TILL GEOLOGY, MINERALOGY AND GEOTECHNICAL BEHAVIOR, SARNIA, ONTARIO

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Dans le présent article, on discute en détail des relations entre la composition minéralogique et le comportement géotechnique des tills argileux épais et aqueux de Sarnia, en Ontario. On a établi des profils physico-chimiques, minéralogiques et de résistance au cisaillement jusqu'à une profondeur de 90 pieds. Des dislocations dans les courbes établies pour les carbonates, la salinité, le Ph du sol, le contenu en eau, ainsi que des valeurs erratiques de la résistance au cisaillement indiquent la limite entre les deux couches de till à 14 m de profondeur. Le lessivage superficiel a enlevé les carbonates situés en surface et les a déposés entre 2 et 6 m de profondeur, produisant ainsi une croûte grise au-dessous de la croûte brune. L'altération par oxydation a transformé les chlorites qui composaient initialement les tills en montmorillonite, modifiant ainsi les propriétés techniques du till sur 1 à 3 m dans la partie supérieure de la croûte. Le profil d'altération est entièrement développé dans le till supérieur. Une bonne connaissance des modes d'altération du sol, en particulier de l'oxydation de chlorite en montmorillonite, fournit un excellent outil d'interprétation stratigraphique.

THE THICK CLAY DEPOSITS AROUND SARNIA, Ontario, which form part of the Saint Clair Clay Plain[1] are the subject of this paper. The study site is located on flat grasslands 7 km southeast of Sarnia within the boundaries of the city landfill site. The clays of this area are believed to be "water-lain" tills and have long puzzled engineers because of their relatively low shear strength at depth below a very stiff to hard, brown surface crust.

The paper is presented in three parts: Part One describes the overall geology, mineralogy and physico-chemistry with depth and uses this and the strength data to separate the deposits into two till sheets; Part Two describes the surficial leaching and oxidation-weathering and relates the smectite so formed to changes in geotechnical engineering behavior; Part Three discusses the stratigraphic implications of clay mineral weathering with special reference to the areas around Lakes Erie and south Huron.

I: GEOLOGY, MINERALOGY AND SOIL PROPERTIES

About 41 m of fairly homogeneous clayey soils exist in the Sarnia area. They are believed to be late Wisconsin-age "tills" derived from previous, unconsolidated sediments and from underlying limestones and shales of Devonian age. At least two tills (representing Port Bruce and Port Huron advances of the Huron lobe almost synonymous in age with proglacial Lake Whittlesey) exist in the area.[2,3,31] The tills are distinguishable on the basis of contained carbonates and other features discussed below.

Except for a very stiff to hard, brown, oxidized and desiccated crust, the Sarnia Clays are grey and relatively soft throughout. Since most tills are understood by engineers to have been heavily preconsolidated by ice loads, the Sarnia "tills" constitute an unusual deposit. The geology and engineering properties of these soils have been described throughout in some detail by several authors.[4,5,6,7,8,9,10,11]

Soil Composition and Engineering Properties

The engineering properties are summarized in Fig. 1. The auger borings, from which shelby tube samples were extracted, extend only to 29 m since the open holes squeezed in at this depth. The surface crust, which is characterized by high in situ vane and unconfined compressive shear strengths, consists of an upper brown zone and a lower grey zone. The upper zone represents oxidation-weathering and desiccation during a time of ground water levels lower than present levels.[6,11] These same low water levels have resulted in at least a slight preconsolidation of the clayey soils throughout their entire depth.

