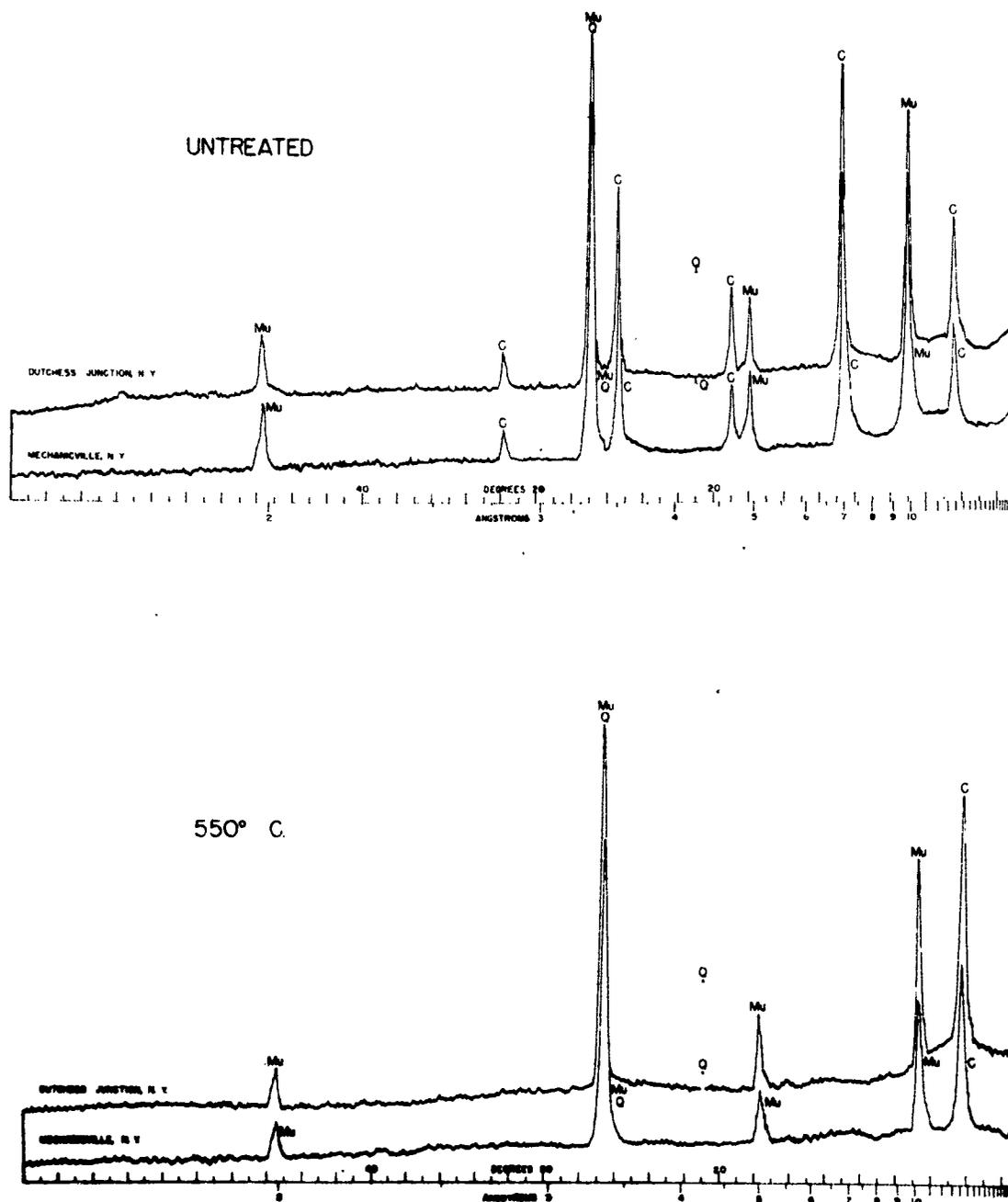


Figure 24. X-ray Diffractometer Patterns of Clay Mineral Constituents for Clays from Dutchess Junction, N. Y., and Mechanicville, N. Y. See pg. 39, paragraph 3, for explanation of abbreviations.

Table 5 is a tabulation of the mineral identifications of this study. In all cases, layer-structure minerals, largely the clay minerals, are more abundant in the minus 2 micron fraction than are the non-layer-structure minerals. In almost all cases, illite is the predominant clay mineral. The "illite" in this study has been identified, in part, from well-defined 10A reflections which show some broadening toward lower angles. These reflections, though narrow, are not as narrow as reflections from clay-size muscovite flakes. Because illite and muscovite are structurally and chemically similar, the "illite" may be degraded muscovite. It has been observed in the laboratory that grinding tends to produce poorly defined diffraction patterns of phyllosilicates. It is possible that the "illite" of these samples is really muscovite, the structure having been partially destroyed by the grinding effect of glacial scouring. Where interlayered between illite and another component occurs, the interlayered component never exceeds 10 per cent by volume.

Aside from illite, the next most abundant sheet silicate is chlorite. Vermiculite occurs occasionally and is almost always present when chlorite or interlayered chlorite are absent. Vermiculite may represent degraded chlorite. In all cases, save one, montmorillonite occurs in minor quantities; the Plattsburg specimen, however, contains major amounts of montmorillonite. In two samples muscovite is present. Quartz, albite, and microcline

are present in almost all samples. Hornblende and calcite occur in many samples and dolomite occurs rarely. These minerals predominate over the clay minerals in fractions coarser than clay size.

Mineralogically, there appears to be no significant difference between quick and non-quick clay. This suggests that the behavior of quick clays cannot be attributed to the presence of any particular mineral or mineral assemblage. In quick clay, flake-like minerals form a significant portion of the clay-size fraction, and the clay-size fraction generally constitutes at least half of the total clay sample. This high per cent of total clay minerals is of importance in explaining quick clay behavior.

Glacial scouring of the igneous-metamorphic shield areas of Canada and Scandinavia supplied much of the abundant quartz, feldspar, hornblende, illite and chlorite of the quick clay. Additional amounts of these minerals and some calcite were supplied to the Canadian clays by the Paleozoic shales, slates, limestones, and marbles of the St. Lawrence Valley. The Adirondack Mountain region and widespread early Paleozoic shales, slates, and carbonate rocks supplied the minerals found in New York clays.

TABLE 5

Mineral Constituents of Quick Clays

Sample	I	MU	C	V	C-V	C-M	I-M	I-V	M	Q	F	Ho	Ca
Vesten, Swed.	x		x?	x			x		x	x	nk	x	
Vesten, Swed.	x		x			x	x		x	x	nk	x	
Dykalla, Swed.	x		x?	x		x?	x		x?	x	nk	x	
Rosersberg, Swed.			x				x				nk		x
St. Vallier, Que.	x		x			x?			x	x	nk	x	x
Rimouski, Que.	x		x							x	nk		
St. Alban, Que.	x		x?				x	x		x	n	x	
St. Thuribe, Que.	x			x						x	nk	x	
St. Stanislas, Que.	x			x						x	nk	x	
Ste. Gene- vieve, Que.	x		x						x	x	nk	x	
Hawkesbury, Ont.	x		x							x	nk	x	x
Nicolet, Que.	x		x							x	nk	x	
Portneuf, Que.	x					x			x	x	n	x	
Portland, Me.	x			x			x			x	n		x
Oslo, Norway	x		x							x	nk		

Mineral Constituents of Non-Quick Clays

St. Joseph de la Rive, Que.	x				x					x	nk	x	x
Trois Pisto- les, Que.	x		x				x			x	n	x	x
Ste. Anne de Beaupre, Que.	x		x				x			x	nk		x
Ellesmere Is. Plattsburg, N. Y.	x		x			x				x		x	
Keeseville, N. Y.			x				x		x	x	nk	x	x
Whitehall, N. Y.	x					x				x	n		x
Glasco, N. Y.	x		x							x	n		x
New Paltz, N. Y.	x		x							x	nk		
Haverstraw, N. Y.	x		x							x	nk		x
Dutchess Junction, N.Y.	x		x							x	n		x
Mechanicville, N. Y.		x	x							x	nk		x

I, Illite; Mu, Muscovite; C, Chlorite; V, Vermiculite; Q, Quartz;
F, Feldspar; n, Albite; k, Microcline; Ho, Hornblende; Ca, Carbonate;
M, Montmorillonite; C-V, Interlayered Chlorite-Vermiculite;
C-M, Interlayered Chlorite-Montmorillonite; I-M, interlayered
Illite-Montmorillonite; I-V, Interlayered Illite-Vermiculite

NATURAL LEACHING

Several investigators have studied the effects produced when sodium chloride is leached from quick clays. Meyerhof (1957) noted that leaching reduced the remoulded shearing strength of a sensitive clay to such an extent that the clay became a viscous liquid. In a study of some Norwegian quick clays, Rosenqvist (1960) observed a considerable reduction in the salinity of the pore water by natural leaching. The leaching was greatest on the highest slopes where the hydraulic gradient was greatest. Rosenqvist observed that leaching below 15 grams of salt per liter produces a noticeable increase in sensitivity. Skempton and Northey (1952) made similar observations. On the other hand, Soderblom (1959) observed only a slight increase in sensitivity when quick clays from the Gota River Valley in Sweden were leached. According to Soderblom, natural leaching of marine clay with water containing carbon dioxide produces dilute solutions of sodium and magnesium carbonate which act as dispersants, thereby increasing sensitivity. Other natural dispersants are alkali sodium humate, sodium sulphite, sodium silicate and certain oxalates and phosphates (Soderblom, 1959).