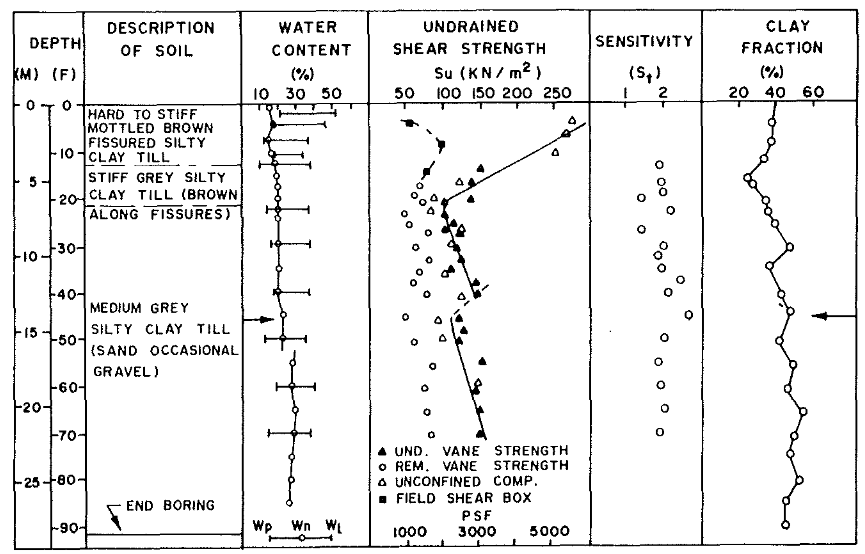

FIGURE 1. Summary plot, engineering properties vs depth, Sarnia clay tills (arrows mark probable contact betwen tills).

The lower grey portion of the crust has probably been produced primarily by upward moisture migration to satisfy surface transpiration and evaporation during the dry climatic period which produced the thick oxidized crust. Very large variations in the thickness of the crustal zone both laterally and vertically at Lambton, Ontario, have been attributed[7] to removal of water by deep rooted trees beneath forested areas. Reference to the carbonate profile in Fig. 2 shows an increase in carbonate within the brown and grey crustal zones; it is suggested in Part Two that this carbonate enrichment may also have played a role in development of increased strengths in the grey crustal zone.

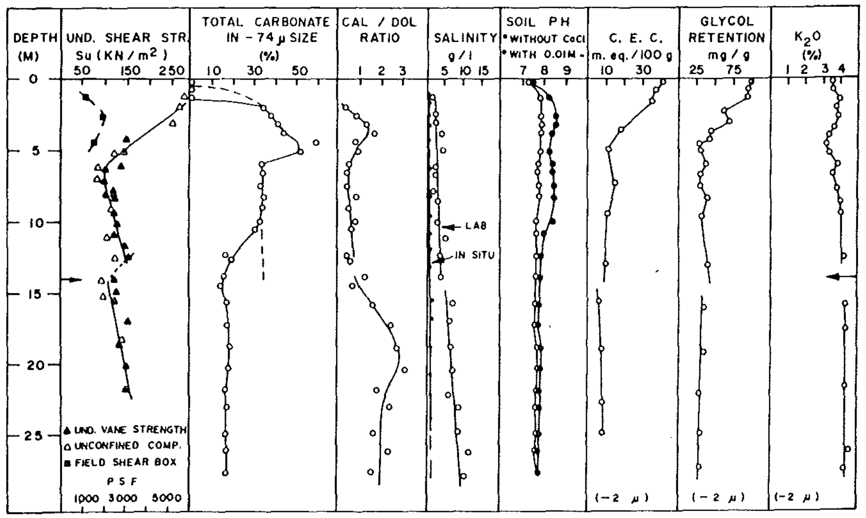

FIGURE 2. Summary plot, physico-chemical properties vs depth, Sarnia clay tills (arrows mark probable contact between tills).

The dashed strength plot represents large scale in situ direct shear tests which are discussed in Part Two. The weakest soils generally occur below the clay crust but at Sarnia, two weak zones having a strength of about 100 kN/m^2 occur at 7 and 15 m depths as shown on the strength profile. A dislocation in the strength versus depth plot occurs approximately at 14 m depth. This is believed to mark the boundary between two separate till layers.

The moisture content profile shows a slight break at 14 m with the moisture content below 14 m depth averaging about 27% compared with about 20% for the undesiccated portion of the upper till. The moisture content is unusual in that it increases with depth as previously described.[4] The liquid limit is fairly constant with depth varying from about 35 to 40% with the higher values in the lower till where the clay size fraction is also higher (~50% compared with ~40%). Both tills contain about 10% sand sizes, the rest being silt.