Random stacking of clay particles produced by coagulation has been suggested to account for the behavior of quick clays (Rosenqvist, 1952; Skempton and Northey, 1952). The random structure is considered metastable and thus easily disturbed. Because most quick clays are marine,

random stacking of clay particles has been attributed to the coagulating effects of electrolytes. However, coagulation of clay particles suspended in distilled water may be induced by freezing. Therefore, sediments of fine coagulated material may accumulate in lakes experiencing periods of freeze and thaw.

Many quick clays are found in areas which have been glaciated. Following deglaciation these areas were uplifted several hundreds of feet. During uplift streams cut deeply into unconsolidated sediments, producing steep walled stream channels. Such steep banks may be unstable and are easily undercut by stream action (Gadd, 1957) or disturbed by an increase in load (Wenner, 1951). Steep slopes may contribute to the instability of quick clays, but most quick clay slides occur on shallow slopes, some as low as 1° (Jakobson, 1952).

EXPERIMENTS ON THE EFFECTS OF LEACHING

Thus far it has been shown that most quick clays are illitic marine sediments containing substantial amounts of clay size material. They have undergone extensive leaching and are particularly sensitive to disturbance.

Adapting techniques described in a series of papers by La Mer and Smellie (1959, 1962) and La Mer et al. (1957), experimental procedures have been developed to simulate deposition of clays in the marine environment and the leaching processes which such clays undergo.

The behavior of quick clays may be related to changes in the structural arrangement of the constituent minerals. Such changes may be reflected in changes in sediment volume, permeability, and shearing strength accompanying leaching. Because particle arrangement may be affected by particle shape, comparative experiments have been conducted using illite, which is flake-like, and quartz, which is equidimensional. Illite and quartz were chosen because they occur most commonly in the sediments under investigation.

Because quick clays are commonly fine-grained, the clay size fraction influence on sediment volume during sedimentation and leaching has also been investigated.

Examining such factors as pore water electrolyte concentration, particle size and particle shape may elucidate the influence each exerts on quick clay behavior.

Clay filter cakes were prepared by vacuum filtration of clay suspensions containing 12.6 per cent clay and having an electrolyte concentration of 35 grams of sodium chloride per liter. The electrolyte concentration used is about the salinity of sea water. Natural leaching was simulated by refiltering sodium chloride solutions of lower concentration through the filter cake, using newly prepared "marine" filter cakes with each less concentrated solution. Leaching was considered complete when the rate of refiltration remained constant. A record was made of the time required to refilter 35 ml of each solution. The minus 44 micron fraction of Fithian, Illinois, illite (Figure 25) was used in one set of refiltration experiments; quartz particles less than 44 microns in diameter, in another.

Because salinity changes appear to alter the shearing strength of clay sediments, the relative shearing strength of each filter cake was measured with a small lead disk. During filtration the filter cake was permitted to form around the disk, 4mm in diameter and 1mm thick, located 20mm from the center and 8mm from the edge of each filter cake. After leaching, the filter cake was placed on a centrifuge, rotated at 1000 revolutions per minute, and the number of seconds required to expel the lead pellet recorded. The pellet method can be considered analogous to Stoke's method for determining viscosity. In Stoke's method, a sphere is permitted to settle under