Additional physico-chemical data are presented in Fig. 2. The profile for total carbonate[12] shows a nearly constant value of 18% for the lower till compared to 35% for the upper till below the leaching and deposition zones. The break in the profile occurs at 14 m with a mixing zone extending 5 m into the upper till. As shown by the profile for the calcite/dolomite ratio, the upper till is dolomite rich and the lower till calcite rich. This conforms to previous observations[2] for equivalent surface tills to the east.

The other physico-chemical profiles also show slight dislocations at 14 m depth (K_2O, cation exchange capacity, glycol retention, salinity and pH). In view of the previous discussion, it is believed that all of these are significant. The pH profile is interesting since, even with a carbonate content of 35%, addition of 0.01M$CaCl_2$ to the soil-water mixture (1:5) releases H^+ from exchange sites causing a drop in pH from 8.5 to 7.8. The lower till did not show this peculiarity.

The salinity profile was obtained using two methods: 1) in situ measurements[13] using a Geonor corrosion probe borrowed from Geocon Ltd.; and 2) laboratory measurements using a conductivity probe in a 1:5 mixture of air dried soil and water.[14] The lower values of about 1 gm/l, obtained in situ using the probe, correspond closely to recent values obtained on water samples squeezed from the tills at high pressures.

The two tills also contain abundant quartz and minor amounts of feldspar. The clay minerals present are abundant dioctahedral illite and trioctahedral chlorite, as shown by the x-ray traces in Fig. 3 and other traces of the (060) reflections before and after chemical treatment.[8] Heat treatment of the clays to 550°C destroys the 7Å peak and causes the 14.2Å peak to intensify and shift to 13.6Å, a characteristic of iron chlorite.[15] Only trace amounts of swelling clay are present in the unweathered tills. The illite basal reflections are slightly different in the two tills, the (001) peaks occurring at 10.16Å for the upper till compared to 10.04Å for the lower till.

On the basis of this discussion, the thick sequence of clayey soils at Sarnia is divided into two till sheets. Although the till sheets are normally in direct contact with one another, recent soils investigations in the Corunna area have shown pockets of silty sand up to 4 m thick occurring within the clayey soil sequence at a depth of about 18 m. Perhaps these have the same frozen lump origin as sand pockets noted in 13 m deep excavations just south of Sarnia.[4] Other authors have encountered a thin sandy basal till directly overlying bedrock which was not reached by our auger borings.

II: SURFACE WEATHERING

Surface oxidation and leaching within the crust has produced very significant compositional changes in the crustal zone of the Sarnia deposits. Some of the physico-chemical mechanisms and their engineering significance have already been discussed[16,17] but since the changes in clay mineralogy are significant to the stratigraphic discussions of Part Three, the weathering processes will be reviewed here.