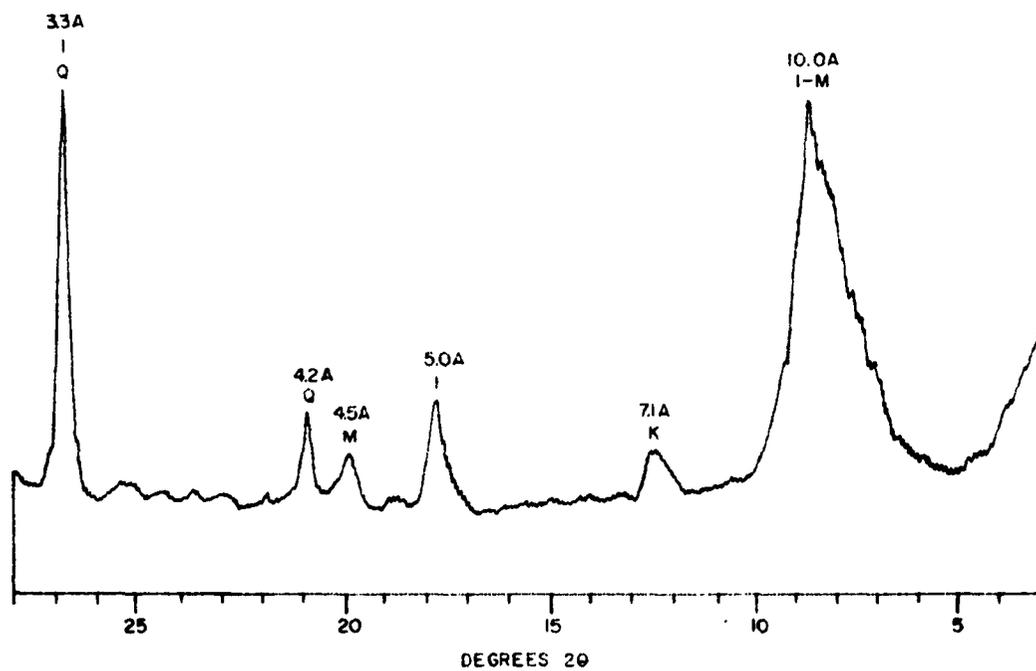


Figure 25. X-ray Diffractometer Pattern of Fithian, Ill., Illite. I, illite; I-M, illite interlayered with montmorillonite; M, montmorillonite; K, kaolinite; Q, quartz; A, angstroms. The amount of interlayered montmorillonite probably does not exceed 10 per cent.

the force of gravity through a medium whose viscosity is desired. The time required to settle a certain distance is a measure of the viscosity. It was found that the Stoke's method was inapplicable to the clay filter cakes because the clay was too viscous to permit settling. The centrifuge method overcomes this difficulty because a force considerably greater than gravity is applied to the pellet. As in Stoke's method, the time which the pellet requires to cover a certain distance reflects the viscosity. Time differences therefore reflect relative viscosities. It was necessary to use a small disk rather than a sphere to obtain a pellet of high enough mass to move through the filter cake with the revolutions per minute used. The results obtained using a centrifuge were reproducible within 5 per cent. Because viscosity and shearing strength both depend in the same way upon the internal cohesion of a material, viscosity can be used as an indicator of shearing strength.

Figures 26 and 27 show the results of these experiments. Leaching of Fithian, Illinois, illite produces a 60 per cent decrease in permeability between 0 and 5 grams of sodium chloride per liter (Figure 26). Between 5 and 35 grams, there is a permeability decrease of 30 per cent, the decrease becoming noticeable after leaching below 15 grams per liter. A 40 per cent increase in shearing strength occurs between 0 and 5 grams of

sodium chloride per liter (Figure 27). No significant increase in shearing strength is observable until after leaching below 10 grams per liter. In contrast, leaching of the silica filter cakes produces no significant change in permeability or shearing strength.

Filter cake volume changes occurring during leaching have been noted. To observe volume changes, it was necessary to deposit several filter cakes one upon another to obtain a suitable column of material. Four illite filter cakes yielded a volume of approximately 18,000 cubic millimeters. Five silica filter cakes were required to obtain the same volume. In all experiments, filter cakes were subjected to a vacuum induced compressive stress of 14.2 pounds per square inch, as measured with a closed tube manometer. Figure 28 shows that Fithian illite undergoes a one-third reduction in volume when leached with distilled water. Silica, in contrast, undergoes no volume change with leaching.

The reduction in volume may be explained as follows: deposition of clay minerals in a saline environment produces a porous structure of irregularly arranged particles, with water occupying the interstices as well as adhering to each clay flake. Leaching below 5 grams of sodium chloride per liter results in a pronounced weakening of the structure causing it to collapse under the vacuum induced pressure. Collapse forces out interstitial water, but adsorbed water probably continues to

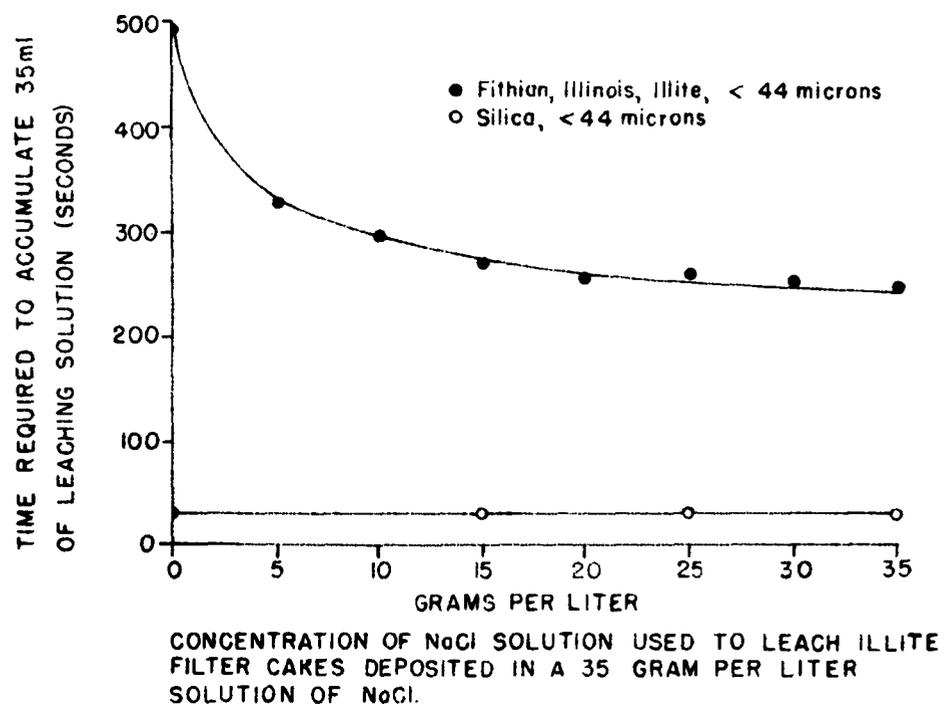


Figure 26. Filter Cake Permeability with Leaching.

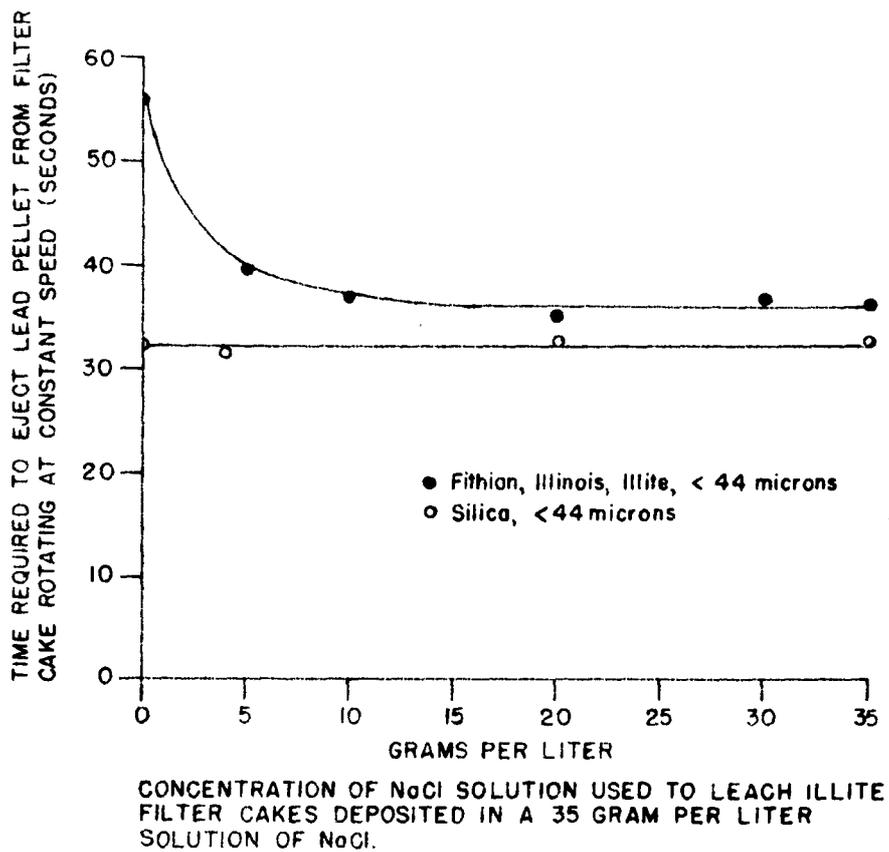


Figure 27. Relative Shearing Strengths of Leached Filter Cakes.