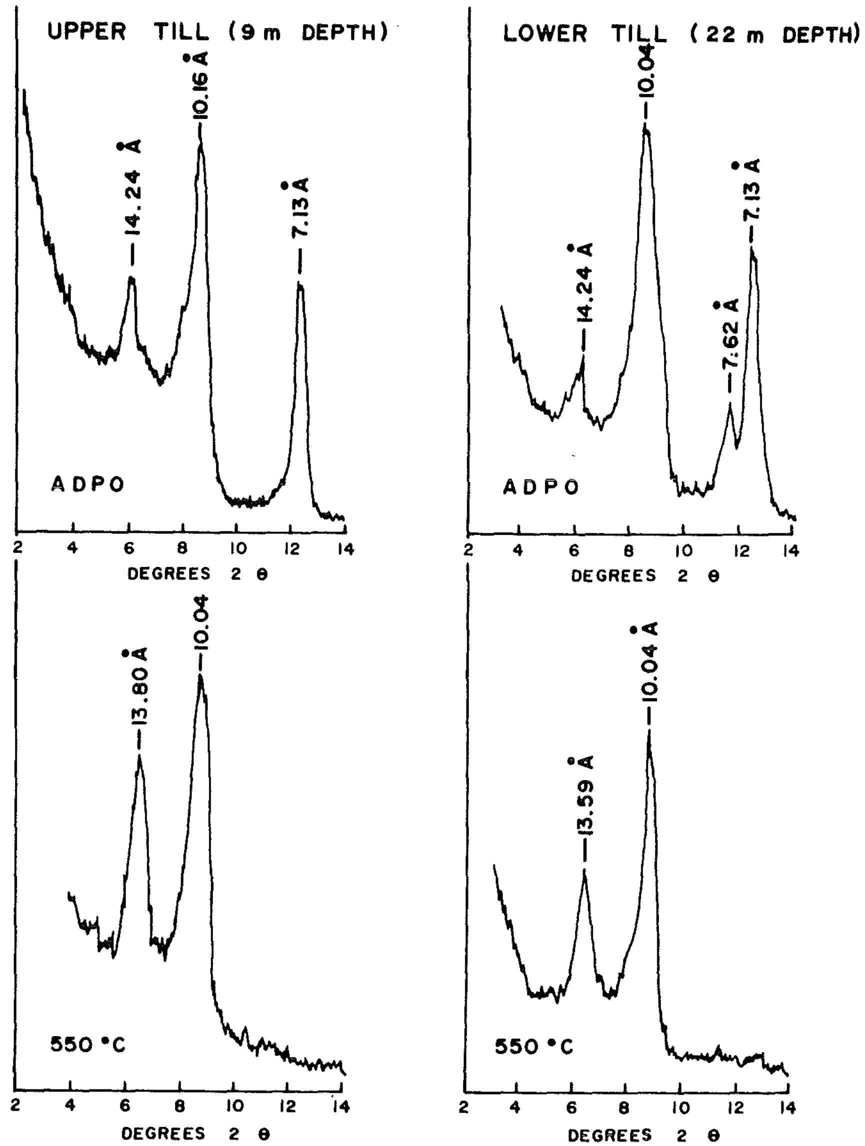

FIGURE 3. X-ray diffraction traces of the clay size fraction, unweathered, upper and lower tills (ADPO = air dried preferred orientation; 550°C = heated for 30 min.).

Carbonate Leaching and Redeposition

The carbonate profile in Fig. 2 shows that the contained carbonates have been removed by leaching from the surface soils. The dashed curve represents leaching to a depth of about 0.5 m (recent tests) and the solid