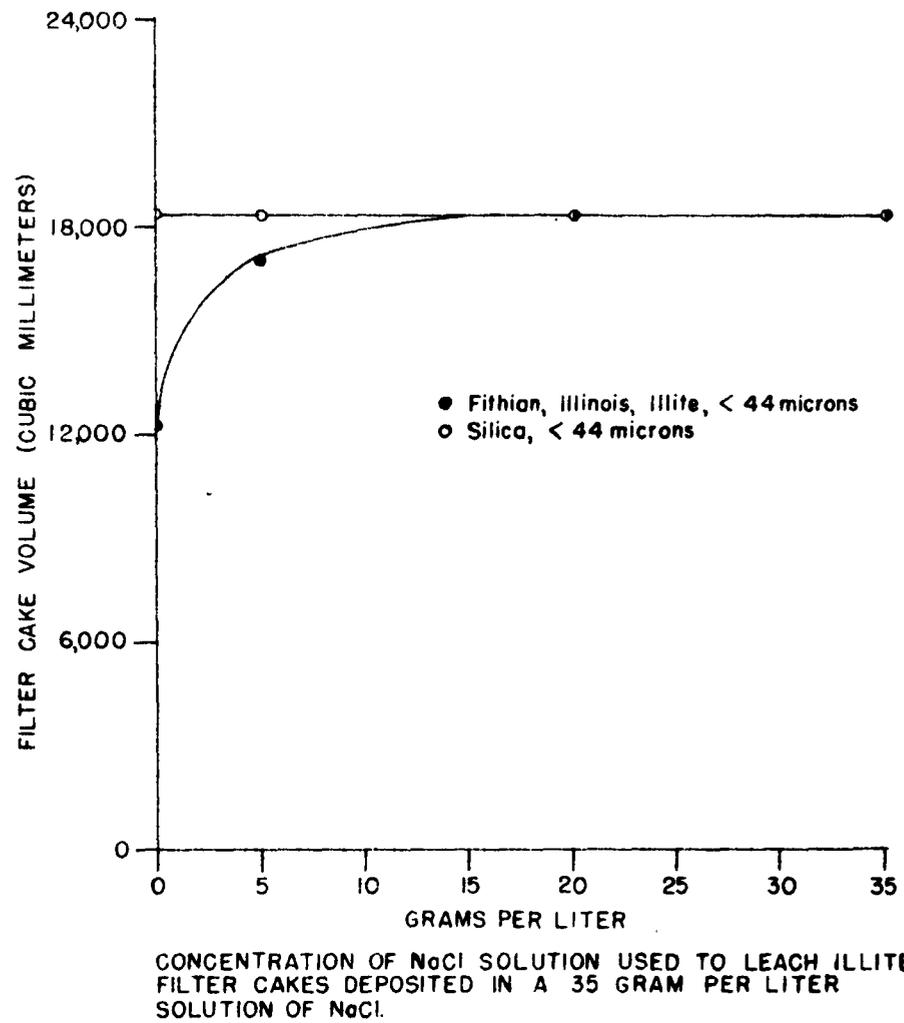


Figure 28. Changes in Filter Cake Volume with Leaching.

adhere to each clay particle. After collapse, the clay flakes may assume a sub-parallel arrangement. The silica filter cakes, as noted above, do not show significant changes in permeability, shearing strength, or volume with leaching of sodium chloride. More or less equidimensional materials such as quartz probably do not form random mesh or "card house" structures when deposited in saline environments. Such structures are evidently favored by coagulation of flake-like minerals. In the quick clay sediments under analysis, clay minerals provide flake-like constituents which are most abundant in the clay size fraction (less than two microns).

When equal amounts of different sediments settle in aqueous solutions containing 35 grams of sodium chloride per liter, the sediment volume accumulated appears to be directly proportional to the amount of sediment finer than two microns (Figure 29). The amount of solution incorporated within the sediment is also directly proportional to the less than two micron fraction. Clearly, as the clay size fraction (and therefore, the clay mineral content) increases, more extensive and continuous porous "card house" structures develop. When filter cakes of different sediments, deposited in 35 gram per liter solutions of sodium chloride, are leached with distilled water, the per cent decrease in filter cake volume accompanying leaching is directly proportional to the less

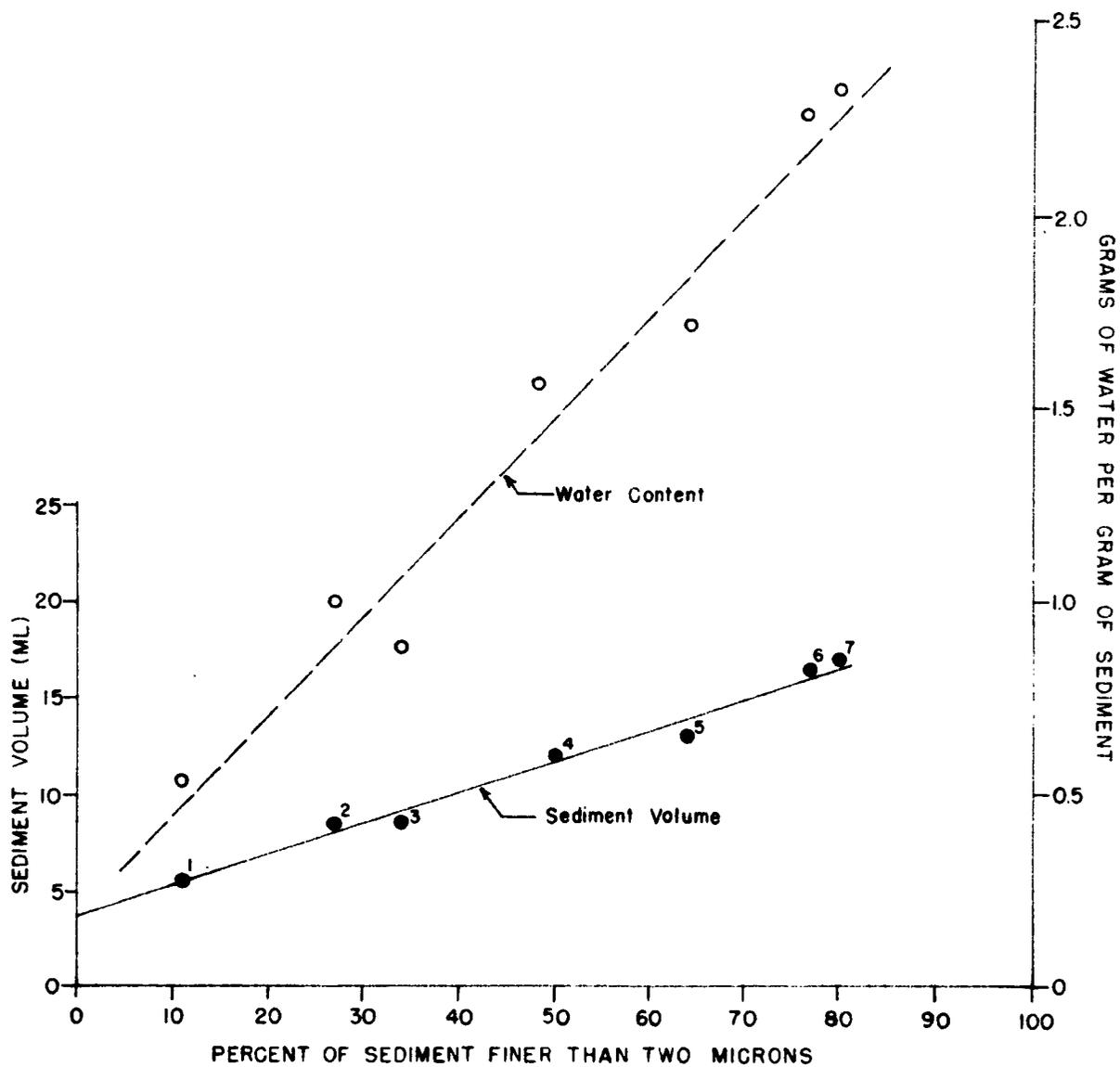


Figure 29. Sediment Volume as a Function of Clay Fraction.
 1. Ste. Anne de Beaupre, Que., 2. Rimouski, Que., 3. Ste. Genevieve, Que., 4. St. Thuribe, Que., 5. Vesten, Sweden, 6. Nicolet, Que., 7. Portneuf, Que.