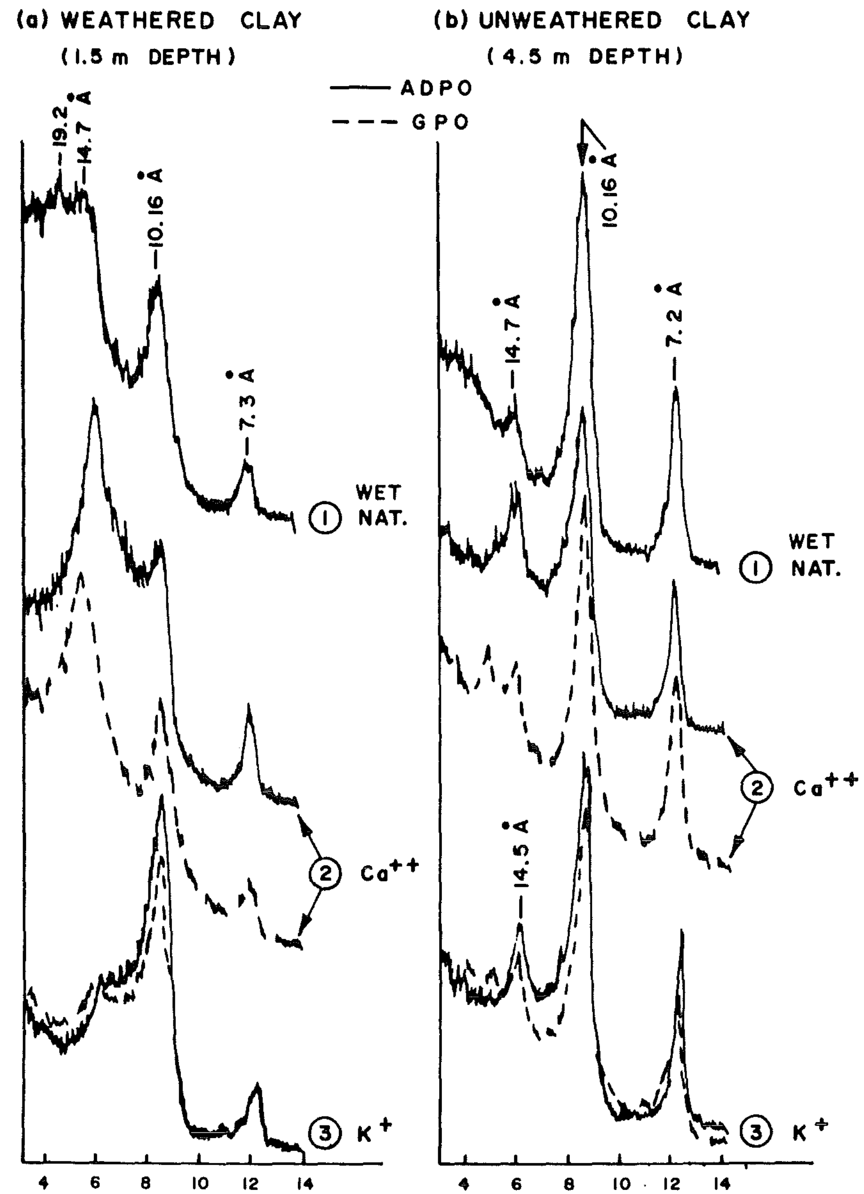

FIGURE 4. X-ray diffraction traces of weathered and unweathered clays, Sarnia upper till. (1) = Natural, water wet (never dried), (2) = Ca++ sat'd, Air dried, preferred orientation (ADPO), glycolated preferred orientation (GPO), (3) = K+ sat'd, ADPO and GPO.

curve shows leaching to 1.5 m reported previously at a nearby site.[16] Judging from the hump in the carbonate curve, it appears to have been redeposited at depth in the lower brown and grey crustal zones. A corresponding decrease in moisture content at these depths suggests that carbonate deposition and desiccation both play roles in crust formation. Precipitation of iron hydroxides is a further feature of crust formation.

Since the carbonate hump is quite large, it is also remotely possible that this represents a "facies change" within the till or possibly even another till sheet. Leaching and desiccation have caused close-spaced fissuring that has reduced the surface soils to a crumbly mass. The intensity of fissuring decreases with depth to a spacing of about 1 m at a depth of 5 m. Between 1.5 and 3.0 m depth, the fissures are in two sets which dip nearly vertically and strike more or less at right angles to one another.

Clay Mineral Alteration by Weathering

X-ray traces of the clay fraction at 1.5 m depth (weathered) and 4.5 m depth (unweathered) are presented in Fig. 4. The unweathered upper till (Fig. 4b) contains abundant illite and iron chlorite as shown by the strong 10Å and 7Å peaks on all traces. A small amount of swelling clay (~3%) is also present as indicated by the small 18Å peaks on trace 2.

In the weathered crust, the clay mineral assemblage is very different (Fig. 4a) the iron chlorite having been extensively destroyed by oxidation to produce up to 15% smectite. This swelling clay appears as a strong group of low angle peaks (14.7 to 19.2A) in trace 1 and as a very strong 16Å peak in trace 2 (glycolated after air drying). The swelling clay is a relatively high charge smectite or low charge vermiculite since it collapses readily to 10Å upon potassium saturation as shown in trace 3.

The quantitative mineralogy[16] is summarized as follows:

	0.3 m	*4.5 m*
Illite	~ 21%	~ 14%
Chlorite	~ 5%	~ 10%
Smectite	~ 15	~ 2
Carbonate	~ 0	~ 35
Quartz and Feldspar	~ 60	~ 40

The increase in swelling clay from the base of the brown crust upwards is responsible for the marked increase in cation exchange capacity from 11 to 41 m.eg./100 g at surface. A similar increase in glycol retention from 25 to 100 mg/g represents the increased surface area associated with the swelling clays. Chlorite oxidation to produce swelling clays in the south Huron area tills has been discussed by several authors,[18 19 20 21 22] so the mechanism is now believed to be fairly well established.