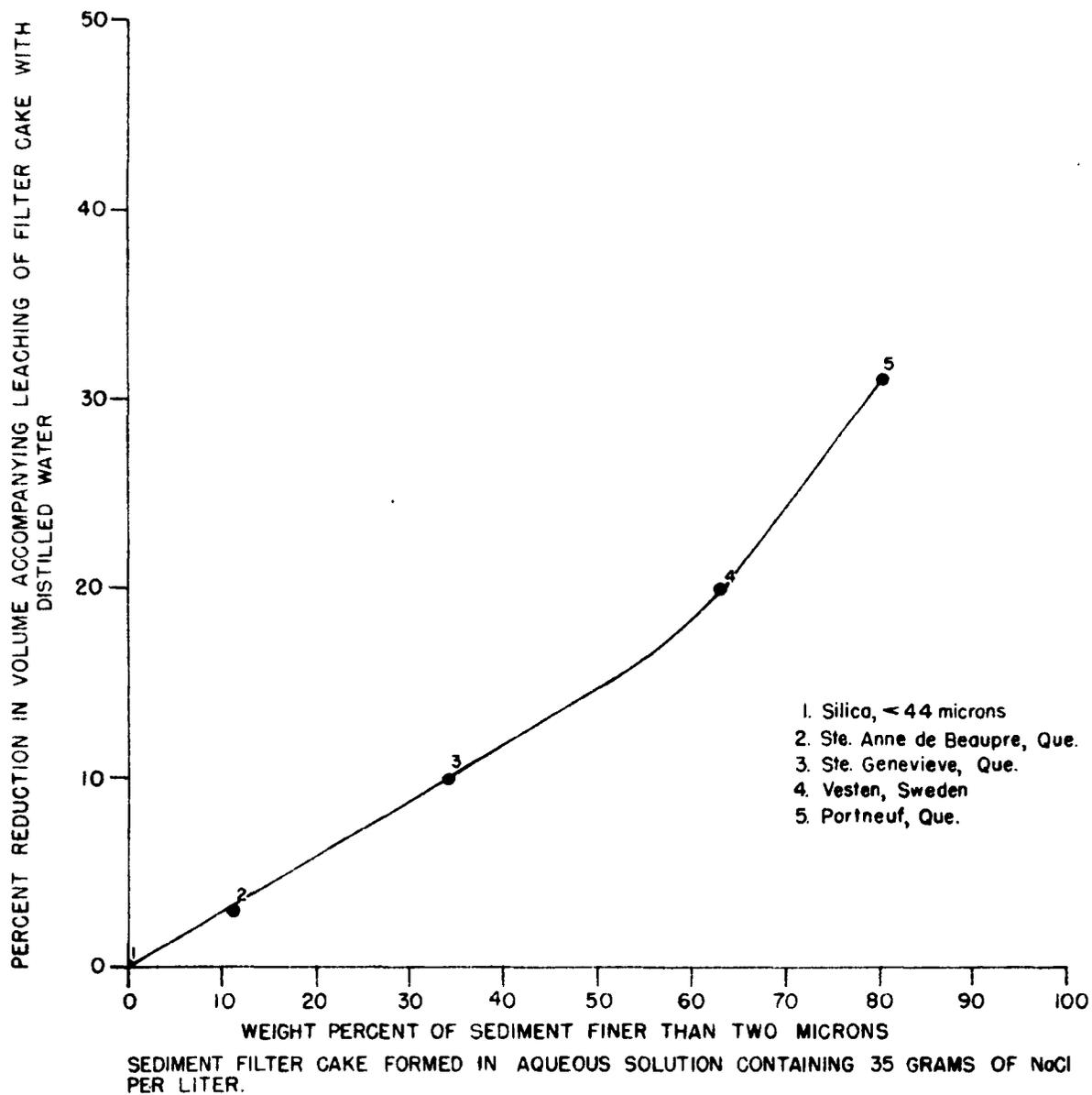


Figure 30. Volume Changes in Filter Cakes Leached with Distilled Water as a Function of Clay Fraction.

than two micron fraction (Figure 30) Expulsion of interstitial water accompanies collapse. The larger size fractions of the sediments seem to have little effect on the volume accumulated or volume reduction.

It is likely that sediments deposited in a marine environment and particularly rich in clay size material (and therefore clay minerals) will liquify and flow when the "card house" structure, made metastable through leaching, collapses in response to some disturbance.

Although, in the natural environment forcing out interstitial water changes the sediment into a flowing clay-water slurry, such flowage does not result in the laboratory experiments since the leached clay is confined to a Büchner funnel. The filter cake collapses in response to a rapidly applied vacuum induced compressive stress and the expelled pore water flow through the funnel into the collecting cylinder. The increase in compaction probably accounts for the increase in shearing strength.

Two reasons may explain why leached quick clays have not consolidated into denser, more viscous sediments under the weight of overburden: (1) an extensive "card house" structure can be supported by a relatively continuous and moderately static body of pore water; (2) leaching progresses slowly under the effect of gravity; thus, in the absence of a suddenly applied load, the "card house" structure maintains a state of metastable equilibrium.

In summary, Figures 26 to 28 indicate that flaky, rather than equidimensional minerals form a random mesh structure when deposited in saline solutions. This structure is particularly metastable when the pore water electrolyte concentration has been reduced to between 0 and 5 grams of sodium chloride per liter. Figure 29 shows that sediments have a large clay size fraction incorporate abundant amounts of water.

These experimental data, along with the geologic data, indicate that several factors contribute to the spontaneous mass flowage characteristic of quick clays. A depositional environment in which coagulation produces a "card house" structure of fine particles is apparently necessary. Coagulation may be induced by dissolved salts, as in marine environments, or by alternate freeze and thaw, as in lacustrine environments. Reduction of pore water salinity below 5 grams per liter is evidently necessary to render a sediment sensitive to disturbance. Disturbance disrupts the "card house" structure resulting in the escape of interstitial water. An adequate amount of interstitial water must be present so that its escape converts the sediment into a clay-water slurry capable of flowing on nearly horizontal surfaces. The incorporation of amounts of interstitial water necessary for such flowage requires an extensive "card house" structure. Because the degree of development of the "card house" structure is directly proportional to the clay size fraction, and therefore the clay mineral content as well, those sediments rich in clay size material will be most susceptible to spontaneous mass flowage.

CONCLUSIONS

Geologic evidence shows that with occasional exceptions quick clays (1) are deposited in a marine environment, the salinity of which is approximately 35 grams per liter, (2) have a pore water electrolyte concentration usually below 5 grams per liter, (3) usually have an abundance of clay size material (generally exceeding 40 to 50 per cent by weight) containing substantial amounts of clay minerals, and (4) contain great quantities of both pore and adhered water (generally exceeding 50 per cent in terms of weight of water per weight of sediment).

Experiments designed to reproduce the geologic environment and to show the interplay of the various geologic factors indicate that (1) illitic clay forms porous structures when deposited in a solution of marine salinity (35 grams of NaCl per liter), whereas, granular particles do not, (2) reduction of pore water electrolyte concentration below 5 grams of sodium chloride per liter renders the porous structure metastable and susceptible to collapse when subjected to compression, and (3) "card house" structure development, pore water content, potential reduction in sediment volume, and the amount of water expelled during sediment compaction are all directly proportional to the clay size fraction of a sediment and therefore clay mineral content as well.

In view of geologic and experimental evidence, spontaneous mass flowage of a sediment results when a

"card house" structure of clay flakes, made metastable by leaching, suddenly collapses in response to disturbance. During collapse, escaping interstitial water gives a sediment sufficient mobility to flow on surfaces which are nearly horizontal.

The three factors most responsible for quick clay formation appear to be an abundance of clay size flake-like minerals, a depositional environment favoring coagulation, and leaching of sediment pore water electrolyte concentration below 5 grams per liter.

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