It should be specially noted that this type of weathering does not involve removal of potassium from the interlayer position of soil mica to produce soil vermiculite and smectite.[23 24] Some depletion of potassium does occur at Sarnia but only in the upper 0.3 m of carbonate free soil in the region of the topsoil where the pH is less than 7. As shown by the K_2O profile in Fig. 2, the potassium present follows closely the percentage of clay size material present as plotted in Fig. 1.

Engineering Significance of Weathering

Although complete discussion of the engineering significance of the surface weathering (in particular the increased smectite content) is beyond the scope of the present paper, the following are significant features:

1. *Compaction:* The surface soils compact to a maximum density of 8 to 15 pcf less than the deeper unweathered soils especially if leached free of carbonate: air drying tends to remove these differences since some of the smectite collapses irreversibly;[16]
2. *Atterberg Limits:* The liquid limit increases from 20% at 2 m depth to 52% towards the surface with a corresponding increase in activity from 0.4 to 1.0.[25]
3. *Swell Potential:* Measured swell potentials (percent swell under 1 psi loading) increase from near zero at 2 m depth to 7% for carbonate free, weathered surface soils;[25]
4. *Residual Friction Angle:* The residual friction angle is reduced in the surface soils to about 18° compared with 27° for the unweathered soils.[6 25] This is very significant in the design of dykage systems and embankments using weathered soil as fill; and
5. *Fissuring:* The extensive near surface fissuring and horizontal clay platelet parallelism in the till produces a bulk strength much lower (dashed curve) than the intact lump strength (solid curve) plotted in Fig. 2: a more complete discussion of fissures and clay fabric including scanning electron photomicrographs may be found elsewhere[17]: an increased bulk permeability along the fissure systems must be considered in landfill location and design.

III: Clay Mineralogy As A Stratigraphic Tool

Clay mineral analyses using x-ray diffraction techniques are becoming routine in till studies even though quantitative analyses are frequently very difficult. In *Till: A Symposium*, several authors[26 27 28] reported rather comprehensive clay mineral analyses for various till strata. Abundant montmorillonite (smectite) was noted to be characteristic of certain till sheets and was used as a stratigraphic indicator and as a till source indicator.

In the present studies, high smectite contents at surface represent weathering and not a different till sheet nor a different source area. Current studies at Cleveland, Ohio, indicate that the high smectite content of the Garfield Heights till probably does not reflect a different source area but extensive in situ oxidation weathering and leaching that has removed all of the original chlorites and carbonates respectively. Over-riding till sheets would be expected to contain some of this smectite especially near the base.

The Port Talbot I, interstadial green clay of Mid-Wisconsin age (~53,000 years B.P.) has been described as an accretion gley derived from weathered Bradville till in the Lake Erie north shore stratigraphic section.[22] It is the only montmorillonite rich soil in the entire section and is of some stratigraphic significance. Since no weathered Bradtville till has yet been encountered, oxidation conditions similar to those existing today at Sarnia were hypothesized to explain its composition.

In interpreting the significance of swelling clays in a given stratum, considerable care must be taken to assess whether it represents erosion of a weathered soil, an in situ weathering situation or a totally different source area.

A further complicating feature is that pseudo-montmorillonite may also be produced by potassium removal from soil micas to create vermiculite which will then expand to 18Å upon adsorption of complex aluminum and iron hydroxide cations at pH values of 3.5 to 4.5.[23, 29] Considerable chemical pretreatment[30] is required prior to x-ray investigations to establish the true nature of these clay minerals.

Acknowledgments

The majority of the research reported in this paper has been sponsored by research funds from the National Research Council of Canada to the first author and a Commonwealth Scholarship to the second author. Special thanks are extended to P. Smith of the Ministry of Transportation and Communications, Ontario, for permission to refer to current compaction studies on soils in the Sarnia area.[25]

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